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SP500

Nutrient Management of Vegetable and Row Crops Handbook

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SL425

Introduction to *Nutrient Management of Vegetable and Agronomic Row Crops*[1]

Kelly T. Morgan[2]

As Florida's population continues to increase, there are more impacts to and competition for Florida's limited water resources. All Floridians can take part in conserving and protecting these resources. The vegetable and agronomic crops industry is extremely diverse and covers many geographic regions of the state. According to the 2012 Florida Agricultural Statistics Service data, Florida ranks second behind California in fresh market vegetable production, with approximately 237,000 acres of vegetables and a farm value exceeding $2 billion in revenue. Agronomic crops, including sugarcane grown in south Florida and field crops grown primarily in north Florida, total approximately 986,000 acres.

The Federal Clean Water Act (FCWA) required states to assess the impacts of non-point sources of pollution on surface and ground waters and then to establish programs to minimize them. Section 303(d) of the FWCA also requires states to identify impaired water bodies and establish total maximum daily loads (TMDLs) for nitrate, phosphate, and total dissolved solids entering these water bodies. In Florida, the Florida Department of Agriculture and Consumer Services (FDACS) has established Best Management Practices (BMPs) based on research, field testing, and expert review to reduce the impact of agricultural production on surface and groundwater quality. BMPs are specific cultural practices aimed at reducing the load of a specific compound, while maintaining or increasing economical yields that have been determined to be the most effective and practicable means for maintaining or improving the water quality of surface and ground waters. At the same time, BMPs should not become obstacles to vegetable and agronomic row crop production. Instead, BMPs should be viewed as a means to balance economical vegetable and agronomic row crop production with environmental responsibility.

The BMPs that apply to production of vegetable and agronomic crops in Florida are described in *Water Quality/Quantity Best Management Practices for Florida Vegetable and Agronomic Crops*. This manual was developed by FDACS in 2005 and revised in 2015 through a cooperative effort between state agencies, water management districts and commodity groups, and under the scientific leadership of the University of Florida's Institute of Food and Agricultural Sciences (UF/ IFAS). The manual has undergone a thorough scientific review. The manual may be consulted online at http://www.freshfromflorida.com/Divisions-Offices/Agricultural-Water-Policy.

Benefits to enrolling in and implementing BMPs include a presumption of compliance with state water quality standards for the pollutants addressed by the BMPs. Even if additional numeric nutrient criteria become part of state standards, producers who enroll in and implement the BMPs still have the presumption of compliance and the eligibility for cost-share for certain BMPs (as available).

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The vegetable and agronomic crop BMPs have adopted all current UF/IFAS recommendations, including those for fertilizer and irrigation.

Through the implementation of a series of targeted cultural practices discussed in this production guide, growers should be able to reconcile economic profitability and responsible use of water and fertilizer.

- Soil and tissue sampling and testing are key BMPs for fertilizer recommendations and soil pH adjustments. To better develop a production system based on these tests, proper sampling practices and test interpretations are provided in this guide.
- The use of drip, overhead, and center pivot irrigation is increasing in Florida but must be managed correctly to improve water-use efficiency and not leach nutrients from the soil. Information on irrigation management methods and automation are discussed.
- Use of alternate fertilizer materials to retain nutrients in the soil but allow adequate supply for crop uptake—such as the use of controlled-release fertilizers and composts—are discussed in this production guide. At the field level, adequate fertilizer rates should be used together with irrigation scheduling techniques and crop nutritional status monitoring tools (i.e., soil tests, leaf analysis, and petiole sap testing).

Use of these BMPs ensures that adequate fertilizer rates may be achieved by combinations of UF/IFAS recommended base rates and supplemental fertilizer applications.

The Four Rs of Fertilizer Management[1]

George Hochmuth, Rao Mylavarapu, and Ed Hanlon[2]

Fertilizers or nutrients are required in most crop production systems in Florida. While all soils in Florida can supply nutrients for crop production, nutrients may not be always available in adequate amounts for economical crop production. Supplying needed nutrients for crop production involves attention to four major fertilization factors (the 4Rs): *right rate*, *right source*, *right placement*, and *right timing*. Attention to these factors will provide adequate nutrition for crop production while minimizing the risk of loss of nutrients to the environment. The 4Rs (terminology promoted by the International Plant Nutrition Institute [2014]) are important components of nutrient best management practices, and university Extension specialists have been promoting these components of nutrient management for many decades. In this publication each factor is described, as well as how the information can be provided from a soil test report to help farmers make efficient use of their investment in fertilizer for crop production and for environmental protection. These factors are often interrelated; for example, placement and timing of fertilizer may need to be addressed together, such as the right placement of bands of fertilizer for side-dressing during the appropriate stage (i.e., right timing) of crop growth during the growing season. While not a formal part of the 4Rs, the importance of irrigation to overall nutrient management is stressed in this publication.

Right Source

Selecting the *right source* of fertilizer or the right material to deliver the nutrients is important. The right source can be related to the following questions:

- What source of nutrient(s) would be the least expensive per unit of delivered nutrient?
- Should an organic source (compost or manure) of nutrient be considered?
- When is a controlled-release fertilizer the right source?
- What sources can simultaneously deliver more than one needed nutrient?
- When should a liquid form be used instead of a dry form?
- When should the salt index of the fertilizer be considered in selecting the right source?

The right source often involves the ease of application of a nutrient and cost per unit of nutrient. In addition, efficiency of nutrient use may be considered. For example, a controlled-release nitrogen source may be preferred to deliver small amounts of nutrients throughout the growing season, instead of larger amounts of nitrogen delivered in a few side-dressings from a soluble source.

The right source may be manure if the farmer would like to take advantage of the organic matter supplied along with the plant nutrients. The organic matter may increase the water-holding capacity and nutrient supply of the soil.

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2. George Hochmuth, professor, Soil and Water Science Department; Rao Mylavarapu, professor, Soil and Water Science Department; and Ed Hanlon, professor emeritus, Soil and Water Science Department; UF/IFAS Extension, Gainesville, FL 32611.

Right Rate

Crops require a certain amount of plant nutrients for production of profitable crops. Part of this nutrient quantity can be supplied from the soil, and the remainder must come from fertilizer, either synthetic sources or organic forms (such as livestock wastes composts) or green manure crops. The first key to practicing the *right rate* concept is soil testing (see Hochmuth et al. 2014). Before the crop is planted and any fertilizer has been applied, soil testing can help determine the portion of the crop nutrient requirement that is already available from the soil. Using a strong research information base, the recommendation for the right rate of fertilizer can be made from the soil test result.

The *right rate* refers to the amount of fertilizer needed for the crop production season and is based on extensive research over locations, crops, varieties, and years. The right rate also refers to the amount of fertilizer applied at one time in the growing season. For example, the farmer needs to know, depending on the cropping system used, the right rate of fertilizer to apply in the following scenarios:

- In the preplant application, while the mulched bed is made for plasticulture vegetables
- As a starter fertilizer for direct-seeded crops like potato, corn, or cotton
- As the amount to inject (fertigation) into the drip irrigation system at any one time
- In a single side-dressing during the growing season for an unmulched crop
- In a single fertigation through the center-pivot irrigation system

Sometimes the right rate to apply at any one time is related to the nutrient involved. For example, in plasticulture vegetables, all of the phosphorus may be applied to the soil while the bed is made. Likewise, a portion of the nitrogen and potassium may be applied while the bed is being made and the remainder applied through the drip irrigation system.

Right Timing

The *right timing* of nutrients takes into consideration the growth pattern of the crop and, therefore, natural changes in nutrient demand during the season. Crop development begins slowing from seed germination or transplanting, then increases through fruiting, and finally slows down at maturation. This pattern for crop development is referred to as *sigmoidal* growth (Figure 1). Anticipating changes in growth and nutrient demand is important so that fertilizer application can be timed to meet the needs of growth. A good example of timing of nitrogen and potassium fertilization to meet changes in crop development can be seen for drip-irrigated tomato (Figure 2).

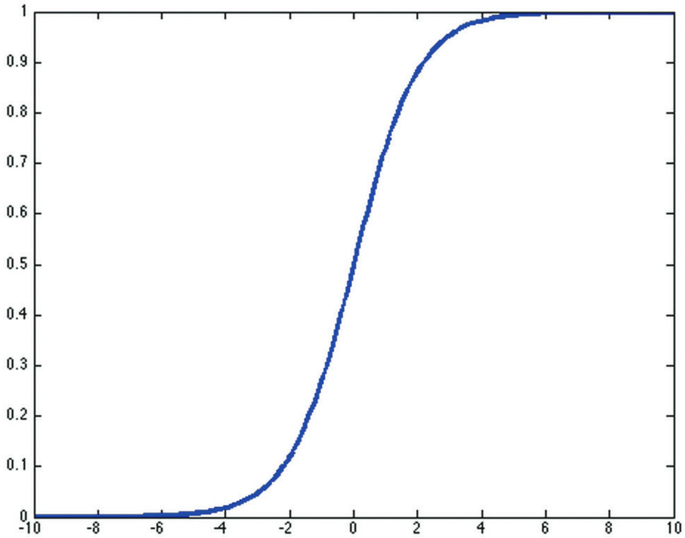

Figure 1. A sigmoidal function—for example, slow crop growth at first, then a zone of rapid increase, followed by attenuation of growth.

Period in the season	Amounts of N and K (K_2O)
Preplant	0 to 70 lb per acre
Weeks 1–2	1.5 lb/acre/day
Weeks 3–4	2.0 lb/acre/day
Weeks 5–11	2.5 lb/acre/day
Week 12	2.0 lb/acre/day
Week 13	1.5 lb/acre/day

Figure 2. Recommendations for injecting N and K_2O for mulched, drip-irrigated tomatoes in Florida.

The right timing is often interrelated with the right rate and right placement. For example, as the drip-irrigated tomato crop develops, the rate changes with time so that smaller rates are applied later in the growing season. Greater rates of nutrients are applied at or just before the time when the vegetative growth rate is maximal and fruits are being developed.

Rainfall is difficult to predict; however, when possible, fertilizer application should be timed to minimize the chance of leaching of nutrients due to heavy rainfall.

Right Placement

For maximum nutrient efficiency, nutrients need to be placed where the plant will have the best access to the nutrients. For most crops, the *right placement* is in the root zone or just ahead of the advancing root system. Most nutrient uptake occurs through the root system, so placing the nutrients in the root zone maximizes the likelihood of absorption by the plant.

Banding and broadcasting are two general approaches to nutrient placement. *Banding* is the placement of fertilizer in concentrated streams or bands in the soil, typically near the developing plant. *Broadcasting* is the spreading of fertilizer uniformly over the surface of the soil. Whether to use banding or broadcasting often depends on the type of crop and the development or spread of the root system. Broadcasting is usually most effective either later in the season when roots of a row-crop have explored the space between the rows, or for forage crops that cover the entire soil surface. Fertigation of nitrogen through a center-pivot irrigation system for corn may be a type of fertilizer broadcasting system.

Placement and timing interact because as the crop develops, the root system expands. Placement of fertilizer ahead of the advancing root system for unmulched crops, like potato or cotton, avoids damage to the root system by the fertilizer application equipment. Another example of this interaction would be for fertigation with a pivot irrigation system. The first side-dressings of nitrogen early in the growth cycle for corn may be applied by knifing liquid fertilizer to the side of the row, followed later in the season with applications through the irrigation system. These combinations of timing and placement maximize the likelihood of nitrogen uptake by the plant related to the expansion of the root system.

The tillage system may affect the placement of nutrients. For example, incorporating a nutrient may not be possible in certain minimum tillage systems. In no-till corn production, early nitrogen and phosphorus applications can be made by banding near the seeds with the planter, with later applications of nitrogen by the center-pivot irrigation system.

The right placement is also related to the nutrient in question. For example, phosphorus can become fixed in unavailable forms when it is mixed in with some soils. The main reason P is banded is that it is immobile in the soils and therefore has to be placed nearer to the roots (or the roots have to grow towards the P granule). In sandy loams, P applied to the surface will get adsorbed and can accumulate over time. Accumulations also occur in soils applied with P sourced from organic or manure related amendments. In these situations, banding of the fertilizer reduces, at least temporarily, the mixing of the fertilizer with the soil and increases the chance that phosphorus will remain in a soluble form for root uptake. For example, banding starter-phosphorus may be preferable to broadcasting.

The right placement may also relate to the form of the nutrient source, such as urea nitrogen. Nitrogen from urea may be subject to loss by volatilization when the urea is left on the surface of soil with a high pH. Incorporating the urea or applying a small amount of irrigation to move the urea into the soil helps reduce volatilization losses.

In certain situations and for certain nutrients, foliar applications of fertilizer may be preferred. For example, micronutrients may be more efficiently applied to the foliage for iron or manganese when the soil pH is high.

Integrated Approach

All nutrient management practices are the result of many years of research and field experience at the commercial farm level (Table 1), and these practices are subject to refinement as farmers gain experience and as new research is completed. Optimal nutrient management rarely relies on a single practice, but rather a combination of practices. Selecting the best combination is the goal of all nutrient management that addresses profitable crop production while protecting the environment from nutrient loss.

Importance of Irrigation Management

In the sandy soils of Florida, there is a fifth R: *right irrigation practices*. Mobile nutrients such as nitrogen and potassium can be leached with the water moving through the soil in the root zone. Excessive irrigation, or irrigation when the soil water-holding capacity is full, will cause nutrients to be leached below the root zone. Farmers should track soil moisture, because coupling knowledge about soil moisture status with crop water requirements is the best way to maximize water-use efficiency and minimize nutrient leaching. UF/IFAS Extension recommends applying 30 lb/acre N after a leaching rainfall of 3 inches in four days or 4 inches in seven days.

In areas where fertigation is possible, the optimal rate, timing, and placement of nutrients can be collectively achieved, especially for N and K. When using fertigation, efficiency in application of fertilizer and irrigation water can be significantly increased, and environmental losses from the production systems can be minimized.

Summary

The concept of the 4Rs is important for maximizing fertilizer-use efficiency, promoting profitable crop production, and protecting the environment from pollution due to losses of nutrients from agricultural land. Selecting the right fertilizer rate, right fertilizer source, right fertilizer placement, and right fertilizer timing are important aspects of best management practices. Farmers should consider all the options for each "right" component and select the best combinations for maximizing crop profitability and minimizing negative environmental impacts.

Growers and crop educators and advisors should constantly measure fertilizer use efficiency associated with the 4Rs and make adjustments to improve efficiency. An example of how to measure nutrient use efficiency by crops is presented by Prasad and Hochmuth (2014). The 4Rs is a nutrient management program promoted by the International Plant Nutrition Institute (http://www.ipni.net/4R). We need to develop sets of 4R practices for the growers in Florida based on factors such as location, soils, crops produced, water management system, nutrient sources, and agronomic/horticultural management options. In the long run, real-time weather data can be dynamically linked to these 4R sets to guide real-time modifications of the practices during a growing season.

Other Publications in This Series on Soil Testing

Hochmuth, G., R. Mylavarapu, and E. Hanlon. 2014. *Soil Testing for Plant-Available Nutrients—What Is It and Why Do We Use It?* Gainesville: UF/IFAS. http://edis.ifas.ufl.edu/ss621.

Hochmuth, G., R. Mylavarapu, and E. Hanlon. 2014. *Developing a Soil Test Extractant: The Correlation and Calibration Processes*. Gainesville: UF/IFAS. http://edis.ifas.ufl.edu/ss622.

Hochmuth, G., R. Mylavarapu, and E. Hanlon. 2014. *Fertilizer Recommendation Philosophies*. Gainesville: UF/IFAS. http://edis.ifas.ufl.edu/ss623.

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International Plant Nutrition Institute. 2014. http://www.ipni.net/4R.

Prasad, R., and G. Hochmuth. 2014. *How to Calculate a Partial Nitrogen Mass Budget for Potato*. Gainesville: UF/IFAS Sciences. http://edis.ifas.ufl.edu/ss614.

Table 1. Examples of scientific principles behind nutrient management and the associated practices.

	Right Source	**Right Rate**	**Right Placement**	**Right Timing**
Scientific principles	Which nutrients are needed; based on soil testing; potential for nutrient loss	Crops vary in nutrient needs; Crop Nutrient Requirement; prevent excessive amounts	Mobility of nutrients; rooting patterns; bedding of crops; mulching; volatilization	Dynamics of crop growth and nutrient demand; risk of nutrient loss
Application of knowledge	Soil-supplied nutrients; crop residue; fertilizers; manures; blends; single-nutrient source; soluble; CRFs	Costs; nutrient use efficiency; likelihood of nutrient loss; variable-rate application	Band; broadcast; foliar; fertigation; production system (e.g., no-till); surface vs. buried	Preplant; at planting; first flower; first fruit; logistics of field timing and equipment; mineralization of manure

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HS948

Reduction of the Impact of Fertilization and Irrigation on Processes in the Nitrogen Cycle in Vegetable Fields with BMPs[1]

Eve-Marie Cockx and Eric H. Simonne[2]

The nitrogen (N) cycle is a set of transformations that affect N in the biosphere. Through a series of microbial transformations in the soil, N is made available to vegetable crops. Thus, knowledge of this cycle by which N passes from air to soil to organisms and back to air, and how the components of the cycle are affected by human activities, is required to design effective strategies for decreasing undesirable losses of N from vegetable production to the environment.

Adequate management of fertilization and irrigation has always been recognized as one of the keys to successful vegetable production in Florida. Thus, fertilization and irrigation practices have aimed at supplying enough nutrients and water to ensure economical yields. Since up to 200 lbs/A of exogenous N are recommended for vegetable production in Florida, and fertilizer use efficiency seldom exceeds 75%, it is likely that fertilization affects the N cycle. Best Management Practices (BMPs) aim at reconciling the needs of economical vegetable crop production with those of environmental protection. Effective BMP implementation, therefore, requires an understanding of how current cultural practices affect certain processes in the N cycle in commercial vegetable fields. It is likely that a complete understanding of these issues by farmers and vegetable professionals will be a prerequisite for the success of the BMP program.

The goals of this article are to (1) present the N cycle as it relates to crop production, (2) describe how fertilization and irrigation affect the processes within N cycle, and (3) explain how the proposed BMPs may help reduce the negative environmental impact of these cultural practices.

The Nitrogen Cycle in a Typical Ecosystem

Because the N cycle is a "cycle", it has no clear beginning and no end (Pidwirny, 2002). Hence, for the sake of presentation, this description of the cycle starts with N in the soil organic matter where N is in the form of amino acids, proteins, and nucleic acids (Fig. 1). In the soil, N found in decomposing organic matter may be converted into inorganic N forms by soil microorganisms (bacteria and fungi) in a process called mineralization (step 1). These bacteria and fungi, also called decomposers, may be found in the upper soil layer. They chemically transform the N found in organic matter from amino-N (NH_2) to ammonium (NH_4^+) (Pidwirny, 2002).

Step 1: Organic matter ---> Ammonium

$R\text{-}NH_2 \text{ ---> } NH_4^+$

Nitrogen in the form of NH_4^+ can then be adsorbed (step 2) onto the surfaces of clay particles in the soil. The NH_4

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2. Eve-Marie Cockx, short-term scholar; and Eric H. Simonne, assistant professor, Horticultural Sciences Department, UF/IFAS Extension, Gainesville, FL 32611.

ion that has a positive charge may be held by soil colloids because they have a negative charge. This process is called micelle fixation (Pidwirny, 2002).

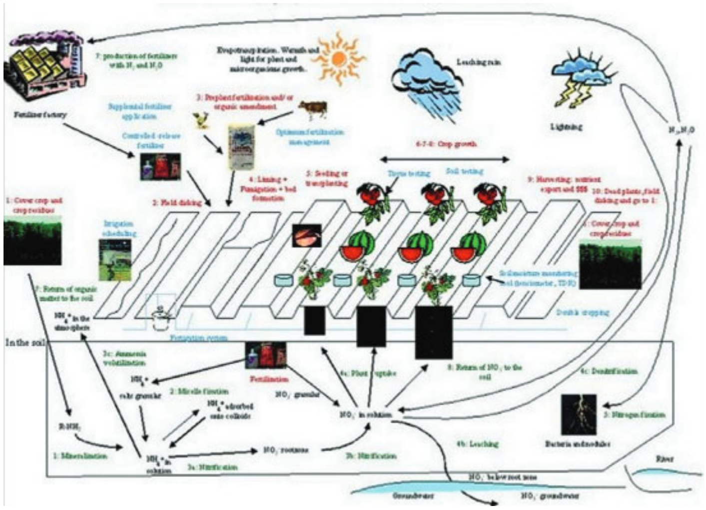

Figure 1. Impact of fertilization, irrigation and other cultural practices in vegetable fields (in red) on the steps of nitrogen cycle (in green) with best management practices (in blue).

Step 2: Ammonium in solution ---> absorbed ammonium ---> ammonium back into solution

NH_4^+ aqueous ---> NH_4^+ ···soil colloid ---> NH_4^+ aqueous

As this fixation is reversible, NH_4^+ may be released from the colloids by way of cation exchange. When released, NH_4^+may be chemically altered into nitrite (NO_2^-) by a specific type of autotrophic bacteria belonging to the genus *Nitrosomonas* organisms. *Nitrosomonas* can synthesize their own organic N compounds from inorganic N sources (step 3a). Then, NO_2^- may be quickly converted into nitrate (NO_3^-) by another type of bacteria belonging to the genus *Nitrobacter* (step 3b). Both of these processes involve chemical oxidation and together are known as nitrification (Pidwirny, 2002; Mahendrappa et al., 1966). Both bacteria utilize the energy released by the oxidation of N compounds in their metabolism of which NO_2^- and NO_3^- are by-products of their metabolic pathways. This 2-step process involves a complex series of reactions that can be summarized as:

Step 3a: Ammonium in solution ---> nitrite in solution

$$55NH_4^+ + 76\ O_2 + 109HCO_3^- \text{--->} C_5H_7O_2N + 54NO_2^- + 57H_2O + 104H_2CO_3$$

Step 3b: Nitrite in solution ---> Nitrate in solution

$$400\ NO_2^- + NH_4^+ + 4\ H_2CO_3 + HCO_3^- + 195\ O_2 \text{--->} C_5H_7O_2N + 3\ H_2O + 400\ NO_3^-$$

These equations highlight two important points: nitrification requires oxygen and it affects bulk soil pH. First, approximately 4.3 mg O_2 are consumed for every mg of NH_4^+ oxidized into NO_3^-. Second, a quite substantial amount of alkalinity in the form of HCO_3^- is consumed when NH_4^+ is oxidized, thereby, indirectly decreasing soil pH (Anon., 1999).

The rate of step 3a (NH_4^+ transformed to NO_2^-) is slower than that of step 3b. Hence, NO_2^- does not normally accumulate in soils, but NO_3^- may. Because NO_3^- has a negative charge, it may not be adsorbed onto the soil colloids. As most NO_3^- salts (such as potassium nitrate, calcium nitrate, magnesium nitrate) have high solubility (high Ksp), most NO_3^- stays in the soil solution.

If NH_4^+ is neither adsorbed onto soil colloids nor transformed in NO_3^-, it may be volatilized (step 3c). However, this occurs rather in agricultural ecosystems where fertilizers (urea and manure) are added, than in undisturbed ecosystems.

Step 3c: NH_4^+ in the soil ---> NH_3 in the air

Nitrate and NH_4^+ in the soil solution are the most common forms of N taken up by vegetable crops. Nitrogen uptake is the most important step of the N cycle in vegetable production.

Step 4a: Ammonium in solution ---> Ammonium inside the root

NH_4^+ aqueous ---> NH_4^+ inside the root

Nitrate in solution ---> Nitrate inside the root

NO_3^- aqueous ---> NO_3^- inside the root

In plant nutrition, N is an essential element. Nitrogen is involved in the composition of all amino acids, proteins and many enzymes. Nitrogen is also part of the puric and pyrimidic bases, and therefore is a constituent of nucleic acids (Mills and Jones, 1996). Typically, N content in plants ranges between 1.0% and 6.0% of the dry weight in leaf tissues (this means that 1 to 6 g of N may be found in 100g of dry tissue). Under N shortage, plants grow slowly and are weak and stunted (Mills and Jones, 1996).

Nitrate and NH_4^+ should be regarded as two different nutrients because they affect plant metabolism differently. Nitrate is negatively charged, while NH_4^+ is positively charged. As nutrient uptake is a process that is electrically neutral, it does not involve any net change in plant electric charge. The absorption of NO_3^- requires the concomitant uptake of a cation or the release of an anion (OH^- or organic acid). Similarly, the absorption of NH_4^+ when the accompanying ions are H^+ or OH^-, affects soil pH. Hence, NH_4^+ uptake may depress the uptake of the essential cations (K^+, Ca^{2+}, Mg^{2+}).

Another difference between NO_3^- and NH_4^+ is that NO_3^- may be stored in the plant before it is used, whereas NH_4^+ needs to be detoxified. Ammonium must be rapidly incorporated into organic molecules because free NH_4^+ disrupts the photosynthesis mechanism by uncoupling redox reactions and affecting the photosynthetic membrane stacks (grana) in chloroplasts. On the contrary, free NO_3^- is not toxic and it can be stored in the plant until utilized or incorporated into organic molecules by the light-activated enzyme nitrate reductase (NR), after being reduced into NH_2 group. Reduced NO_3^- is added to a glutamic acid residue in a transammination reaction that generates glutamine (Mengel and Kirkly, 1987; Mills and Jones, 1996). Differences in NO_3^- and NH_4^+effects on plant growth can be summarized in the old saying: "NH_4^+ greens a plant, while NO_3^- grows a plant."

Consequently, an optimum NO_3-N: NH_4-N ratio exists for vegetable production. The optimum NO_3-N : NH_4-N ratio for vegetables grown in hydroponics is 75 : 25 (Marti and Mills, 1991; Sasseville and Mills, 1979; Simonne and Mills, 1991). When NH_4^+ is the dominant form of N available for plant uptake, a smaller plant will result. When the root system is in fact overloaded in its ability to detoxify absorbed NH_4^+, then NH_4^+ will be translocated to the top portion of the plant. There, carbon sources otherwise used for leaf and stem growth are instead used into detoxification of the NH_4^+. Protein synthesis pathway dominates the production of the cell wall (Mills and Jones, 1996; Marti and Mills, 1991; Sasseville and Mills, 1979).

If NO_3^- is not taken up by the roots, it can be transported below the root zone and leached (step 4b) or denitrified (step 4c). As NO_3^- is soluble in water, it is easily leached from the root zone by excessive rainfall or irrigation (step 4b). In Florida's sandy soils, the bottom of the root zone is typically 12 inches for shallow-rooted crops and 3 feet for deepest rooted vegetable crops. The actual rooting depth of vegetables may be limited by the presence of compaction layers, acidic layers, or a spodic horizon.

Step 4b: Nitrate in the root zone ---> Nitrate in the groundwater

NO_3^- in the root zone ---> NO_3^- in the groundwater

Because the water holding capacity of Florida sandy soils is typically 10% (v:v), the top 12 inches soil can hold 1 inch of water. Hence, rainfall of 3 inches in 3 days, or 4 inches in 7 days are considered to be leaching rains that take NO_3^- below the root zone (Simonne and Hochmuth, 2003 b).

Once below the root zone, NO_3^- easily enters the hydrologic system. Karst geology is commonly found throughout Florida. A sand layer of variable thickness covers a limestone base (Fig. 2). Through repeated wet/dry cycles, limestone slowly dissolves, creating swales and sinkholes. Through sinkholes, leaching rain is directly in contact with groundwater and is not filtered; NO_3^- may be found in underground water, springs and in the streams.

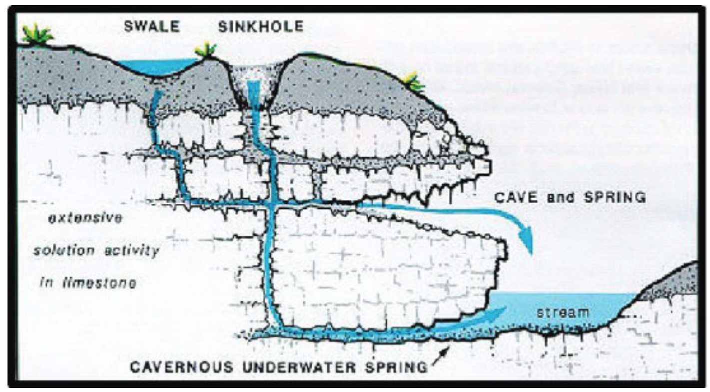

Figure 2. Connection of surface water with groundwater though swales and sinkholes in karst geology found in Florida.

Elevated NO_3^- concentration in ground water has been associated with water quality/health issues and eutrophication. First, short-term exposure to drinking water with a NO_3^-–N concentration above 10 mg/L NO_3-N is a potential health problem primarily for infants. Their immature digestive systems are more likely than adult digestive tracts to allow the reduction of NO_3^- to NO_2^-. In some rare cases, the presence of NO_2^- in the digestive tract of newborns has lead to a disease called methemoglobinemia or "blue baby" syndrome (McCasland et al., 1998).

The second impact of NO_3^- on water quality is when it accumulates into waterways and causes the eutrophication of N-limited ecosystems. Eutrophication is a condition in an aquatic ecosystem when exogenous quantities of the limiting factor (N in north Florida and P in south Florida) result in algae blooms.

NO_3^- in waterways ---> NO_3^- in algae blooms

Algae blooms cloud the water making it difficult for larger submerged aquatic vegetation (SAV) to get enough light and compete for dissolved oxygen. The SAV may dieback thereby reducing available habitat of aquatic animals, which in turns affects the whole food chain in the aquatic ecosystem. In addition, algae blooms increase the Biological Oxygen Demand (BOD), thereby competing with other aquatic animals.

Nitrate that is neither taken up by the plant nor leached may be denitrified. Denitrification (step 4c) occurs commonly in anaerobic soils and is carried out by heterotrophic bacteria. This kind of bacteria must consume energy-rich organic molecules for survival. The most common denitrifying bacteria include several species of *Pseudomonas*, *Alkaligenes* and *Bacillus*. The process of denitrification involves the reduction of NO_3^- into dinitrogen (N_2) or nitrous oxide (N_2O) gas. Both of these gases then diffuse into the atmosphere (Pidwirny, 2002). No oxygen is required for this process that occurs in anoxic conditions. On the contrary, oxygen is produced and may be used by nitrifying bacteria in other layers of the soil. Denitrifying bacteria use N as the final electron acceptor in their metabolism. Denitrified N in the form of N_2O or N_2 forms joins the largest store of N in the cycle found in the atmosphere (Shroder, 1981). The atmospheric store is estimated to be approximately one million times larger than the total N contained in all living organisms.

Step 4c: Nitrate in soil ---> N oxides gases in the atmosphere + Oxygen

NO_3^- in soil ---> N_2O and N_2 forms in the atmosphere + Oxygen

Dinitrogen in the atmosphere may return to earth by three ways: rain (step 5a), fertilizer production (step 5b), or N fixation (step 5c). Small proportions of atmospheric N_2 return to the soil in rainfall or through the effects of lightning; an estimated 10^{13} g per year of N_2 (22,000 Million lbs per year of N_2) are fixed and transformed in ammonia by lightning (Kimball, 2003). Nitrogen fertilizers are produced by condensation of N_2 and H_2 which produces NH_3 (Haber-Bosch process; Anon., 2003b).

Step 6: Dinitrogen + Dihydrogen ---> Ammonia + energy

N_2 (g) + $3H_2$(g) ---> $2NH_3$(g) + energy (Anon b, 2003)

The bulk N_2 returned to earth, however, is biochemically fixed in the soil by specialized micro-organisms like bacteria, actinomycetes, and cyanobacteria. This process is called nitrogen fixation (step 5). It may occur in plants that harbor nitrogen-fixing bacteria within their root nodules. Free-living bacteria may also fix N_2, but on a smaller scale. The amounts of N fixed by free-living, non-photosynthetic bacteria in the soil may achieve an approximate maximum of 15 kg/ha/year (13.4 lbs/A/year).

Step 5: Dinitrogen in the air ---> Ammonia for the plant

N_2 in the air ---> NH_3 for the plant

Biological nitrogen fixation can be represented by the following equation, in which two units of ammonia are produced from one unit of nitrogen gas, at the expense of 16 units of ATP (energy) and a supply of electrons and protons (hydrogen ions):

Step 5: $N_2 + 8H^+ + 8e^- + 16$ ATP ---> $2\ NH_3 + H_2 + 16$ADP + 16 Pi (Anon, 2003a)

The low N contribution of the free-living, non photosynthetic bacteria, is the result of limited availability of suitable organic substrates (energy sources) and low bacterial populations in the soil environment. Nitrogen fixation is characteristically higher in tropical soils, where substrate availability, temperature and moisture are more favorable to the maintenance and activity of an actively growing bacterial population (Hubell and Kiddler, 1998).

The best-studied example of N fixation is the association between legumes and bacteria in the genus *Rhizobium*. The main legume crops commercially grown in Florida are peanuts (*Arachis hypogaea*), snap bean (*Phaseolus vulgaris*) and pink-eyed and black-eyed pea (*Vigna unguiculata*). These *Rhizobium* and legumes are able to survive independently (soil nitrates must then be available to the legume), but this association is beneficial to both organisms. In exchange for some N, bacteria receive carbohydrates from the plants. Special structures (nodules) in roots allow them to be connected with the roots of the plant. Scientists estimate that biological fixation globally adds approximately 140 million metric tons of N to soil and sea ecosystems every year. However, the actual amount of N fixed in each ecosystem depends on the environmental conditions and the nature of biological system(s) present, which are capable of N fixation. Nitrogen fixation rates may vary from almost 0 up to 1,000 kg/ha/year (892 lbs/A/year) (Hubell and Kiddler, 1998).

The last step of the N cycle is the return of organic matter to the soil (Step 7). Organic matter returns to the soil in the form of crop residues, incorporation of cover crops, and/or organic amendments such as compost or manure. This organic matter will be mineralized and then, follow the steps of the cycle again.

The N cycle described above, (from the mineralization of organic matter to the return to the soil of organic matter) occurs in an undisturbed ecosystem. However, higher vegetable yields may be achieved with intensive production practices, fertilization and irrigation. Therefore, vegetable production may affect some steps of the N cycle.

Impact of Fertilization, Irrigation, and Other Production Practices Used for Vegetable Production on the Processes in the Nitrogen Cycle

Vegetable production does not alter the N cycle. Instead, vegetable production may change the relative importance of some parts of the N-cycle. Cultural practices affect the N cycle in vegetable fields either directly by (1) modifying soil microorganism population (fumigation), (2) adding N to the root zone (fertilization), (3) affecting water movement (irrigation), or indirectly by changing temperature (mulching), pH (liming) or adding organic carbon source into the root zone (cover crop).

Soil fumigation is a chemical or physical process that kills viable weeds, seeds, soil-borne pathogens (mainly *Phytopthora* and *Pythium* species) and nematodes (rootknot, ring or sting species).

For approximately 30 years, the vegetable industry in Florida has relied on methylbromide and chloropicrin mixture as broad-spectrum soil fumigants. With the complete phase out of methyl bromide by 2005 in the US as a part of the Vienna convention for the protection of the ozone layer (Anon., 1985) modified by the Montreal (Anon., 1987) and Kyoto (Anon., 1992) protocols, alternative fumigants, such as metam sodium (sodium-N-methyldithiocarbamate), metam potassium (potassium-N-methyldithiocarbamate) and 1,3 dichloropropene (Telone) are under evaluation (Motis and Locascio, 2002; Locascio and Dickson, 2002; Hochmuth and Davis, 2002). Because they are biocides, these soil fumigants kill not only pathogenic microorganisms, but also beneficial soil microorganisms, including *Nitrosomonas* and *Nitrobacter* which are responsible for nitrification. It is estimated that soil microorganism populations reach their pre-fumigation levels approximately 2 to 3 weeks after fumigation. Therefore, soil fumigation, regardless of the type of fumigant used, slows nitrification, which results in less NH_4^+ being converted into NO_3^- (step 3a, 3b) (Fig. 3). The decrease in nitrification after fumigation suggests that producers using fumigants may need to adjust their starter fertilizer applications on vegetable crops and apply N in the NO_3^- form rather than the NH_4^+ form. Nitrate is then available for the vegetable crop (Welsh et al., 1996).

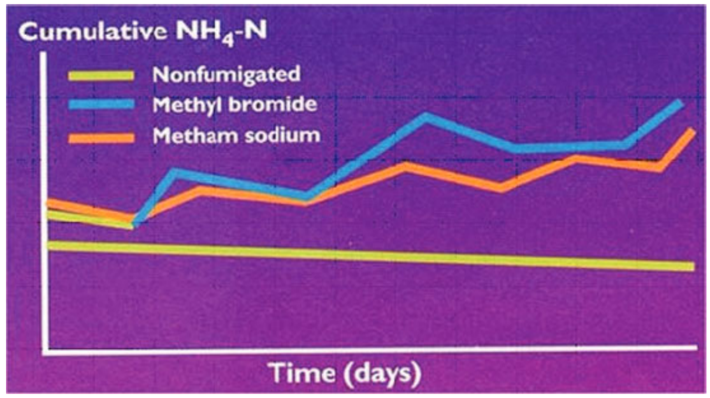

Figure 3. Effect of soil fumigation on the level of NH_4^+ converted into NO_3^-, during nitrification process.
Credits: Welsh et al., 1996.

Fertilization is the second cultural practice that directly affects the N cycle in the root zone of vegetable crops. Fertilization affects not only plant uptake, but also mineralization, nitrification, and denitrification and ammonia volatilization (Table 1). When fertilizers or salts are added to the soils, microorganisms compete with vegetable crops for NO_3^- and NH_4^+. Thus, additions of fertilizers increase formation of the final product of each process described above by increasing the activity of bacteria. Typical N fertilizer efficiency ranges only between 40% and 60%. The equation of urea hydrolysis shows how losses can occur, particularly of ammonia.

Urea hydrolysis: $CO(NH_2)_2 + H^+ + 2H_2O$ ---> $2\ NH_4^+ + HCO_3^-$

Urea + Hydrogen ion + Water ---> Ammonium + Carbonate

$HCO_3^- + H+$ ---> $CO_2 + H_2O$ (added H lost from soil solution)

During hydrolysis, soil pH can increase above 7 because the reaction requires H^+ from the soil system. In alkaline soils, less H^+ is initially needed to drive urea hydrolysis on a soil already having low H^+. In an alkaline soil, removing more H^+ (from a soil solution already low in H^+), can increase pH even higher (Anon, 2003e).

$NH_4^+ + OH^-$ ---> NH_4OH --->$NH_3 + H_2O$

Irrigation is the third factor that affects the N cycle and most vegetable crops grown in Florida are irrigated. Although average total rainfall is 50 to 56 inches/year in Florida, rainfall distribution is not adequate for vegetable production and irrigation must be used. In addition, rainfalls of more than 1 inch/day are common, which may create temporary anoxic (anaerobic) conditions in flooded soils. By creating anoxic and then dry conditions, irrigation and rainfall may affect each process of the N cycle, from mineralization to N fixation (Table 2). In plasticulture systems, it has been estimated that an irrigation of 24 gal/100ft results in an inch vertical movement of the water front in a Lakeland fine sand.

Other common cultural practices used in vegetable production and that indirectly affect the N cycle include plastic mulching, cover crops, and liming.

Polyethylene mulch has been used for commercial vegetable production in Florida for more than 30 years. There are approximately 70,000 acres of mulched vegetables in Florida, ranking it near the top of the US for this production method. Mulching is used because it creates a physical barrier to weeds, it reduces erosion and increases soil moisture and temperature. Thus it influences processes of the N cycle that are temperature dependant (Table 3).

Cover cropping is another cultural practice that indirectly affects the N cycle. Growers use cover crops because they reduce erosion, add organic matter (OM) and N (legume cover crops) to the soil, and because, in some cases, they reduce populations of nematodes. Cover crops also trap residual soil N and reduce N loss to ground water. Finally, the addition of OM and N (from the cover crop or from crop residues) creates a favorable environment for microbial growth (Wang et al., 2002) and may temporally increase soil water holding capacity of the soil.

Mineralization is affected by the C:N ratios of organic amendments (Table 4). Materials rich in N (having a low C:N ratio) favor mineralization (residues of legumes, animal slurry or organic fertilizer based on blood or other proteins). Those with a low content of N (elevated C:N ratio such as cereal straw) favor immobilization, because such materials contain too little N, at least in readily decomposable form, to satisfy the requirement of the microbial population responsible for their decomposition (Haynes, 1986 b). When organic residues with a high C:N ratio (sawdust 400:1, oat straw 80:1) are added to agricultural soils, extra fertilizer N should be added concomitantly in order to lower the C:N ratio below 20 to 25 and thus avoid net immobilization and consequent N deficiency in the vegetable crops (Allison, 1973).

Mineralization is not the only process influenced by addition of OM. Carbon supply (from cover crop, crop residues, or organic amendments) affects denitrification directly by supplying the necessary substrate for growth of denitrifiers and indirectly through the consumption of O_2 by other microorganisms that deplete O_2 in the soil. When OM is added to the soil, it increases C levels and could potentially result in increasing denitrification (Haynes, 1986 b).

Lastly, the presence of a cover crop can decrease the level of nitrate leaching. A lack of vegetation (fallow) for at least part of the year is a key factor stimulating NO_3^- leaching from arable cropping systems. A major source of groundwater NO_3^- from agriculture land can originate from post-harvest mineralization of crop residues, rather than from the fertilizer itself. Mineralization usually continues after uptake by an arable crop has ceased, causing a considerable accumulation of nitrate during the late summer and early winter. Only a fraction of this residual fertilizer is absorbed by the following crop, and the remainder is available to leach during the following months. When land is left fallow, after being cropped, leaching can be a particular problem due to rainfall (Powlson, 1993). Therefore, mulching, establishment of cover crops, and crop residues have a direct positive impact on the N cycle.

Liming is the third cultural practice that indirectly affects the N cycle. Lime is applied to (a) eliminate toxicities of Al^{3+} and Mn^{2+}, (b) supply adequate levels of Ca^{2+} and Mg^{2+}, (c) facilitate the utilization of water, and (d) increase soil pH and create conditions which maximize the availability of the essentials nutrients. In addition, it is necessary to apply maintenance doses of lime to offset the acidifying effects of NH_4-containing fertilizers (Somner and Yamada, 2002). Soil acidity affects the plant root environment, which ultimately affects plant growth and performance. Most plants grow better in slightly acidic soils rather than in strongly acidic soils. When a soil is too acidic for proper plant growth, lime may be applied to reduce the acidity (Kidder, 1999).

Because acidity determines the general chemical environment in the soil, soil pH influences the rate of mineralization, nitrification, denitrification and plant uptake. Each of these processes typically proceeds more readily in a neutral or slightly acidic soil than in a strongly acidic soil (Table 5 and Table 6; Haynes, 1986 a, b, c; Haynes and Sherlock, 1986).

In summary, fertilization, irrigation and several other cultural practices also influence the N cycle. Their effects on it may be favorable. However, these practices may alter the cycle as well. The main disturbance comes from NO_3^- leaching. Nitrate leaching largely depends on environmental effects and on water movement. Consequently, NO_3 leaching may be difficult to control. Intensive irrigation or excessive rainfall may be responsible for important leaching losses. Nutrient BMPs and irrigation scheduling aim at reducing the impact of vegetable production on the N cycle while maintaining or increasing productivity.

How Water and Nutrient-Management BMPs Can Reduce the Undesirable Side Effects of Cultural Practices on the Nitrogen Cycle in Vegetable Fields

Programs to minimize nonpoint source pollutants on surface and groundwater originated in the Water Pollution Control Act of 1948 and were formally established with the Federal Clean Water Act (FCWA) of 1977. Section 303(d) of the FCWA requires states to identify impaired water bodies and establish total maximum daily loads (TMDL). A TMDL is a calculation of the maximum amount of a pollutant that a water body can assimilate from point or non-point sources and still meet water quality standards for its intended use (fishing, swimming, and drinking). TMDL involve quantitative analyses of water bodies where one or more water quality standards are not being met, and are aimed at identifying the management strategies necessary to attain those water quality standards. Under section 303(d) of the Clean Water Act, every two years each state must identify bodies that do not meet water quality standards. Water bodies are "water quality-limited" estuaries, lakes, and streams that fall short of surface water quality standards, and that are not expected to improve within the subsequent two years (Anon, 2003e).

Florida has acted to protect water resources through another act, the Surface Water Improvement and Management (SWIM) Act passed in 1987 by the Florida legislature. The SWIM act directed the state to develop management and restoration plans for preserving or restoring priority water bodies. The legislation designated a number of SWIM water bodies including Lake Apopka, Tampa Bay, Indian River Lagoon, Biscayne Bay, St. Johns River, Lake Okeechobee, and the Everglades. Vegetable producing areas are often close to these water bodies. The goals of this act are to protect water quality and natural systems, create governmental and other partnerships, and manage watersheds (Anon, 2003d).

In Florida, water and fertilizer management are inextricably linked. Changes in one will almost inevitably affect the efficiency of the other. The goal of proper water management is to keep both the irrigation water and the fertilizer in the root zone. Therefore, knowledge of the root zone of a particular crop is needed so that water and fertilizer inputs can be managed properly throughout the season (Anon., 2003e).

Best Management Practices (BMPs)

Best Management Practices (BMPs) are specific cultural practices that aim at reducing the loads of specific compounds while increasing or maintaining economical yields. The implementation of BMPs may be key in reducing the consequences of alterations of the N cycle in vegetable fields. Implementation of BMPs at the farm level is a key to maintaining the quality and the quantity of ground and surface waters. In most cases, BMPs have been determined to be effective for reducing or preventing pollution. The *Florida Vegetable and Agronomic Crop Water Quality and Quantity Best Management Practices Manual* (Anon., 2003c) will regulate the 142,000 ha, $1.4 billion vegetable industry in Florida (Witzig and Pugh, 2001). The seven sections of the manual are Pesticide Management, Conservation Practices and Buffer, Sediment Control, Irrigation and Nutrient Management, Water Resources, Seasonal and Temporary Farming Operations, and Record Keeping and Accountability. Each section is divided into specific BMPs. Each BMP description is 2 to 3 pages long, consisting of a title, pictures, working definition, set of things to do (BMPs), things to avoid (potential pitfalls), supplemental technical criteria, and references (Hochmuth, 2000; Simonne et al., 2003; McCasland et al., 1998).

BMPs should help at reducing the negative impact of cultural practices, particularly on water quality (Table 7). The expected impacts on water quality may be direct or indirect and may lead to different environmental benefits.

Research and growers have helped determine some of the major water and nutrient management practices (Table 8). This information can be used on vegetable farms to ensure that fertilization results in economically viable production without measureable negative impacts on the environment and alteration of the N cycle.

This article has described how cultural practices may influence the steps of the N cycle. They can affect it directly by fertilization, irrigation or fumigation. Other cultural practices such as liming, mulching, establishment of cover crops also affect the cycle but indirectly. These practices create conditions that may or may not be favorable to the N cycle. However, with the emergence of the BMPs, some remedies against alteration of the cycle seem to give impressive results. The different processes of the nitrogen cycle, how fertilization, irrigation and other cultural practices affect them and finally the possible remedies brought about by the BMPs, are summarized in Table 9. BMPs are interconnected and unseparable. They have an indirect effect on water quality. Hence, BMPs should be used together, and the weakest BMP will determine the efficiency of the entire BMP plan.

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Table 1. Processes of the N cycle affected by nitrogen fertilization.

Processes affected by fertilization	Enhanced by	Reduced by
Mineralization	- Addition of cations, whose ability to stimulate mineralization follows the same order as their replacing power on cation exchange sites in soils. $Al^{3+} > Fe^{3+} > Ca^{2+} > Mg^{2+} > K^{+} > Na^{+}$ (Singh et al., 1969; Broabent and Nakashima, 1971; Agarwal et al., 1971; Westerman and Tucker, 1974; Heilman, 1975; Laura, 1977) - Adequate source of C and N for microbial growth. - O_2 - High temperature	- Fertilization may influence the activities and population diversity of the microbial biomass through changes in microbial environment.
Nitrification	- Addition of NH_4^+ or NO_2^- increases population of nitrifiers (Jones and Hedlin, 1970)	- Nitrification inhibitors: High concentration of NH_4^+(> 800µg N/ g of soil) inhibit activity of microorganisms
Dentrification	- Influence on the proportion of gas produced. At high concentration of NO_3^-, N_2O is the predominant gas (Blackmer and Bremmer, 1978)	
Plant uptake	- Split application of granular fertilizer (2 or 3 side-dresses) - Weekly or daily fertigation schedules (for drip irrigation and plasticulture; Simonne and Hochmuth, 2003a) - Controlled-release fertilizers (CRFs) - Actively growing root system	- NH_4^+ has an inhibitory effect on NO_3^- uptake. - Lack of oxygen in the rootzone - Low N levels and higher C in the soil
Ammonia volatilization	- Application method, such as, no incorporation of fertilizers (manure and urea). - Manure characteristics, such as dry matter content - Application to soils of fertilizers with low cation exchange capacity - High rates of N fertilizer (>100 lbs N/a) (Combs, 2000). -Ammonia volatilization accounts for 5.5% to 12.8% of applied N as NH_4^+-N or urea respectively, without additional air circulation of the mean natural wind speed. The losses increased to 33.3% with maximum rates volatilization occur within 5 days after fertilizer application (Mattos et al., 2003; Sullivan et al., 2003).	-Incorporation of fertilizer. When manure is incorporated, NH_4^+ can attach to soil exchange sites thus slowing or stopping the reactions leading to NH_3 (Combs, 2000).

Table 2. Processes of the N cycle affected by irrigation.

Processes affected by irrigation	Enhanced by	Reduced by
Mineralization	- The optimum soil moisture for mineralization is between -10 and -50KPa, close to the recommended Soil Water Potential range for vegetable (Myers et al., 1982) - Alternation of dry and wet period. It exposes organic matter that was not previously accessible to microbial decomposition, by physically disrupting the soil aggregates. It allows the release of NH_4^+.	- Low moisture content (at moisture potentials from -800 to -1500 Kpa). - High soil moisture contents. They create anaerobic conditions (developed when extreme irrigation is applied or when fields are flooded). In that case, mineralization is dependant on anaerobic bacteria, less efficient (Yoshiba, 1975; Campbell, 1978; Patrick, 1982).
Dentrification	- Water satured soil and anoxic conditions.	- Aerobic conditions
Plant uptake	- Water is involved in many functions of the plant: It is a solvent for inorganic salts, sugars and organic anions, it is the medium in which all biochemical reactions take place (photosynthesis). - Irrigation scheduling based on demand for water, transpiration rate (ET_0) and crop stage of growth (Kc or CF).	- Under water stress, all the physiological relationship associated with water may be altered (uptake, photosynthesis)
Leaching	Extreme irrigation or rainfall just after the application of fertilizer, particularly when the crop is not able to take it up. N applied to spring crops at the time of sowing, remains in the soil for several weeks before uptake begins. Nitrate is then at greater risk of lost than that from equivalent application to crops that are already established. Studies on agricultural lands have indicated that leaching of applied fertilizer N can be substantial and that NO_3-N can move rapidly especially in light sandy soils under intensive irrigation (10–100 kg N/ha (8.9-89 lbs/A) lost with fertilizer inputs of 100-300 kg/ha (89-268 lbs/A) (Simonne et al., 2003)	- Proper irrigation scheduling - Rain-free growing season - Increasing soil water holding capacity
N fixation	- Healthy bacteria populations - Long root systems - Phosphate fertilization	- When drought stress, the rate of N_2-fixation and the translocation of the products of N_2-fixation to the shoot decrease (Venkateswarlu and Rao, 1987). - When the soil remains flooded, lack of oxygen may reduce nitrogenase activity (Giller, 2001)

Table 3. How polyethylene mulching indirectly affects processes of the N cycle.

Processes affected	How mulching affects the N cycle
Mineralization Nitrification	Mulching improves moisture retention. More uniform soil moisture is maintained (Olson, 2003).
	Mulching increases soil temperature. It creates the optimum range (25 to 35°C) for microbial activity (Justice and Smith, 1962; Thiagalingam and Kanchiro, 1973; Kowalenko and Cameroun, 1976). The temperature may raise to 50°C under plastic mulch without disturbing indigenous nitrifiers that have temperature optima adapted to tropical areas (Mahendrappa et al., 1966).
Plant uptake	NO_3^- uptake becomes greater than NH_4^+ uptake at around 23°C and increases up to 35°C (Frota and Tucker, 1972).
Leaching	Mulching reduces NO_3^- leaching due to excessive rainfall.
N fixation	Most of the N-fixation bacteria can grow at temperatures up to 40°C. Higher or lower temperatures inhibit N_2-fixation (Giller, 2001).
Ammonia volatilization	As temperature increases above 75°F the percentage of NH_3/NH_4^+ increases and consequently ammonia volatilization. This increases the partial pressure differences and encourages volatilization (Cowley et al., 1999).

Table 4. The C:N ratios of selected organic materials.

Material	Typical C:N ratio[b]
Microbial tissue	8:1[a]
Chicken manure	9:1 to 20:1[b]
Soil humus	10:1[a]
Green legumes	12:1[b]
Legume residues	23:1[b]
Green grass	40:1[b]
Grain straw/dry grass	80:1[b]
Pine needles	225:1[b]
Sawdust	400:1[a]

[a] Source: Volk and Loeppert, 1982.
[b] Source: Butler, 2003.

Table 5. How liming indirectly affects processes of the N cycle.

Processed affected by pH	Effects of pH	Effects of liming an acidic soil
Mineralization	- Since mineralization of native soil organic N is carried out by a diverse range of microflora, the process does not show a marked sensitivity to pH (Alexander, 1980). Nonetheless, liming acidic soils often cause an increase in the N mineralization rates (Table 6).	- Acceleration of the decay of plant tissues, simple carbonaceous compounds and soil organic matter (Alexander, 1977). - Increase in mineralization (Nyborg and Hoyt, 1978) (cf Table 6). The greater tolerance of mineralization than nitrification to low pH is reflected in the finding that ammonium is generally the dominant form of N in acidic soils while nitrate predominates in nonacidic soils (Haynes and Goh, 1978; Rorison, 1980).
Plant nutrient uptake	- At pH=4 to 5 maximum absorption of NO_3^- occurs (Rao and Rains, 1976), which will result in an increase of rhizosphere pH (efflux of H^+ in exchange for NH_4^+). - At pH=7 to 8 maximum absorption of NH_4^+ occurs (Rao and Rains, 1976), which will result in a decrease of the rhizosphere pH (efflux of HCO_3^- or OH^- in exchange for NH_4^+).	- Liming to the 6.0 to 6.5 pH range increases the availability of essential nutrients. - Liming reduces the risk of aluminum and manganese toxicity. - Liming adds Ca and Mg to the root zone.
Ammonia volatilization	- As pH increases, the equilibrium ratio of NH_3: NH_4^+ in solution increases, and volatilization is more likely to occur because an increase in NH_3 in solution results in an inequilibrium between liquid NH_3 and gaseous NH_3.	- Adding lime and increasing the pH increase the NH_3: NH_4^+ ratio.

Table 6. The mineralization of organic nitrogen in 40 soils incubated with or without lime[z,y].

Treatment		Organic N mineralized in 120 days	
		Concentration (µg N g^{-1})	Percentage of total soil N
No lime	Average	34	1.6
	Range	-1 to 136	-0.1 to 3.8
Lime[x]	Average	72	3.5
	Range	3 to 212	0.4 to 5.6

[z] Source: Nyborg and Hoyt (1978)
[y] Soils sample ranged in texture from sandy loam to clay, pH (0.1 M CaCl) from 4.0 to 5.6 (average 5.0) and in total N content from 0.076 to 0.458% (average 0.21%).
[x] lime added to raise soil pH to 6.7

Table 7. Supporting research, expected impact on water quality and benefits of proposed BMPs for vegetable crops grown in Florida.

Proposed fertilization and irrigation BMPs	Supporting research in Florida	Expected impact on water quality	Society, grower, and environmental benefits
Soil Survey	Complete	Remote	Increase overall farming efficiency
Soil testing and soil pH management	Complete	Indirect	Provides basis for adequate nutrient applications
Micronutrient management	Complete	Indirect	Apply adequate amounts and form
Proper use of organic fertilizer materials	Extensive	Indirect	Supply some nutrients; increase soil water holding capacity
Linear bed foot system for fertilizer application	Complete	Indirect	Make adequate fertilizer calculation for plasticulture
Chemigation/fertigation	Complete	Indirect	Increase overall farming efficiency; supply adequate fertilizer/chemical amounts in the bed
Use of controlled-release fertilizer	Very limited	Direct	Supply adequate fertilizer and irrigation amounts; reduce leaching risk
Optimum fertilization management	Complete	Direct	Supply adequate fertilizer amounts
Supplemental fertilizer application	Extensive	Indirect/Adverse	Replace leached fertilizer based on leaf or petiole results
Proper irrigation scheduling	Incomplete	Direct	Reduce leaching risk from irrigation water
Irrigation system maintenance and evaluation	Complete	Indirect	Increase overall farming efficiency; increase irrigation and fertilization uniformity
Water supply	Complete	- Mostly indirect - Direct	- Define water quality parameters for proper irrigation management - Use of back-flow prevention device

Table 8. Major irrigation and nutrient-management practices that aim at reducing the negative consequences of alteration of the N cycle in vegetable fields.

Cultural Practice	Working definition	Things to do: BMPs	Things to avoid: potential pitfalls
Crop Establishment	- Crop establishment is the process by which an initial amount of irrigation water is delivered to a seed or seedling in the fields to ensure that it will become well-established.	- Consider weather forecast. Irrigation-water needs may be smaller. - Consider using drip irrigation and/or tailwater recovery systems, to make good use of irrigation water. - Consider using soil moisture-determination equipment or techniques such as tensiometers so that over-watering of fields is minimized. - Evaluate the different types of soils on your farm.	- Do not leave irrigation pump stations and systems unsupervised during crop establishment. - Do not irrigate for crop establishment during or immediately after a storm event.
Double cropping	- Successive cropping of existing mulched beds is a good practice that makes effective use of polyethylene mulch, soil fumigant and residual fertilizer.	- Be observant for any nutrient deficiencies in the first crop. - Take a representative soil sample in the bed away from any first-crop fertilizer bands. - Use either drip irrigation or an injection wheel to apply the fertilizer. - Apply an amount of N equal to the crops own nutrient requirement as long as N was not applied in excess of the nutrient requirement for the first crop.	- Do not add extra fertilizer when planting the first crop with the misconception that this fertilizer will aid growth at the second crop. - Do not exceed the fertilizer recommendations for the first or second crop.
Tissue testing	- It is the analysis and diagnosis of the plants nutritional status based on its chemical composition. It allows having a more efficient fertilizer management and minimizing impacts on the environment.	- Begin the plant sampling soon after the crop is established and continue at regular intervals.	- Do not sample only one part of the field but different areas, to be more representative.
Fertigation	- Precision application, known as fertigation, follows plant needs more closely than traditional fertilizer methods and helps reduce nutrient leaching.	- Locate the injector so that a minimum amount of water is delivered to the field before the fertilizer reaches the crop. This will reduce the potential of over watering crop with associated leaching. - Use split application to prevent over-irrigation and leaching.	- Avoid excessive irrigation that could cause nutrients to be leached below the root zone.

Table 9. Processes of the N cycle, cultural practices that affect them, irrigation and nutrient BMPs that can reduce the consequence of the alterations of the N cycle.

Step	Nitrogen cycle	Cultural practices that affect the cycle	Irrigation and nutrient BMPs
1	Mineralization	Fertilization Fumigation Irrigation Plastic mulching and bedding Liming Cover-crop and crop residues	Soil survey Soil testing and soil pH Proper micronutrient fertilization Proper use of organic fertilizer materials Fertigation Controlled-release fertilizer (CRF) Optimum fertilization management Supplemental fertilizer application Irrigation scheduling Tissue testing Double cropping Crop establishment
2	Adsorption/desorption	Fertilization Cover crops Chicken litter	
3	Nitrification	Fertilization Manure Fumigation Irrigation Plastic mulching Liming	
4a	Plant nutrient uptake	Fertilization Irrigation Liming	
4b	Nitrate leaching	Fertilization Irrigation Cover-crop Plastic mulching	
4c	Dentrification	Fertilization Irrigation Plastic mulching Cover-crop and crop residues	
5	Nitrogen fixation	Fertilization Irrigation Plastic mulching	

Comparison of Soil Test Extractants for Available Soil Phosphorus in High pH Sandy Soils of South Florida[1]

Kelly T. Morgan and Kamal Mahmoud[2]

Introduction

This document addresses the selection of soil nutrient extractants in high pH soils and discusses their relationship to both nutrition and fertilizer management. This document's objective is to describe the impact of selected soil extractants on nutrient management and their ability to determine soil phosphorus availability.

The target audience for this series dealing with citrus nutrition includes Certified Crop Advisers; citrus, vegetable, and sugarcane producers; fertilizer dealers; and other parties interested in crop fertilization practices.

With the exception of organic soils in the Everglades Agricultural Area and mineral soils in Miami-Dade County, soils used for citrus, vegetable, and sugarcane production in south Florida are sandy in the upper 18 inches. These sandy soils are typically low in water- and nutrient-holding capacities, and they have low organic matter content. During the past 50 years in south Florida, soil pH has increased to levels greater than 6.5 with high to very high concentrations of calcium (Ca) because of irrigation and repeated lime applications. Many farms containing these sandy soils border the Everglades Agricultural Area and ultimately drain into the Everglades. The Everglades Forever Act mandates that landowners ensure water leaving the agricultural areas does not exceed well-defined phosphorus (P) loads. Agricultural producers are required to implement best management practices (BMP) to maintain long-term economic viability, while fostering environmental stewardship.

Because of the hydrological characteristics of south Florida's sandy soils, many agricultural producers rely largely on seepage irrigation from elevated water tables. These elevated water tables, combined with the sandy soils' low nutrient-holding capacity, increase the leaching potential of nutrients from these soils.

Fertilizer can be a large production cost to most farmers. Unfortunately, nutrients (including P) can also be major contributors to groundwater contamination. Management strategies, such as soil testing, should be used as a BMP in vegetable production to maximize crop yields and quality, while minimizing nutrient loss to the environment. Nitrogen concentrations in soil are typically not determined because this element leaches so readily and it does not accumulate in sandy soils. Nitrogen therefore, must be replaced each year for optimum production.

Soil should be tested each year to determine the amount of P required to maintain high production levels. Nitrogen and P move at different rates in the soil based on their affinity for soil particles and soil water content. However, once these elements reach the groundwater, they can move off the farm by mass flow as water enters ditches.

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Large quantities of P reach the water table and impact off-site surface water bodies. The dynamics of soil P must be understood to determine the fertilizer application's environmental impact.

High soil pH and large quantities of iron, aluminum, and/or calcium cause soluble P applied as fertilizer to precipitate out of the soil solution through time, making it unavailable to crops. Therefore, those growing on high pH soils must apply large quantities of P to maintain crop production and compensate for the binding of P in these soils. If P is not provided, then crops can become deficient, resulting in reduced yields and stunted plants with drooping, curled, and purple leaves. Soluble P that has not been transformed into insoluble precipitates is vulnerable to leaching. Standard soil test methods developed for agriculture have been used to assess environmental risk of P loss from soils. Application of soil test P as an environmental indicator requires additional calibration to specific soil types.

From 2008 to 2011, we conducted a demonstration project to evaluate the ability of common soil extractants used by commercial soil testing laboratories to accurately extract P from soils with high pH and calcium carbonate. Several different soil tests for P were used to estimate available P (e.g., Mehlich-1, Mehlich-3, Bray, Olsen, and AB-DTPA).

Mehlich-1 is a soil test extractant containing two acids (hydrochloric and sulfuric acids) and is sometimes called a double acid extraction. The strong acids dissolve nutrients in the soil that would normally be available to plants in acidic soils and are only appropriate for acidic soils (pH less than 6). UF/IFAS has been using the results to base P recommendations, but it is considering using Mehlich-3 extractant, which is highly buffered compared with Mehlich-1 and can be used with a wider range of soil pH. Bray and Olsen extractants are typically used for alkaline soils (pH greater than 7). Olsen, a relatively new extractant that determines available nutrients in neutral and calcareous soils, is mostly used for soils high in Ca ammonium bicarbonate. Olsen was also used in our study. Therefore, we needed to compare and/or determine the best soil P test method for growers to use as a base for their P application recommendations.

For example, at a pH less than 7, P will be readily soluble, and most extractants should extract P amounts close to the P amount available for plant uptake. However, in soils with high Ca concentrations and a pH greater than 7, an increasing portion of soil P will precipitate in the form of various calcium phosphate compounds. These compounds dissolve in acidic solutions, but they are not available for plant uptake. Therefore, the relationship among soil extractants must be determined, so soil test results using the various extractants can be compared with one another. A representative soil-test P index can also be determined for soils with elevated pH and calcium content. The soil-test P index is the amount of P in the soils at which additional P application would not be necessary to obtain optimal and realistic yields.

Most soil extractants use standard extractant to soil ratios of 10:1 or less (10 ml of solution per gram of soil), and they are typically used on soils with less than 200 mg kg^{-1} of extractable soil P. Initial results with the five test extractants indicated that extractable soil P concentrations did not increase with increasing water and bicarbonate extractable P greater than 300 mg kg^{-1}, when the extractant to soil ratio was 10:1 or less. The lack of correlation with increased soil P suggested the standard ratio was not reliable at extractable soil P concentrations greater than 300 mg kg^{-1}. The ratios found in Table 1 for Mehlich-1 (M1), Mehlich-3 (M3), Bray, Olsen, and AB-DTPA should be used.

The sequential analysis procedure determines the amount of P in a soil at increasingly less available forms of P. The most readily available form of P is water soluble, or hydroxide soluble, followed by bicarbonate extractable forms. However, not all water and bicarbonate P forms are readily available to the plant. These soil P forms are considered partially plant available sources. Thus, extractants providing soil P concentrations at or slightly greater than the sum of water- and bicarbonate-extractable P, approach the amount of P available to plants with some level of overestimation. Figure 1 illustrates the relationship between Mehlich-1 extractable P and water-extractable P for the five farms used in our study. The line in the figure indicates a 1:1 ratio between the two extractions. Thus, if the Mehlich-1 solution extracted only water-extractable P, the data would fall on the 1:1 line. It can be observed under the demonstration soil characteristics that the majority of data points for all farms are above the 1:1 line, indicating Mehlich-1 overestimates water-extractable P. Mehlich-3, Bray, and AB-DTPA also overestimate water-extractable P. Contrary to the other extractants, Olsen underestimates water-extractable P (Figure 2).

The results indicate that current soil P test using Mehlich-1 may not accurately represent available soil P in soils with high pH and Ca concentrations because of reduced P availability. Sequential analysis of soils with apparent soil P precipitation by Ca indicates the water and bicarbonate soluble forms are most available to tomato plants. Tests comparing sequential analysis results and extractable soil P indicate that all common soil P test extracts overestimated available soil P when compared with water and bicarbonate soluble forms of soil with pH greater than 7.2.

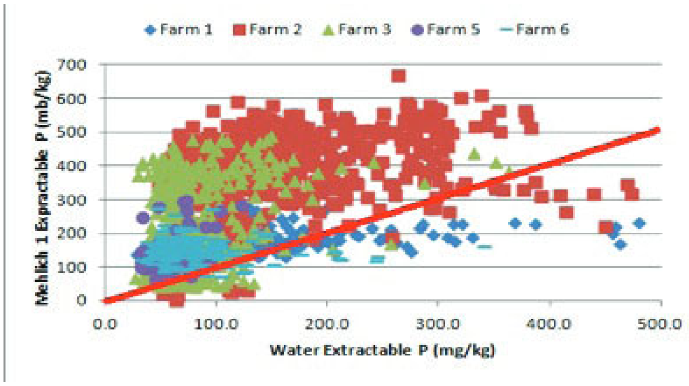

Figure 1. Water-extractable P for five farms in demonstration compared with Mehlich-1 extractable P. Note that water-extractable P above the red 1:1 ratio line indicates an overestimation of water-extractable P by Mehlich-1.

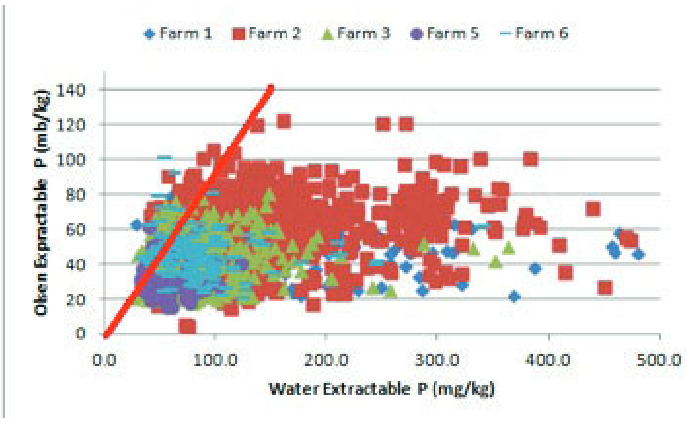

Figure 2. Water-extractable P for five farms in demonstration compared with Olsen-extractable P. Note that water-extractable P above the red 1:1 ratio indicates an underestimation of water-extractable P by Olsen.

However, all extracts worked well in soil with P less than 300 ppm, Ca less than 1500 ppm, and pH less than 7.2. The Mehlich-1, Mehlich-3, and Bray provided results similar or greater than available P. Thus, Olsen and AB-DTPA may provide better numbers for soil test P indexing.

Table 1. Soil Extractant Ratios.

Extractant	P Concentration Category	P Conc. (mg kg^{-1}) Standard Ratio	Optimum Ratio	P Conc. (mg kg^{-1}) Optimum Ratio
M1	Low	59.9 ± 3.86	1:40	70.4 ± 4.88
M1	Low	69.2 ± 9.72	1:40	74.8 ± 3.38
M1	Medium	134.3 ± 5.17	1:40	162.7 ± 26.84
M1	Medium	139.4 ± 6.52	1:40	160.9 ± 35.16
M1	High	431.2 ± 2.93	1:40	441.2 ± 16.27
M1	High	364.8 ± 33.66	1:40	409.0 ± 52.81
M3	Low	43.6 ± 1.78	1:40	49.5 ± 5.47
M3	Low	46.5 ± 1.60	1:40	53.4 ± 3.34
M3	Medium	124.1 ± 5.31	1:40	153.3 ± 7.77
M3	Medium	128.1 ± 8.06	1:40	141.9 ± 12.37
M3	High	362.4 ± 14.49	1:40	375.7 ± 43.62
M3	High	326.9 ± 8.74	1:40	378.2 ± 18.06
Bray	Low	37.7 ± 1.76	1:40	48.5 ± 1.36
Bray	Low	48.1 ± 1.14	1:40	53.8 ±3.16
Bray	Medium	124.5 ± 4.58	1:40	137.1 ± 6.88
Bray	Medium	113.0 ± 5.35	1:40	117.5 ± 1.01
Bray	High	316.6 ± 9.27	1:40	369.4 ± 65.07
Bray	High	317.0 ± 33.48	1:40	345.1 ± 20.65
Olsen	Low	11.6 ± 0.18	1:50	16.3 ± 2.22
Olsen	Low	13.6 ± 0.52	1:50	20.1 ± 1.19
Olsen	Medium	28.7 ± 1.20	1:50	50.1 ± 2.37
Olsen	Medium	29.0 ± 2.74	1:50	46.9 ± 1.13
Olsen	High	63.2 ± 7.66	1:50	88.3 ± 3.27
Olsen	High	48.0 ± 3.54	1:50	72.8 ± 3.63
AB-DTPA	Low	15.6 ± 0.30	1:30	33.1 ± 0.92
AB-DTPA	Low	18.4 ± 0.11	1:30	37.1 ± 6.67
AB-DTPA	Medium	47.9 ± 0.85	1:30	89.1 ± 5.81
AB-DTPA	Medium	45.5 ± 0.32	1:30	72.3 ± 0.88
AB-DTPA	High	79.7 ± 1.53	1:30	268.5 ± 42.15
AB-DTPA	High	53.0 ± 0.51	1:30	198.5 ± 8.99

UF IFAS Extension
UNIVERSITY of FLORIDA

SL408

Soil Testing for Plant-Available Nutrients—What Is It and Why Do We Use It?[1]

George Hochmuth, Rao Mylavarapu, and Ed Hanlon[2]

Farmers need soil-testing procedures to assess soils for potential plant-available nutrients. Soil testing is the foremost best management practice (BMP). It helps farmers achieve profitable crops while protecting the environment from excessive fertilization and nutrient losses. This publication describes the important steps required to test soil for potential plant-available nutrients. This information will be useful to county UF/IFAS Extension agents when training farmers and crop consultants about proper soil testing and nutrient management.

Scientists generally accept 17 elements as essential for plant growth (Barker and Pilbeam 2007). These elements are carbon (C), hydrogen (H), oxygen (O), phosphorous (P), potassium (K), nitrogen (N), sulfur (S), calcium (Ca), magnesium (Mg), iron (Fe), boron (B), manganese (Mn), copper (Cu), zinc (Zn), molybdenum (Mo), nickel (Ni), and chlorine (Cl). A certain amount of each of these nutrients—the crop nutrient requirement (CNR)—is critical for crops to complete their life cycles and to produce an optimal yield. Carbon and oxygen are supplied from air, and hydrogen from water. The remaining nutrients can be supplied from the soil; however, the soil may not always contain enough of these nutrients for optimal crop production. Farmers need to know the portion of the CNR that can be supplied from the soil, because these nutrients are essentially free to the farmer. If the CNR cannot be supplied entirely from the soil, then the soil-supplied nutrients can be augmented with fertilizers or other nutrient sources such as manures or composts. Nearly 150 years ago, scientists developed chemical tests to assess the concentrations of plant-available nutrients in a soil sample and then to use that assessment to make recommendations for supplemental fertilizer.

What Is Soil Testing?

The Soil Science Society of America defines soil testing as "the application of soil science research to the rapid chemical analyses to assess the available nutrient status of a soil." Agronomic soil tests do not measure the total amount of a plant nutrient in the soil, or even the exact amount of plant-available nutrient for the season. Soil tests provide an index (i.e., indication, or assessment) of the nutrient-supplying capacity of the soil (see "Soil text index" section below). Soil testing is most applicable to nutrients of low mobility in soils—such as P, K, Mg, Ca, and micronutrients—because these nutrients will remain in the soil after the soil has been tested. This low mobility is in contrast to mobile soil nutrients—such as nitrogen—that may rapidly transform or leach from the soil in the time between soil testing and crop planting.

Why do We Use Soil Testing?

We test soil to determine how to get the best crop yields and how to use fertilizer and other nutrient sources most efficiently. When soil testing was originally developed, the

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goal was to enhance crop yields by identifying productive soils. Today, crop productivity is still a goal, but another goal is to avoid excessive fertilizer applications and, thereby, protect the environment.

The soil test is a process that includes the following five activities: (1) collecting the soil sample, (2) processing the soil sample in the lab, (3) analyzing the sample for its extractable nutrient content, (4) interpreting the results of the analysis, and (5) using the information to make a fertilizer recommendation (Sikora and Moore 2014). Activities 1 through 4 are discussed in this publication, and activity 5 is discussed in the EDIS publication SS623, *Fertilizer Recommendation Philosophies* (Hochmuth et al. 2014).

Collecting the Soil Sample

The usefulness of the soil-testing process depends on the quality of the soil sample. A quality soil sample is representative of the soil for the field in question, and a quality sample is collected properly, in terms of depth and numbers of subsamples.

Depth

Soil samples for predicting fertilizer needs are collected from the top six inches of soil in the field, because the top six inches is the part of the soil typically tilled with plows and disks and the upper six-inch layer of soil also contains a large portion of the nutrient-absorbing roots.

Number of Subsamples

Before sampling, the field should be divided into "management units," which are representative of areas that will receive different cultural practices, such as different crops or different planting dates (Figure 1). Management units may also represent soil types with different native mineral composition. (Current management units may be different from previous cropping-system-management units and may also have different nutrient content.) Your different management units should be sampled separately, because they may require different approaches to fertilization. A large field may have enough inherent variability to justify determining individual management units of 20 to 40 acres. To take a soil sample from a management unit, first collect 20 subsamples with a soil sampling probe, and then composite the subsamples in a plastic bucket and mix them. Take a sample volume of about a half-pint from the bucket of mixed soil and submit it to the lab in the paper bag provided for soil-testing submissions. Additional information on management units and soil sampling schemes can be found in the EDIS document SS402, *UF/IFAS Nutrient Management Series: Soil Sampling Strategies for Precision Agriculture* (Mylavarapu and Lee 2014).

Additional Information Needed

In addition to the soil sample, the lab will require you to fill out some forms to provide information about the crop to be grown and the specific nutrient analyses being requested. This information will help the lab make the best fertilizer recommendation for the farmer.

Soil Sampling and Precision Agriculture

Typically, soil testing and fertilizer recommendations are made for the entire management unit, even though there may be considerable variation across the management unit, which may be 20 acres in size. However, some growers are adopting precision agricultural techniques. For example, some farmers are applying fertilizers in precise techniques where the fertilizer rate is varied throughout a field according to the nutrient levels in the soil. Precision agriculture uses *variable-rate application* of fertilizers so that areas in the field needing more or less fertilizer can receive the appropriate rate. For variable-rate application to work, soil

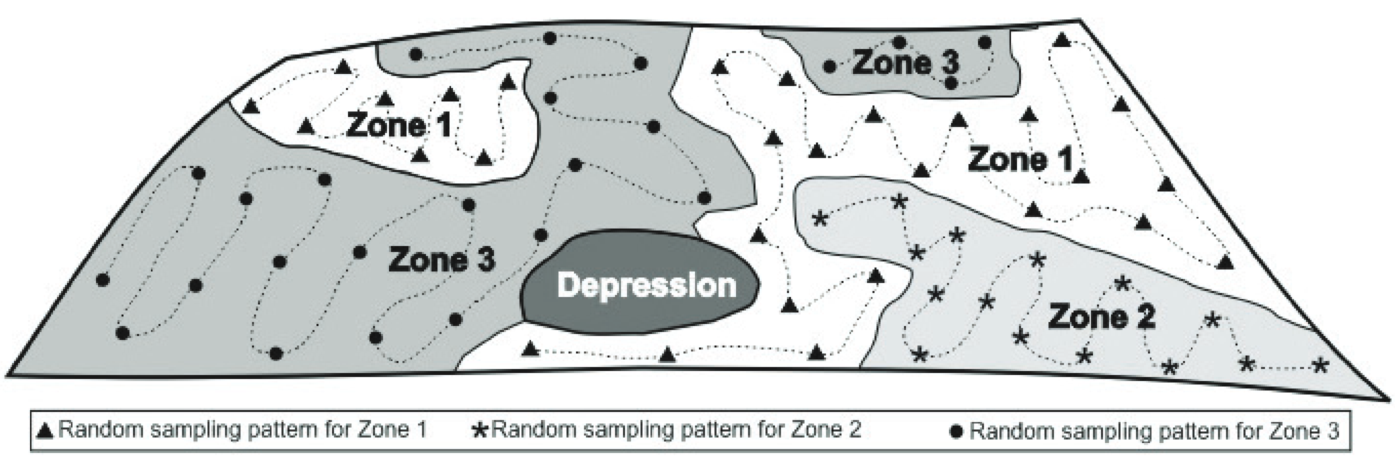

Figure 1. Scheme illustrating random soil sampling on a commercial agricultural farm or a landscape
Credits: Greg Means, Soil and Water Science Department, UF/IFAS Extension

samples need to be taken on a more detailed basis. One way to take more detailed soil samples is to use a grid-sampling approach. Grids may be as small as two acres each. Other techniques for variable-rate application of fertilizers have been based on changes in soil type as described by National Resources Conservation Service (NRCS) soil maps, yield maps derived from previous crop yields, and various combinations of these and other techniques (Mylavarapu and Lee 2014).

Processing and Analyzing the Soil Sample

When the sample arrives at the laboratory, most labs analyzing agricultural soils use the following steps:

1. The soil is dried at approximately 100°F to remove soil moisture.

2. The soil is sieved to remove old plant parts and stones. A clay-dominated soil may need pulverizing to break up clods.

3. A small portion of the sample is taken for processing in the lab.

4. The soil sample is mixed (usually by shaking) with a solution called an "extractant."

5. After mixing, the sample's liquid portion is filtered and analyzed for its nutrient content. Analytical equipment will vary, depending on the nutrients being determined and the individual lab design and setup.

6. The concentration of extracted nutrient from the liquid portion is converted to the dried-soil basis and is referred to as the *soil-test index*.

7. The index is then given an *interpretation* as to the ability of that soil to provide enough of a nutrient for optimal crop yield. For example, a *low* interpretation means that the soil cannot supply all of a particular nutrient for crop production. A *high* interpretation, however, means that the soil can supply all of a particular nutrient for crop production.

8. The final step is for the lab to make a fertilizer recommendation for those soil samples that received interpretations of less than *high*. The fertilizer recommendation provides the recommended rate, but the rate is not the only part of a recommendation. A complete recommendation also contains guidelines about placement and timing of the fertilizer application, which can help farmers use fertilizer efficiently while also protecting the environment.

The Role of Soil Test Extractants

The extractant, a solution that is mixed with the soil sample, is crucial to the soil test. Briefly, the extractant is developed for specific types of soils and growing conditions, such as soil reaction (pH) and the need for micronutrient results. The extractant is often a solution of various chemicals including water, acids, and certain organic chemicals. For example, the UF/IFAS Extension Soil Testing Lab now uses the Mehlich-3 soil test extractant—which is composed of acetic acid, ammonium nitrate, nitric acid, ammonium fluoride, and ethylene diamine tetra acetic acid (EDTA). There are at least a dozen soil test extractants in common usage by agricultural soil testing labs in the United States, but not all extractants are useful for all agricultural regions. Each extractant was developed to meet particular goals, but some extractants were developed to have wide applicability among soil types and tested nutrients. These latter extractants are called *universal extractants*, and Mehlich-3 is one such extractant. The Mehlich-3 extractant is more applicable than Mehlich-1 (used by UF/IFAS Extension until August 2013) for Florida's high-pH agricultural soils (Mylavarapu et al. 2014).

Interpreting the Results of the Soil Test Index

As mentioned earlier, the concentration of nutrients extracted from the soil sample is called an *index*. The soil test index is an indication of the soil's nutrient-supplying capacity and its expected relative yield (Table 1). The total amount of a nutrient in the soil is of little importance in determining fertilizer recommendations, because only a portion of a nutrient may be available for plant use during the growing season. For example, a soil's nutrient availability includes a myriad of chemical reactions that a nutrient may undergo with time, and a nutrient may reside in multiple forms (some insoluble). Therefore, the soil test index is often referred to as an *availability index*. The availability index tells us, based on previous research, the relative level of a nutrient that will probably contribute to the crop nutrient requirement during the growing season.

Table 1. Soil-test-index interpretation with expected crop yield

Low	**= less than 75%**
Medium	**= 75% to 100%**
High	**= 100% of expected yield**

The extractant used by a lab must be *correlated* with crop response (Mitchell and Mylavarapu 2014). This correlation means that if the extracting process results in a low interpretation, then that unfertilized soil will produce a low-yield crop. If the extracting process results in a high interpretation, then the unfertilized soil will produce a high-yield crop. Further, the extractant must be *calibrated*, which means that the lab using the extractant can accurately associate a fertilizer recommendation with each soil test result interpretation. The greatest amount of fertilizer will be recommended for *low*-testing soil, less for medium-testing soils, and likely no fertilizer for *high*-testing soils.

Sometimes farmers send a portion of the same sample to several labs and question why the soil test indexes are different among labs. The use of different extractants probably explains the difference. There must be considerable soil testing and crop response research conducted to develop the soil test. Farmers should ask the lab about the particular soil test extractant and its research base. We will discuss correlation and calibration in more detail in EDIS publication SS622, *How a Soil Test Is Developed—Correlation and Calibration* (Hochmuth, Mylavarapu, and Hanlon 2014).

Important Guidance About the Soil Test Index

The soil test index is usually expressed as a nutrient concentration in the air-dry soil. For example, it may be expressed in parts per million (ppm) or milligrams per kilogram (mg/kg). These two expressions are equivalent. The instruments accurately determine the nutrient concentration in the soil using these units of expression.

However, these determinations are occasionally converted into other units for making fertilizer recommendations. In doing this, sometimes an inaccurate and faulty assumption is made—that an acre of six-inch-deep surface soil weighs 2 million pounds. Using that faulty assumption, the concentration value (ppm) is multiplied by 2 to result in the new expression of "pounds per acre." The inaccuracy occurs because soils of different textures and organic-matter contents result in different bulk densities of soils and will, therefore, have differing mass per unit volume.

Another potential fallacy of this particular conversion approach is that the expression "pounds per acre" may be open to misuse in making fertilizer recommendations. Even if the expression "pounds per acre" is employed, it is still an index and must be interpreted as *low*, *medium*, or *high*. The index "lb per acre" cannot be used directly to determine a fertilizer amount by arithmetic.

EXAMPLE

Let's assume the maximum phosphorus (P_2O_5) for a crop is 150 lb per acre (this rate would only be recommended on a *low* index), and further assume that the soil test index was 25 ppm for a submitted soil sample. The index was converted to 50 lb/acre of P by multiplying the concentration index by 2 as explained above. Next, to convert the index from lb/acre P to lb/acre P_2O_5, the index is multiplied by 2.3 to get 115 lb per acre P_2O_5. Then, 115 is subtracted from 150 to get 35 lb per acre P_2O_5, and this rate is used as the fertilizer recommendation.

This series of calculations and assumptions result from a misunderstanding of the soil test index. Using the current IFAS Mehlich-3 interpretation, the index of 25 would be interpreted as *low* and a recommendation of 150 lb per acre of P_2O_5 would be recommended, not 35 lb. So, a concentration index should not be converted to a rate value such as lb per acre, because the index is a concentration and must be interpreted before a recommended fertilizer rate can be determined. Conversion of the index in ppm to another unit (such as "pounds per acre") is unnecessary, and it does not matter if the index is in elemental or oxide form, in the case of phosphorus or potassium.

Frequency of Soil Testing

Soil testing should be a regular, annual process in most cases. However, for high-value crops, soil testing should be carried out on a seasonal basis. Records (see "Soil Test and Fertilization Records" section below) of soil testing results are important to help determine sampling frequency. For example, if several successive years of soil testing show no decline in the index for a particular nutrient, then sampling frequency can be reduced to every two or three years. Unless farmer experience and records indicate otherwise, annual soil testing is recommended in Florida. Buildup of nutrients is less likely to happen in our sandy, low cation-exchange-capacity soils, so annual soil testing will help you avoid planting crops on low nutrient-content soils.

Soil Test and Fertilization Records

Farmers should maintain records of a field's soil test history and fertilization practices. These records will help track fertilizer inputs and can help increase the efficiency of fertilizer use. Records will also help track buildup of certain nutrients that may be detrimental to crop productivity and may have negative environmental impacts. For example, if phosphorus builds up to excessive levels, then loss of soil by erosion could result in phosphorus enrichment of a nearby water body. Or, as another example, leaching may be a problem in some sandy soils of Florida.

Summary

Soil testing is important for determining the portion of the crop nutrient requirement that can be supplied from the soil. Soil testing is most effective in regard to nutrients that are not highly mobile in the soil. Soil testing is an important best management practice. Farmers practicing correlated and calibrated soil testing will benefit from proper fertilizer-rate applications and will protect the environment from nutrient pollution due to inappropriate fertilization practices.

Other Publications in This Series on Soil Testing

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Soil and Plant Tissue Testing[1]

Maria L. Silveira[2]

Soil testing is the best tool for monitoring soil fertility levels and providing baseline information for cost-effective fertilization programs. This information allows for management actions that adjust soil fertility status in order to meet specific forage-nutrient requirements. Routine soil testing can identify nutrient deficiencies and inadequate soil pH conditions that may negatively affect forage production. Soil tests can also indicate nutrients that are present at adequate levels, providing the opportunity to eliminate unnecessary soil amendments.

A major limitation associated with soil testing is that it typically accounts for the plant-available nutrient pool present in the surface (4 to 6 inches) soil layer. However, the subsoil can be an important source of water and nutrients, particularly in perennial crop systems. In addition, some nutrients are highly mobile in the soil and can easily leach into subsoil, resulting in nutrient accumulation at deeper soil depths. Unlike soil testing, plant tissue analysis can account for the plant-available nutrient pools present at multiple soil depths, including deeper horizons. Because of the extensive root system in some plants, plant analysis is a complement to the soil test to better assess the overall nutrient status of a perennial forage system, while revealing imbalances among nutrients that may affect crop production.

Purpose of Tissue Testing

Plant tissue analysis involves the determination of nutrient concentrations from a particular part or portion of a crop at a specific time and/or stage of development. The basic principle of plant analysis interpretation is that yield will be limited by critical nutrient concentrations for each specific crop. The critical level—defined as the nutrient concentration in a plant sample below which yield is significantly reduced—varies among forage crops. Since multiple factors can influence crop-tissue nutrient concentrations, tissue testing should be used with caution and in conjunction with a routine soil-testing program. Recent efforts in Florida have shown that when plant tissue analysis was used in combination with soil testing, there was improved predictability of P and K availability to plants (Silveira et al. 2011). Plant tissue analysis is currently being used in Florida to guide P fertilization of established bahiagrass (*Paspalum notatum* L. Fluegge) pastures. In Louisiana, Mondart et al. (1974) suggested that 90% of maximum bermudagrass (*Cynodon dactylon [L.]* Pers.) yields were obtained when average plant tissue P concentration was 2.0 g kg^{-1}. A critical lower limit of 2.6 g kg^{-1} P has been estimated for dallisgrass (*Paspalum dilatatum* Poir) (Kelling and Matocha 1990). When used in conjunction with soil testing, tissue analysis will improve our diagnostic toolbox for developing nutrient management programs that predict when crops need additional nutrients, while avoiding unintended impacts of excess fertilization on the environment.

Best Time to Test Soil and Plant Tissue

Although soil can be tested at any time, testing at the same time each year is recommended. Furthermore, soil and tissue sampling in early- to mid-fall (mid-October to November–December) is ideal, because it provides ample

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time for lime to be applied (if needed) and to achieve effectiveness before the growing season in Florida. If soil pH needs to be adjusted, it is recommended to apply lime at least 3 to 4 months prior to the spring fertilization in order to allow time for the material to react in the soil. In recently fertilized hay fields, delay sampling at least four to six weeks so that recent fertilizer application has a chance to be utilized by the crop. Also, avoid taking soil samples when the soil is saturated with water, as this will give inaccurate results.

Plant tissue samples should be collected at the same time and from the same vicinity as soil samples. The plant part, maturity stage, and time of sampling are important factors that can affect plant nutrient composition. Tissue samples should be collected when the plant is actively growing, so careful planning is the key.

Soil and Plant Tissue Sample Collection

Soil and plant tissue testing results and interpretation are only reliable if the samples are collected properly. In other words, *test results are only as good as the sample taken*. It is very important to submit soil and plant tissue samples that are comprehensive of the area of interest so that test results are reliable and fertilizer recommendations can be made for the entire area. For soil testing, this can be accomplished by submitting a composite sample. A minimum of 15 to 20 subsamples (approximately 6 inches deep) should be collected per 40-acre field. Samples should be taken at random in a zigzag pattern over the entire area (Figure 1). Areas that are managed or cropped differently or have different soil types should be sampled separately. Similarly, areas that show clear problem signs (i.e., poor forage production, disease) should also be sampled and analyzed separately. Avoid sampling areas not typical of the total field, such as near water, feed, or shade.

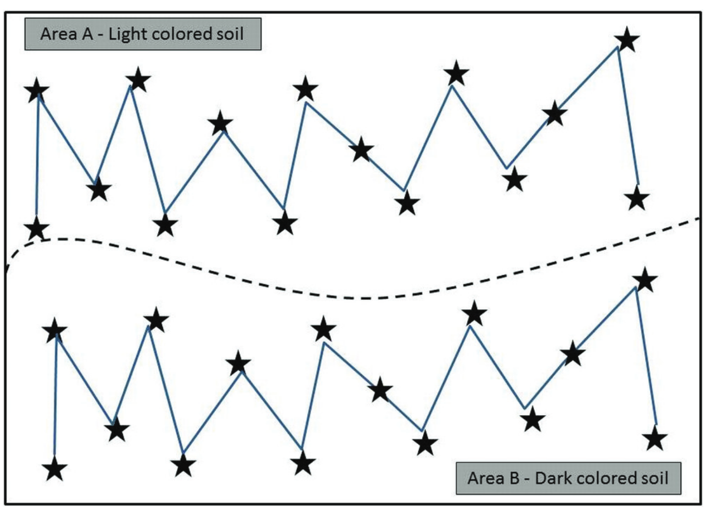

Figure 1. Schematic representation of soil sampling locations within a paddock. Each star represents a sampling location. Areas A and B (separated by dashed line) should be sampled and analyzed separately, because they are different soil types.
Credits: Maria L. Silveira

Collecting a good, representative soil sample is well worth the time and effort it requires. Soil samples can be taken using a soil probe or a shovel. Consistency is important, so collect every sample as close as possible to the same depth. For each area or field sampled, place all the subsamples (15–20) in a clean plastic bucket and mix thoroughly. A handful (~1 pint) of soil should be sent to a reputable laboratory for analysis. If multiple samples are sent to the lab, pack them in sturdy containers to avoid cross-contamination among the samples. It is recommended that a routine soil test (pH, lime requirement, and available plant nutrients) be conducted at least every three years. The frequency of soil sampling will depend on several factors, including soil type, nitrogen application rate, nitrogen fertilizer source, and forage utilization (grazing vs. haying). In intensively managed production systems that receive relatively high fertilizer inputs, annual soil and tissue testing is recommended.

Similar to soil samples, plant tissue samples must be representative of the field. The number of plants to sample in a specific area will depend on the general conditions of plant vigor, soil heterogeneity, and forage management. A truly representative sample can be obtained by sampling a large number of plants so that the sample represents the entire field. Collect at least 1 oz (30 g) of fresh material. Sampling is not recommended when plants are injured by insects and diseases. To avoid contamination, plants should not be sampled soon after spraying pesticides or herbicides. Care should be taken to minimize soil contamination on the sampled plant material. In addition, plants should not be sampled under temperature or moisture stress. Ideally, samples should be collected during a time of the day when climatic conditions are mild, generally early to mid-morning or early evening. The plant part, maturity stage, and time of sampling are also important factors that can affect plant nutrient composition. Forage grasses and hay fields should be sampled prior to seed head emergence or at the optimum stage for forage utilization. As the plant matures, nutrient concentrations decline, so it is critical that plants are sampled at the proper stage of maturity. Care should be taken to select the plant part that accurately reflects the nutrient status of the plant. *The top portion of the plant (the portion on which cattle would graze) should be sampled.* Do not sample seeds, because they are not useful for assessing nutrient status of forage crops and may introduce large errors in the report interpretation. If deficiency symptoms are suspected, plants showing these symptoms should be sampled and analyzed separately from "normal" or apparently healthy plants. After sampling, tissue should be placed in properly labeled paper bags and sent immediately to a reputable laboratory for analysis. Avoid plastic bags, because they can hold heat and moisture. Take precautions when handling your newly collected plant tissue. Because fresh plant material may start decomposing shortly after collection, send the plant material to the laboratory as quickly as possible. If you cannot mail the tissue samples immediately to the lab, then place them in a refrigerator until ready for shipping. For more information on bahiagrass tissue sampling and interpretation, refer to EDIS article SS475, *Tissue Analysis as a Nutrient Management Tool for Bahiagrass Pastures* at http://edis.ifas.ufl.edu/ss475, or contact your local county UF/IFAS Extension's livestock agent or other university personnel.

Sample Submission and Results Interpretation

Make sure you correctly fill out all forms and accurately label boxes and samples before sending to the laboratory, so you know exactly which samples apply to each area of interest.

A soil test generally includes the determination of pH, phosphorus, potassium, calcium, and magnesium. Micronutrients (e.g., zinc, copper, iron, and manganese), organic matter, and physical properties (e.g., percentage of sand, silt, and clay) can also be determined. Lime, phosphorus, and potassium application rates are based on soil test results. The only exception is nitrogen fertilization, which should not be based on soil test results. Nitrogen fertilization is based on crop management and expected yields. Caution should be exercised when interpreting fertilizer recommendations generated by commercial laboratories, because they typically use different soil-fertility approaches. For example, while UF/IFAS fertilizer recommendations are based on crop nutrient requirement, the fertilizer recommendations generated by commercial labs (particularly out-of-state) may be targeted to build up nutrient levels in the soil. However, given that most Florida soils are coarse-textured and have limited physical capability to retain nutrients, the nutrient "build-up" approach is not appropriate for both economic and environmental reasons.

The soil and tissue test report will indicate whether crops should respond to fertilization. Extensive research has been done to determine the relationships between available nutrients, fertilization application, and yield responses. For instance, if the soil test indicates that potassium levels are high, then the crops will not respond to additional potassium fertilization. Of greater importance than the actual nutrient concentration is the classification of the degree of nutrient sufficiency. The degree of nutrient sufficiency is reported as three categories: *low*, *medium*, or *high*. Table 1 is a typical representation of current interpretation of soil test results for agronomic crops in Florida. In addition to the soil test results, economic issues (e.g., fertilizer cost, hay prices) must also be considered when choosing the most adequate fertilization management strategy.

Table 1. Current Mehlich-3 soil test interpretation for agronomic crops in Florida (Mylavarapu et al. 2013)

Element	Low	Medium	High
	Part per million (ppm)		
Phosphorus (P)	≤ 25	26–40	> 41
Potassium (K)	≤ 25	26–40	> 41
Magnesium (Mg)	≤ 10	11–23	> 24

Current tissue testing interpretations are only valid for established bahiagrass (Table 2); thus, if the area is managed for other purposes—such as hay, sod, or seed production—a different interpretation approach should be used. *For established bahiagrass pastures,* tissue analysis has been recently incorporated into the revised IFAS fertilizer recommendations as a management tool to guide proper P fertilization. Revised IFAS recommendations state that tissue analysis should be performed when soil tests are low in P (less than 25 ppm of Mehlich-3 extractable P). Assuming the soil pH is within the optimal range for bahiagrass (around 5.5) and the tissue P concentration is below the critical concentration of 0.15%, then P fertilization is expected to improve bahiagrass production. Recommended P application rates vary from 25 lb P_2O_5/acre for low- and medium-N input options (50 and 100 lb N/ac., respectively), to 40 lb P_2O_5/ac. for high-N option (160 lb N/ac.).

Table 2. Critical concentrations of N, P, and K in bahiagrass tissue (Mackowiak et al. 2013)

Element	Critical concentration (%)
Nitrogen (N)	< 1.5
Phosphorous (P)	< 0.15
Potassium (K)	< 1.2

Once soil tests and/or plant tissue analyses have been conducted, soil amendment management decisions can be implemented to ensure efficient and effective fertilization strategies for the required forage production goals. The target or goals of production vary according to numerous factors—such as exclusive hay production, hay plus stocking, exclusive stocking by ruminants, desired stocking rate, and cow-calf and/or stocker production. The choice and selection of fertilizer sources and the rates and timing of applications are governed by availability and cost of product. The fertilization strategies are therefore driven by production for a targeted dry-matter response and by the need to sustain the pasture system. If you need further assistance with interpretation of soil test results or fertilization recommendations, consult with your local county UF/IFAS Extension agent or other university personnel.

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Extraction of Soil Nutrients Using Mehlich-3 Reagent for Acid-Mineral Soils of Florida[1]

Rao Mylavarapu, Tom Obreza, Kelly Morgan, George Hochmuth, Vimala Nair, and Alan Wright[2]

Introduction

Soil testing is a multistep process starting with the collection of a sample that adequately represents the area or field to be tested. Once the sample is received, the laboratory begins a three-step process: (1) nutrient extraction from the soil sample and analysis; (2) interpretation of test results; and (3) nutrient recommendations (Mylavarapu 2009). Each step's procedures are specific to the inherent soil characteristics and the location of the soil, and are subject to a wide variety of factors, such as crops being grown, prior soil and nutrient management, and the soil's physical and chemical properties. Therefore, it becomes important to consider all of these factors carefully when choosing an appropriate chemical extractant for soils in a region. Due to wide-ranging soil conditions across Florida and the United States, multiple soil test methods exist.

Extractants

Extracting potential plant-available nutrients from soil prior to planting is accomplished with specific reagents that mimic the extraction of nutrients from the soil by plant roots using similar pH ranges found near crop roots. The amount of nutrients removed by a particular extraction procedure is not a direct measure of actual supply of those nutrients. Rather, it is an index that can be used to field-calibrate the test for nutrient availability (Alva 1993).

During the 1970s, Florida along with several other southeastern US states adopted Mehlich-1 (M1) as the official extractant for acidic soils. This adoption was a result of the continued search for improved methods, accuracy, low cost, and quick turnaround time that are critical for the labs (Mylavarapu et al. 2002; Mylavarapu 2009). The advent of Inductively Coupled Plasma Spectrophotometers (ICPs) has rapidly enhanced laboratory throughput from a few dozen to a few hundred samples per day.

Dr. Adolf Mehlich—while working as a consultant at the North Carolina Department of Agriculture during the 1950s and 1970s—developed the Mehlich-1, Mehlich-2, and Mehlich-3 series of soil extractants for the acidic soils of the United States, each one as an improvement over the previous in the sequence. While Mehlich-2 failed completely at the outset, Mehlich-1 and Mehlich-3 soil extractans were found effective. Therefore, only Mehlich-1 and -3 are discussed below.

Mehlich-1 (Dilute Double Acid)

Mehlich-1, or the dilute double-acid extractant, is one of the earliest versions of "universal" soil extractants (single chemical reagent that can extract all the essential plant nutrients), and is especially suited for the acidic, low organic matter, mineral soils of the southeastern United States. Adopting the M1 procedure enabled universal extraction of all standard plant nutrients in the soil sample, including P, K, Ca, Mg, Zn, Cu, Mn, and B. The M1

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extractant is composed of two dilute acids: 0.05M HCl and 0.0125M H_2SO_4 (Table 1). Mehlich-1 was the soil extractant used as the standard method by the UF/IFAS Extension Soil Testing Laboratory for acidic-mineral soils in the state. This extractant is well designed for soils in the acidic pH range with low CEC (Mylavarapu and Miller 2014).

Table 1. Comparison of Mehlich-1 and Mehlich-3 soil extractants

	Mehlich-1	Mehlich-3
Valid pH Range	pH < 6.5	Most normal soil pH ranges
Extraction of P	Limited in soils with high Fe and Al accumulations	Fluoride facilitates dissociation of phosphates from Fe and Al oxides
Extraction of Micronutrients	Dilute acid mixture, only some micronutrients extracted	EDTA (chelate) extracts micronutrients
Exchangeable Cations	Poor extractant for high CEC soils	Ammonium nitrate extracts exchangeable cations

However, M1 should not be used to extract neutral or alkaline soils. When exposed to a neutral or alkaline pH soil, M1 rapidly loses effectiveness because the dilute acids are effectively neutralized. M1 is also rendered ineffective in soils with high cation exchange capacity (CEC), high Al and Fe accumulation, and high organic matter (>5%) content.

Mehlich-3 (M3)

In order to overcome the limitations of M1, Mehlich improved the chemistry and developed the Mehlich-3 (M3) extraction solution (Mehlich 1984). In the M3 extractant, the two dilute double acids used in M1 have been replaced with 0.2M CH_3COOH, 0.015M NH_4F, 0.013M $HN0_3$, 0.001M EDTA, and 0.25M NH_4N0_3. Presence of 0.001M EDTA essentially enhanced the extraction of micronutrients, particularly Cu. It was expected that this extractant would also make the extraction of Mn and Zn consistent and result in a better correlation with plant uptake. In the M3 development process, emphasis was placed on detection of micronutrient deficiencies compared with toxicities. Soil sample pH in the acidic range of pH ~ 2.5 (accomplished through the addition of 0.2M CH_3COOH) was required during the M3 extraction process to take advantage of the fluoride component. A pH of 2.5 helped prevent reaction of Ca and F to form a CaF_2 precipitate. The fluoride facilitated the extraction of phosphates associated with Fe and Al while ammonium nitrate (NH_4NO_3) effectively extracted exchangeable cations. State extension laboratories in several southern US states have since moved to the M3 extraction procedure because of its improved efficiency (particularly for micronutrients) and its broad range of applicability (slightly beyond neutral pH) (Zhang et al. 2014). Also, the M3 procedure has been the only soil test extraction method that has been validated through interlaboratory studies for extraction of plant-available phosphorus and used as a reference method for testing soil materials for extractable P (Zhang et al. 2009).

Standardized Soil Test Procedures

The North American Proficiency Testing program is instrumental in facilitating the soil testing process by regular sample exchange among nearly 150 state and commercial labs currently enrolled, with about six labs using M1 and over 50 labs using M3 (NAPT 2014). Therefore, it becomes important for agricultural extension personnel and crop professionals to know how the M3 soil test results relate to crop performance and current nutrient recommendations. Extensive field calibration and verification studies are required for implementing a specific extraction procedure in any state (Eckert and Watson 1996). However, the cost and the required length of time are usually prohibitive, and therefore calibration equations based on laboratory analyses are necessary interim measures for most soil testing laboratories (Sims 1989).

Based on this information, a study was conducted with the objective of developing conversion data between M1 and M3 for acid-mineral soils of Florida. Development of such conversion equations for soil nutrients provides a close approximation of data from various soil testing laboratories using different extractants.

Agronomic Crop Nutrient Requirement

Multiple soil and edaphic factors dynamically influence the availability of soil nutrients to plants, particularly P. The first ever attempt in soil testing was, therefore, made to estimate P availability among all other nutrients. Unique P extracting reagents were developed and used for predictive soil testing, primarily to estimate availability of soil P to crops for agronomic sustainability. With the advent of universal extractants such as M1 and M3 plus the ICP technology, other macro- and micronutrients are now being simultaneously determined using a single extractant.

Interpretation of the nutrient concentrations determined in a soil sample must be matched with the crop nutrient requirement. This aspect is accomplished through correlation and field calibration work by the soil fertility specialists. By definition, once the soil concentration of nutrients exceeds the *Medium* interpretation category, positive response to added fertilizer is not expected by agricultural crops, landscape plants, or turf, and therefore no recommendation for application of that particular nutrient is made. It is important that the methods employed best reflect the dynamic factors that contribute to the nutrient availability. M1 has worked well for more than 20 years when used with acidic mineral soils of Florida.

With time, in southwest Florida and at other Florida locations, the pH of the native acidic mineral soils has increased to 7.0 or higher in agriculturally managed fields that have received long-term overapplication of lime and liming materials (Morgan 2010). This increase in pH has rendered the M1 extractant ineffective. The weak double-acid mixture in the M1 extractant is neutralized once the soil pH is 7.0 or higher. Similar trends are being observed in home landscapes around the state. For example, soil samples analyzed from 48 home landscapes in a Sarasota County residential community had a mean soil pH of 7.5 with an overall range from 6.5 to 8.1. Comparison of soil extractant data on these landscapes showed that that M1 overestimated the P availability for the majority of the sites (Shober and Pearson 2010). This inability of the M1 soil test to predict crop response will impact areas subjected to fertilizer restrictions that call for soil test evidence of potential for plant response before application. Also, a similar survey of soils from new residential developments in the Orlando metro area (no landscapes established) showed that soils had a mean pH of 5.95 but a maximum soil pH of 8.71 (Shober and Pearson 2010). Increase in soil pH is also related to the increased use of irrigation with water from the limestone aquifer. As pH increased, most vegetable farmers stopped liming, so the continued increase in pH was probably more due to irrigation with high pH water and its liming effect.

Due to these new data, it is imperative that a more reliable extraction technique be adopted for mineral soils in Florida. Based on the results from multiple field calibrations in Iowa, Mallarino and Sawyer (1999) concluded that the capacity of the M3 soil test to predict crop responses to added P across soils of varying pH is much better compared with the Bray soil test, the P extraction method previously adopted by Iowa. The Bray extraction is similar to the M1 extractant used in Florida.

Research data have revealed that the M3 extractant (Mehlich 1984) has a better promise as a soil extractant for the soils in the United States, particularly in the South. M3 has the advantage of potentially being used for extraction of other macro- and micronutrients (Mehlich 1984) and has been determined to be useful as a P extractant on a wide range of soil types (Hanlon and Johnson 1984; Tran et al. 1990). Studies on multiple field sites in Iowa showed that the M3-P results were much better in many high-pH soils and M3 is possibly well suited for several other soils in neighboring states (Mallarino and Sawyer 1999). M3 extraction procedure is being increasingly used in several states in the southern region (SERA-IEG-6 2009) because of its improved efficiency in nutrient extraction (particularly micronutrients) and its broad range applicability to soils with pH > 7.0 (Mylavarapu 2002; Zhang et al. 2014). In anticipation of adopting M3 as the extractant for Florida soils, Mylavarapu et al. (2002) developed conversion equations between M1 and M3 for 519 samples from several counties in the state. Depending on the resources available, field calibration data can be developed for M3 in the future. M3-based interpretations have been estimated for citrus (Obreza and Morgan 2011). Recently, M3 has been adopted as the extractant solution for all sugarcane grown on Histosols (McCray et al. 2012).

Mehlich-3 for Environmental Assessments

Soil test results are also being integrated into water quality assessment tools. Therefore, it is critical that a diagnostic tool adopted for a particular soil category is technically adequate and effective. Inappropriate techniques can lead to unnecessary rates of nutrient applications leading to avoidable and negative water quality impacts. Mehlich-3 has been shown to be a more effective extractant than M1 for metals that determine environmental risk of P loss from soils.

For extraction of soil-bound phosphorus in a high Al and Fe environment, the ideal extraction reagent is ammonium oxalate, which is used for research purposes. However, due to the length of time and reaction conditions required, the oxalate procedure is not compatible for routine laboratory testing and speed. Harris et al. (2004) developed correlations with Mehlich extractants and found that M3 had the best correlation with oxalate extraction method compared to M1 extractant (Figure 1). Use of M3 as a soil extractant also showed significant advantage in predicting P movement through different horizons in the soil profile, enhancing the validity of the Florida Phosphorus Index (PI), a crucial tool for assessing the vulnerability of various soils for P losses to the environment. One of the factors computed for the PI is the ratio of a soil test P to extractable Fe and Al, followed by a calculation of the Capacity Index (or Capacity Factor; Nair and Harris 2004; Nair et al. 2010;

Chakraborty et al. 2011). Based on data that showed M3 as a more effective extractant for Fe and Al, it was recommended that M3 be used instead of M1 for calculation of the Capacity Index to determine environmental risk of P loss from soils. Also, the tool will estimate how much P can be safely added to the soil, which requires a thorough extraction of Fe and Al oxides.

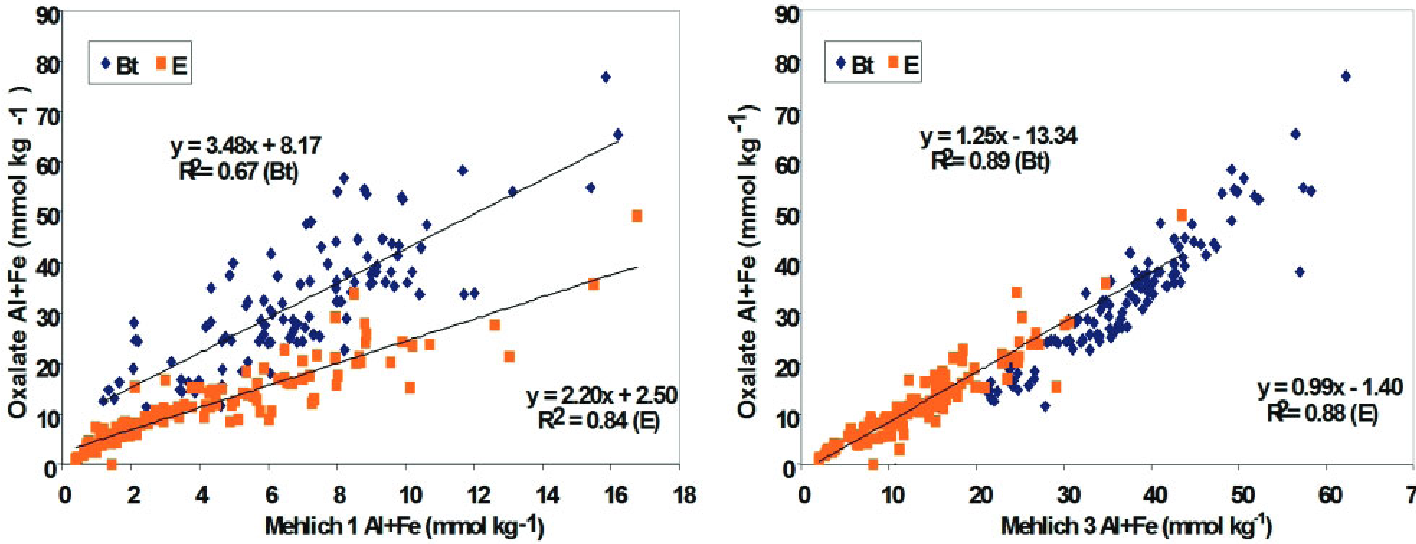

Figure 1. Illustration of M3 as a more effective extractant for Fe and Al in soils than M1 when compared with the standard oxalate extractable Fe and Al
Credits: Harris et al. (2004)

Adoption of M3 for Florida

Due to the stated reasons, the UF/IFAS Plant Nutrient Oversight Committee approved the change from M1 to M3 in 2010. Consequently, a technical committee was constituted within the Department of Soil and Water Science to develop interpretations for M3. The committee looked at a large data set from a more recent comparative study of more than 280 samples from many soil series and most counties in Florida. The samples were analyzed for plant nutrients using both M1 and M3 extractants and showed enhanced correlations for phosphorus, potassium, and magnesium.

The committee initially looked at the data summarized in the following Tables—2a, 2b, and 2c—and determined that interpretations could be drawn as the first approximation. The rounded-off values derived from the normalized values in Tables 2a, 2b, and 2c were used as the basis to develop the interpretation (Table 3), and the interpretation categories are not based on the correlation models. The committee discussed the interpretation categories and determined that *Very Low* and *Very High* categories were redundant. Since no recommendations for nutrient application are made once the test result is *High*, the committee concluded that the *Very High* category did not serve any purpose. Similarly, because very few agriculturally managed soils tested in the *Very Low* category for P, the *Very Low* category did not effectively serve any useful purpose. Also, most vegetable crops have the same nutrient recommendation for both *Very Low* and *Low* categories. Therefore, in the M3 interpretation, *Very Low* and *Very High* categories were not included. This approach also helped dispel any misperceptions that these categorizations somehow related to negative environmental impacts. These categories purely demonstrate only the agronomic crop requirements of nutrients and, therefore, do not have any implications on water quality. Based on this approach, interpretations for M3 were adopted (Table 3) in August 2013.

In March of 2014, the committee reassessed the interpretations and examined the adequacy of the correlations (Figures 2–4). It was noted that M3 extracted more phosphorus in many soils with a wide range of pH and organic matter content because the fluoride in M3 increased the extractability of P from aluminum and iron phosphates. Figure 2 illustrated the increased M3 value compared with M1. The correlation equation in Figure 2 indicated a greater slope of 1.35 with larger M3 extractable soil P concentration than the extractable P from the same soil by M1. Thus, the low P index of 15 mg kg^{-1} for M1 equates to an M3 concentration of 27 mg kg^{-1} (Table 2). Likewise, the high P index increases from 30 mg/kg to 47 mg/kg. Unlike P, soil extractable K and Mg are nearly identical between M1 and M3 (Figures 2 and 3).

Based on these observations, the technical committee revised the M3 interpretation in March 2014 (Table 4). The new interpretations have been correlated with the M1 interpretations, as closely and realistically as possible, so the actual nutrient recommendations are not changed.

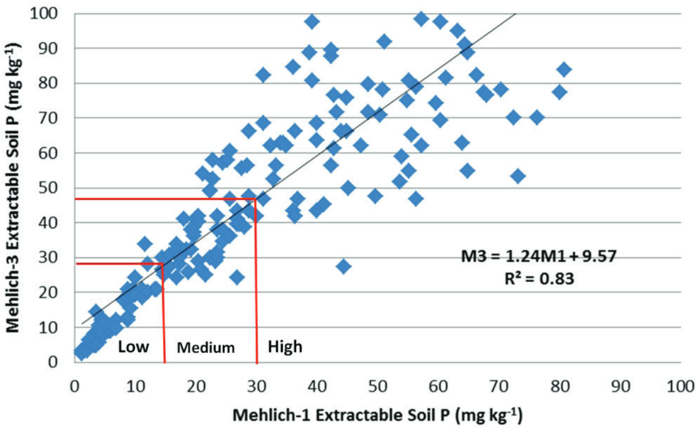

Figure 2. Correlation between M1 & M3 extraction methods for soil P
Credits: Rao Mylavarapu

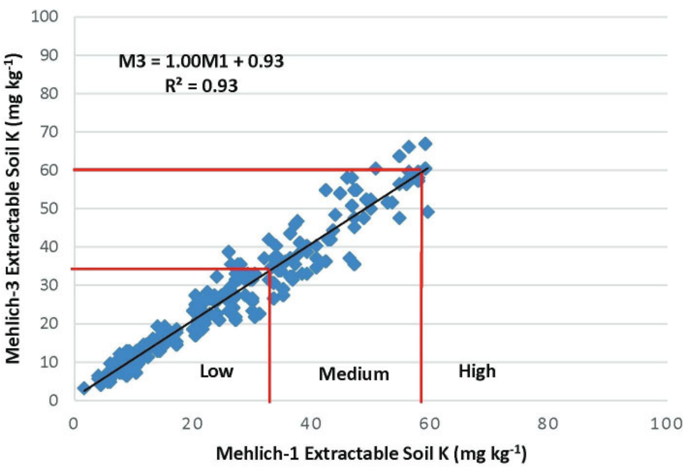

Figure 3. Correlation between M1 & M3 extraction methods for soil K
Credits: Rao Mylavarapu

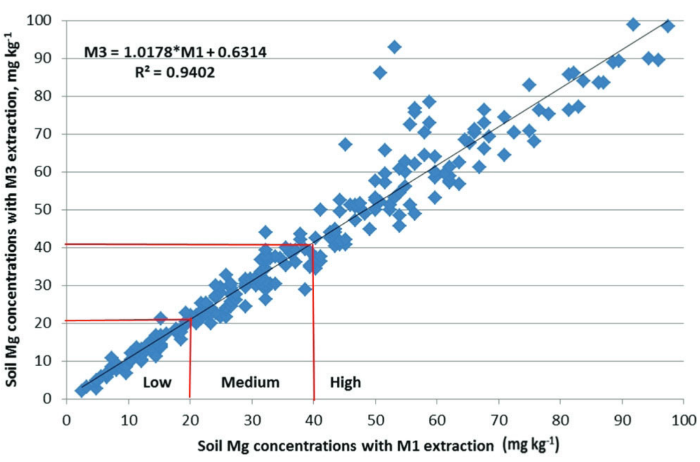

Figure 4. Correlation between M1 & M3 extraction methods for soil Mg
Credits: Rao Mylavarapu

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Table 2a. Categorical Values for Stepwise Scaling of M1 values to M3 values for P, mg kg^{-1}

M3-P Values Based on M1-P Categorical Level					
	V-LOW	**LOW**	**MEDIUM**	**HIGH**	**V-HIGH**
Low Value	2.4	12.9	12.9	21.8	53.2
High Value	24.2	33.8	66.1	134.6	951.1
Average	10.2	22.0	38.2	69.1	200.1
Normalized	9.9	24.6	39.4	69.9	70+
Source: Mylavarapu (2009)					

Table 2b. Categorical Values for Stepwise Scaling of M1 values to M3 values for K, mg kg^{-1}

M3-K Values Based on M1-K Categorical Level					
	V-LOW	**LOW**	**MEDIUM**	**HIGH**	**V-HIGH**
Low Value	0.81	12.9	12.9	49.2	129.0
High Value	25.8	32.24	68.5	130.6	505.4
Average	12.6	23.4	39.5	82.2	211.4
Normalized	11.3	23.8	40.0	80.7	81+
Source: Mylavarapu (2009)					

Table 2c. Categorical Values for Stepwise Scaling of M1 values to M3 values for Mg, mg kg^{-1}

M3-Mg Values Based on M1-Mg Categorical Level			
	LOW	**MEDIUM**	**HIGH**
Low Value	2.4	13.7	9.7
High Value	15.3	38.7	625.4
Average	9.6	22.7	81.8
Normalized	9.6	22.7	53.8+
Source: Mylavarapu (2009)			

Table 3. Initial Interpretation Table for M3 Extractable Soil Nutrient Concentrations, mg kg^{-1}

	M3 Categories		
Nutrient	**LOW**	**MEDIUM**	**HIGH**
P	≤25	26–40	41+
K	≤25	26–40	41+
Mg	≤10	11–23	24+
Source: Mylavarapu (2009)			

Table 4. Revised Soil Test Interpretation for Mehlich-3 Extraction Method for Agronomic and Horticultural Crops and Landscapes

	Mehlich-3, mg kg^{-1}		
Nutrient	**LOW**	**MEDIUM**	**HIGH**
P	≤25	26–45	>45
K	≤35	36–60	>60
Mg	≤20	21–40	>40
Source: Mylavarapu, Obreza, Morgan, Hochmuth, Nair, and Wright (2014)			

Plant Tissue Analysis and Interpretation for Vegetable Crops in Florida[1]

G. Hochmuth, D. Maynard, C. Vavrina, E. Hanlon, and E. Simonne[2]

Introduction

Improved fertilizer management for vegetables is important in view of today's need to reduce production costs, conserve natural resources, and minimize possible negative environmental impacts. These goals can be achieved through optimum management of the fertilizer applied. Understanding the crop nutrient requirements and using soil testing to predict fertilizer needs are keys to fertilizer management efficiency.

Plant tissue testing is another tool for use in achieving a high degree of precision in fertilizer management. Timely tissue testing can help diagnose suspected nutrient problems or can simply assist in learning more about fertilizer management efficiency.

This guide is provided to assist vegetable growers, Cooperative Extension Service personnel, and consultants in conducting a meaningful plant tissue testing program. Guidelines are provided for collecting samples, proper handling of the sample, and choosing an analytical lab. Information is also presented on basic plant nutrition so that the reader understands the nutrient requirements of each vegetable crop and the process of identifying nutrient deficiencies.

The final section of the guide presents the deficiency, sufficiency, and toxicity ranges for plant nutrient concentrations. This is the interpretation portion. Values presented in the tables have been drawn from research from many areas of the country with emphasis on research conducted in Florida. Missing values in the tables indicate areas of research need. The final section of the guide also presents recommendations for nutrient deficiency correction.

Plant Nutrition

Essential Elements

Plants require light, water, minerals, oxygen, carbon dioxide, and a suitable temperature to grow. These absolute growth requirements must be available within appropriate ranges and in balance with others for optimum growth to occur.

A total of 17 elements are known to be required for plants to grow and reproduce normally. The elements are carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), iron (Fe), boron (B), manganese (Mn), copper (Cu), zinc (Zn), molybdenum (Mo), chlorine (Cl) and nickel (Ni).

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The atmosphere provides C and O, and H is provided by water. Together, these three elements are combined into simple organic compounds during the process of photosynthesis. The other 14 elements are supplied mostly from the soil, including native soil fertility, residual lime and fertilizer, or from current lime and fertilizer applications. Other less important sources of plant nutrients are well water (Ca, Mg, S, Fe) and the atmospheric deposition (S and N).

The macronutrients (N, P, K, Ca, Mg, S) are those found in comparatively high concentrations in plants and are measured in percent (%). Micronutrients (Fe, B, Mn, Cu, Zn, Mo, Cl) are present in comparatively minute concentrations in plants and are measured in parts per million (ppm).

Roles of Essential Elements in Plant Growth

Each of the essential elements has at least one specifically defined role in plant growth so that plants fail to grow and reproduce normally in the absence of that element. However, most of the essential elements have several functions in the plant. A basic summary of some of these functions follows:

Carbon, from carbon dioxide (CO_2) in the atmosphere, is assimilated by plants in the photosynthetic process. It is a component of organic compounds such as sugars, proteins, and organic acids. These compounds are used in structural components, enzymatic reactions, and genetic material, among others. The process of respiration degrades organic compounds to provide energy for various plant metabolic processes.

Oxygen, derived from CO_2, also is a part of organic compounds such as simple sugars. Atmospheric oxygen is necessary for all oxygen-requiring reactions in plants including nutrient uptake by roots.

Hydrogen derived from water (H_2O) also is incorporated into organic compounds in the photosynthetic process. Hydrogen ions are involved in electrochemical reactions and maintain electrical charge balances across all membranes.

Phosphorus is used in several energy transfer compounds in plants. A very important function for P is its role in nucleic acids, the building blocks for the genetic code material in plant cells.

Potassium plays a major role as an activator in many enzymatic reactions in the plant. Many enzymes responsible for cellular reactions require K as a co-factor. Another role for K in plants occurs in special leaf cells called guard cells found around the stomata. By regulating the turgor pressure in the guard cells, the degree of opening of the stomata is controlled and thus the level of gas and water vapor exchange through the stomata is regulated. Turgor is largely controlled by K movement in and out of guard cells.

Nitrogen is found in many compounds including chlorophyll (the green pigment in plants), amino acids, proteins, and nucleic acids. A large part of the plant body is composed of N-containing compounds.

Sulfur is a component of sulfur-containing amino acids such as methionine. Sulfur also is contained in the sulfhydryl group of certain enzymes.

Calcium is a component of calcium pectate, a constituent of cell walls. In addition, Ca is a co-factor of certain enzymatic reactions. Recently, it has been determined that Ca is involved in the intimate regulation of cell processes mediated by a molecule called calmodulin.

Magnesium plays an important role in plant cells since it appears in the center of the chlorophyll molecule. Certain enzymatic reactions require Mg as a co-factor.

Iron is used in the biochemical reactions that form chlorophyll and is a part of one of the enzymes that is responsible for the reduction of nitrate-N to ammoniacal-N. Other enzyme systems such as catalase and peroxidase also require Fe.

Boron functions in the plant are still not well understood. Boron seems to be important for normal meristem development in young plant parts, such as root tips.

Manganese functions in several enzymatic reactions that involve the energy compound adenosine triphosphate (ATP). Manganese also activates several enzymes and is involved in the processes of the electron transport system in photosynthesis.

Copper is a constituent of a protein, plastocyanin, involved in electron transport in chloroplasts, and copper is part of several enzymes, called oxidases.

Zinc is involved in the activation of several enzymes in the plant and is required for the synthesis of indoleacetic acid, a plant growth regulator.

Molybdenum is a constituent of two enzymes involved in N metabolism. The most important of these is nitrate reductase, the enzyme involved in the reduction of nitrate-N to ammoniacal-N.

Chlorine plays a possible role in photosynthesis and might function as a counter ion for K fluxes involved in cell turgor.

Nickel is now recognized by plant scientists as an essential element for plants. It is involved in the enzyme urease and is a part of several other enzymes involved in plant metabolism.

Mobility of Essential Elements within the Plant

Approximately 80% of all nutrients absorbed by roots are translocated to the shoots. When nutrient supply is abundant, they are delivered directly to the shoots often within minutes of absorption. Accordingly, plants may absorb and accumulate essential elements in far greater quantities than are necessary for immediate use. These accumulated elements are available for use later in the plant life cycle when demands are high for fruit production and/or when nutrient supply from the soil is restricted. The ability of an element to move from one plant part to another is called mobility and the process is known as retranslocation. The mobility of the essential elements in plants is shown in Table 1.

The mobility of an element influences the location where deficiency symptoms (see the following section) are likely to be observed on the plant. For example, Mg deficiency symptoms occur on the oldest, generally lower leaves, because Mg is retranslocated to the younger leaves of the plant. Conversely, Ca deficiencies occur at the growing point or in storage organs like roots and fruits because Ca, being immobile, is not retranslocated to these sites during Ca stress conditions.

Nutrient Deficiency Symptoms

Vegetable plants exhibit deficiency symptoms that are characteristic for each element, and are, therefore useful for diagnostic purposes. However, in many cases, the symptoms may be masked by symptoms of other nutritional disorders, those caused by unfavorable environment, or stress caused by plant pests. In these situations, plant tissue analysis provides useful information to complement and confirm visual diagnosis. Nutritional disorders of vegetables rarely occur in well managed crops. The general symptoms associated with deficiencies and excesses of the essential elements follow:

Nitrogen is absorbed as NH_4^+ and NO_3^-. It is a mobile element in the plant and deficiency symptoms therefore show up first on the lower leaves. Symptoms consist of a general yellowing (chlorosis) of the leaves. On tomatoes, there might be some red coloration to the petioles and leaf veins. If the problem persists, lower leaves will drop from the plant.

Healthy plant leaves contain between 2.0 and 5.0% N on a dry weight basis. Deficiencies of N show up most often where errors are made in fertilizer management resulting in insufficient N supply to the crops. More often in commercial vegetable production, there is a problem from excess N application. Plants receiving excess N usually are lush and tender with larger and darker-green leaves. Excess N (especially in warm and sunny conditions) can lead to "bullish" tomato plants. These plants produce thick, leathery leaves that curl under in dramatic fashion producing compact growth.

Phosphorus is typically absorbed as $H_2PO_4^-$ by an active (energy-requiring) process. P is very mobile in the plant. Deficiencies therefore show up on the older leaves of the plant because P is translocated out of these leaves to satisfy the needs of new growth. P deficiency shows up as stunting and a reddish coloration resulting from enhanced display of anthocyanin color pigments. Deficient leaves will have only about 0.1% P in the dry matter. Normal, most-recently matured leaves of most vegetables, will contain 0.25 to 0.6% P on a dry weight basis. Excess P in the root zone can result in reduced plant growth probably as a result of P retarding the uptake of Zn, Fe, and Cu.

Potassium is absorbed in large quantities by an active uptake process. Once in the plant, K is very mobile and is transported to young tissues rapidly. Deficiency symptoms for K show up first on lower leaves as flecking or mottling on the leaf margins. Prolonged deficiency results in necrosis along the leaf margins and the plants can become slightly wilted. Deficient plant leaves usually contain less than 1.5% K. Deficiencies of K lead to blotchy ripening of tomatoes where fruits fail to produce normal red color in some areas on the fruit.

Calcium, unlike most elements, is absorbed and transported by a passive mechanism. The transpiration process of plants is important in the transport of Ca. Once in the plant, Ca moves toward areas of high transpiration rate, such as rapidly expanding leaves.

Most of the uptake of Ca occurs in a region on the root just behind the root tip. This has practical importance for vegetable culture because it means that growers must keep healthy root systems with numerous actively growing root tips. Root diseases and nematodes may severely limit Ca uptake by the plant.

Calcium is immobile in the plant, therefore, deficiency symptoms show up first on the new growth. Deficiencies of Ca cause necrosis of new leaves or lead to curled, contorted growth. Examples of this are tipburn of lettuce and cole crops. Blossom-end rot of tomato also is a calcium-deficiency related disorder. Cells of the tomato fruit deprived of Ca break down causing the well-known dark area on the tomato fruit. Sometimes this breakdown can occur just inside the skin so that small darkened hard spots form on the inside of the tomato while the outside appears normal. On other occasions, the lesion on the outside of the fruit is sunken or simply consists of a darkening of tissue around the blossom area.

Since Ca movement in the plant is related to transpiration, environmental conditions that affect transpiration also affect Ca movement. Periods of high humidity can lead to tipburn of lettuce because the leaves are not transpiring rapidly enough to move adequate Ca to the leaf extremities.

Calcium concentrations in healthy, most-recently matured leaves will be from about 0.6 to 5.0%. Deficiencies, however, can occur temporarily given certain environmental conditions as previously discussed. Therefore, it is important to consider irrigation in the overall Ca fertilization program.

Magnesium is absorbed by the plant in lower quantities than Ca. Unlike Ca, Mg is highly mobile in the plant and deficiencies first appear on the lower leaves. Deficiency symptoms consist of an interveinal chlorosis, which can lead to necrosis of the affected areas. On tomato leaves, advanced Mg deficiency leads to a mild purpling of the affected areas.

Magnesium is usually found in concentrations of 0.2 to 0.8% in normal leaves. Conditions that lead to deficiency are usually related to poorly designed fertilizer programs that supply too little Mg, or when Ca and/or K compete with Mg for uptake.

Sulfur is absorbed mainly in the form of sulfate (SO_4^{-2}) by a mechanism that is not well understood. Sulfur is somewhat mobile in the plant so deficiency symptoms are fairly evenly distributed on the plant but mostly on the upper leaves. Deficiency symptoms consist of a general yellowing of the leaves. Deficiencies of N and S appear somewhat similar but N deficiency occurs on the lower leaves whereas S deficiency occurs in the upper part of the plant.

Plant leaves usually contain between 0.2 and 0.5% S on a dry weight basis. This range is similar to that for P. Plants can generally tolerate quite high concentrations of S in the growing media. This is one reason for the wide use of S-containing materials to supply nutrients such as Mg and the micronutrients, and explains why S deficiency is not very common in vegetable crops.

Iron is absorbed by an active process as Fe^{2+} or as iron chelates, which are organic molecules containing iron sequestered within the molecule. Uptake of Fe is highly dependent on the Fe form and adequate uptake depends on the ability of the root to reduce the pH nearby and reduce Fe^{3+} to Fe^{2+} for uptake. Iron chelates are soluble and aid in keeping Fe in solution for uptake. The uptake of the whole chelate molecule is low and usually Fe is removed from the chelate before uptake.

Iron is not mobile in plants and symptoms appear on the new leaves first. Symptoms consist of interveinal chlorosis that may progress to a bleaching and necrosis of the affected leaves. Usually, the chlorosis begins on the lower part of the leaflets and not at the tips. Normal leaves contain 30 to 150 ppm Fe on a dry-weight basis.

Conditions that lead to Fe deficiency are inadequate concentrations of Fe in the soil solution or basic soil conditions (pH above 7.0). Fe deficiency is corrected by adding Fe to the fertilizer or by foliar sprays of Fe. Usually one or two sprays of 0.5 ppm Fe solution will correct a temporary Fe deficiency.

Manganese is absorbed as Mn^{2+} ions and uptake is affected by other cations such as Ca and Mg. Manganese is relatively immobile in the plant and symptoms of deficiency first appear on the upper leaves.

Deficiency of Mn resembles that of Mg, however Mn deficiency appears on the upper leaves of the plant. Manganese deficiency consists of interveinal chlorosis; however, the chlorosis is more speckled in appearance compared to Mg deficiency. Manganese deficiency also slightly resembles Fe deficiency of tomato however Mn deficiency appears as chlorotic speckling over most of the leaf while Fe deficiency usually appears first on the lower part of the leaflets.

Critical concentrations of Mn in leaves ranges from 20 to 100 ppm for most plants. High levels of Mn can be toxic to plants. Toxicity appears as marginal leaf necrosis in many plants. Concentrations of Mn on the order of 500 to 800 ppm can result in toxicity in many crops. Excess Mn in the soil solution can reduce uptake of Fe by the plant.

Situations that lead to deficiency are mostly related to inadequate Mn supply in the soil solution, from basic soil conditions, or to competition effects of other ions. Toxicity can occur from excess Mn supply especially when plants are in acidic soil. Solubility of Mn in the soil solution is increased by low pH.

Zinc uptake is thought to be by an active process and can be negatively affected by high concentrations of P in the media. Zinc is not highly mobile in plants. Deficiency of Zn results in young leaves with interveinal chlorosis. Sometimes Zn deficiency will lead to plants with shortened internodes.

Healthy leaves contain about 25 to 150 ppm Zn. High levels of Zn can lead to toxicity where root growth is reduced and leaves are small and chlorotic. Zinc deficiency may occur in cold, wet soils, or in soil with a very high pH where Zn is rendered unavailable to the plant.

Copper is absorbed by plants in very small quantities. The uptake process appears to be an active process and it is adversely affected by high Zn concentrations. Copper is not highly mobile in plants but some Cu can be translocated from older to newer leaves. The normal level of Cu in plants is on the order of 4 to 20 ppm.

Copper deficiency on young leaves leads to chlorosis and some elongation of the leaves. Excess Cu, especially in acidic soil may be toxic to plants.

Molybdenum is absorbed as molybdate (MoO_4^{-2}) and the uptake can be suppressed by sulfate. Normal tissue concentrations of Mo are usually less than 1 ppm.

A deficiency of Mo first appears on leaves that are intermediate in age and older. The leaves become chlorotic and the margins roll. Unlike other micronutrients, Mo deficiency occurs in acidic soil conditions.

Boron uptake by plants is not well understood. Boron is not mobile in the plant and seems to have many uptake and transport characteristics in common with Ca.

Boron deficiency affects the young growing points first, e.g., buds, leaf tips and margins, and root tips. Buds develop necrotic areas and leaf tips become chlorotic and eventually die. Tomato leaves and stems become brittle. Healthy leaves contain 20 to 100 ppm B; levels higher than 150 ppm may lead to toxicity. Cole crops, beets, and celery have rather high B requirements, otherwise only small amounts of B are needed by plants and supplying excessive B from fertilizer or from foliar sprays can lead to toxicity.

Chlorine is supplied for plant nutrition as the chloride ion and is required in very small amounts for normal plant growth. Chloride is involved in photosynthesis and functions as a counter-ion in maintaining turgor pressure in cells. Chlorine deficiency symptoms are not common but include wilting. The chloride ion is very common in the environment and is often found as a constituent in fertilizers; therefore, deficiency symptoms are rare. High concentrations of chloride in the nutrient solution can be toxic to plants in hydroponic culture.

Nickel is required in small amounts by plants, 0.5 to 5.0 ppm Ni. Nickel is common in soil, and truly deficient soils have not be found. Deficiency symptoms include chlorosis similar to that of iron deficiency. Nickel deficiency also can be similar to zinc deficiency. These similarities in deficiencies make it difficult to diagnose true Ni deficiency in plants. A buildup of urea in leaf tips may occur in Ni-deficient plants.

Key to Nutritional Disorders of Vegetable Crops

The key in Table 2 can be used to assist in diagnosis of visual symptoms of nutrient disorders. Color photographs, available in many books (see general reference list at the end of this publication) may be useful in conjunction with the key.

Critical Concentrations

As reported in the section on nutrient deficiency symptoms, there is a general concentration range for each essential element that results in normal plant growth. This is called the adequate or sufficient nutritional concentration range (Fig. 1). Plant growth remains relatively constant within the range of concentrations found in the zone of sufficiency.

The so-called critical concentration occurs at the point where growth is reduced 10% because of a shortage of the element in question. The critical concentration is in the transition zone, which is the borderline between elemental sufficiency and deficiency. Critical concentrations for an element can be different depending on stage of growth and plant part used for the reference tissue.

The zone of sufficiency (level part of the graph) is the area where an increase in tissue nutrient concentration is not accompanied by an increase in growth (Fig. 1). This is the range in nutrient concentrations in which the grower should attempt to control the fertilizer program. The objective is to maintain tissue nutrient concentrations on the lower side of the range with good fertilization techniques. Managing plant nutrient concentrations on the right of the zone indicates over fertilization and resulting luxury consumption of nutrients by the plant.

The deficient zone occurs at tissue elemental concentrations lower than those in the transition zone and is accompanied by a drastic restriction in growth. Plants show deficiency symptoms as the nutrient concentration falls within this zone. This is the vertical portion of the curve (Fig. 1).

At the other end of the scale is the toxicity zone where tissue elemental concentrations are greater than those in the adequate zone. A gradual decrease in plant growth occurs in the toxicity zone. As the tissue concentration rises further, toxicity symptoms, often necrosis, begins (Fig. 1).

The curve shown in Fig. 1 is obtained by growing plants at a wide range of concentrations of the element being studied. Meanwhile, other nutrients and factors influencing growth are held constant so that changes in growth can be attributed solely to the nutrient being studied. Either greenhouse or field experiments may be designed to generate the data necessary to develop the relationship between plant growth and tissue concentrations of a particular element.

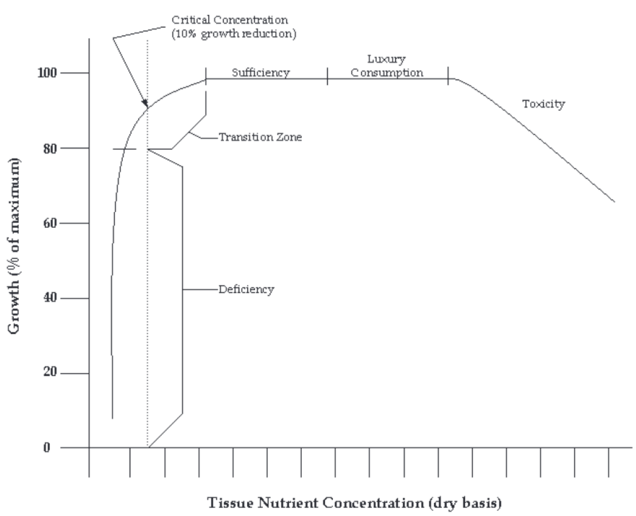

Figure 1. Crop growth in relation to concentration of a nutrient in the diagnostic tissue sample.

Application of Plant Analysis

Plant analysis assists in diagnosing nutritional problems or potential problems in the crop from which the samples are taken, i.e., the current crop. Potential problems can be circumvented, particularly if they are discovered early in the crop (before bloom) cycle by routine leaf analyses. For example, young cabbage plants that appear normal might have a very low N concentrations for that stage of growth. When checking fertilizer application records, it is found that an error was made, and only 1/10 of the intended rate was applied. Additional N can be applied and the crop can be saved, whereas if symptoms of N deficiency had developed before diagnosis, the crop may have been lost or there may have been a substantial yield reduction. With micro-irrigated or fertigated (drip) crops, the nutritional status of the crop can be monitored continuously, and fertigation adjustments can be made as needed.

Plant analysis results also have application for fertilizer management of the same crop grown in subsequent seasons. Fertilizer rates can be increased or decreased based on tissue test results and yields of previous crops. Given certain conditions, plant analysis results can be used to manage timing of supplemental sidedress or topdress fertilizer applications.

Results of plant tissue analysis along with results of soil analysis provide useful tools for the grower in managing the rate and timing of fertilizer applications for vegetables. However, each has limitations and they should not be used for purposes not intended.

Tissue testing is not recommended if the crop has received foliar sprays containing nutrients, especially micronutrients. There is no way to completely remove residues from leaf surfaces and these residues result in higher test results than actually in the plant tissue.

Sample Collection, Preparation, and Handling

Why Sample

There are two main reasons to test plant tissue for nutrient status. The first reason is to monitor the nutrient within the plants during the growing season. This technique is a good management strategy so long as the grower has a means of regulating nutrition in field conditions, for example, addition of nutrients through the micro irrigation system.

The second reason for tissue testing is to diagnose a suspected nutritional deficiency or toxicity. This diagnostic sampling is usually only done after a problem has been detected. In the case of deficiencies, the sampling should only be undertaken if the grower has enough time to apply extra fertilization AND the addition will actually enhance production. Too often, supplemental fertilization at the end of the season does not result in higher production, but only in greener foliage. With toxicities, information obtained on the current stressed crop can only be used to make management decisions that may benefit subsequent crops. For example, diagnosis of copper toxicity can only be treated by liming the field for the next crop.

The most frequent use of leaf tissue analysis is to diagnose a suspected nutrient deficiency. It is best to perform this analysis as soon as possible after the symptoms are evident. Once a deficiency manifests itself, the optimum yield may have already been lost. Losing the market window in shortseason crops due to a nutrient deficiency is devastating. The loss of market value due to poor leaf color in greens, for example, is also a consideration. Therefore, routine tissue sampling and analysis at the proper time(s) in the season can pay dividends for the grower.

When to Sample

A grower wishing to develop a routine program of tissue sampling to ensure proper nutrition for his or her crop throughout its growth cycle should begin shortly after the crop emerges from the soil (first true leaf) and continue at weekly or biweekly intervals. By means of a routine sampling and analysis program, the grower can fine-tune his fertilization program. Tissue analysis can serve as an indicator as to which nutrients are in adequate, deficient, or high concentrations. If a grower believes the nutritional status of his crop is satisfactory, he may benefit from a single sample taken just before fruit set and perhaps a second sample during mid-production. These samples would bracket that period when a deficiency would be most detrimental to optimum yield.

For routine sampling, a 'reference' tissue (most often leaves) is used to index plant nutritional status. Samples are collected on the basis of physiological age of the plant (not on calendar date) such as prebloom, tasseling, midgrowth, or heading.

What to Sample

There are several types of vegetable plant reference tissues including petiole, leaf, but rarely fruits. Some work has been done with vegetable plant petioles for nitrates in greenhouse crops and some field vegetable crops, but the standard vegetable reference tissue is the leaf. It is essential to use the same plant part as the one used to develop the interpretative data.

It is not practical to harvest and prepare entire plants for chemical analysis. Therefore, a plant part is used for convenience. However, it is essential that the plant part selected for chemical analysis accurately represents the nutritional status of the plant during its entire life cycle. For many vegetable crops, the most-recently-matured leaf (MRML) provides the most sensitive indicator of the nutritional status of the plant, sometimes only the petiole of this leaf is used for plant analysis. Specific plant parts for sampling each vegetable crop are specified in the section on sampling.

For most crops, and for many nutrients, mature, physiologically active leaves should be sampled. This is often referred to as "the most-recently-matured leaf" (MRML) including the blade and its petiole. The MRML is the leaf that has turned from a light-green juvenile color to a darker-green color and has reached full size. The exception to the rule of the MRML is the analysis of Ca, Cu, B, and S, which are relatively immobile in the plant. Therefore, an analysis of the mature leaves in this case may not reveal the Ca, B, Cu, or S deficiency in the younger leaves. When a nutrient deficiency of this nature is suspected, young (not fully expanded) leaf tissue is needed for analysis.

How to Sample

The sample is a whole leaf sample and it should not contain any root or stem material. For sweet corn or onions, the leaf is removed just above the attachment point to the stalk or bulb. For compound leaves (carrots, peas, tomatoes, etc.), the whole leaf includes the main petiole, all the leaflets and their petioliules. For heading vegetables, it is most practical to take the outermost whole wrapper leaf. When sampling particularly young plants, the whole above-ground portion of the plant may be sampled.

A proper leaf sample should consist of about 25 to 100 individual leaves. The same leaf (i.e., physiological age and position) should be removed from each sampled plant. Plants damaged by pests, diseases, or chemicals should be avoided when trying to monitor the nutrient status of the crop.

Individual plants, even side-by-side, may have a considerably different nutrient status. Therefore, by sampling a sufficiently large number of plants, the error due to this variability can be minimized. Figure 2 indicates the potential sampling error due to varying sample sizes. More accuracy in determining the actual nutrient status is derived from a larger sample size.

For a nutrient deficiency diagnosis, one composite tissue sample should be collected from the area exhibiting the disorder and a second sample from otherwise "normal" plants for comparison. Both samples should be of similar physiological age and from the same cultivar. The "disorder" sample and the "normal" sample must be properly separated from each other so a valid comparison can be made after analysis.

It is advisable to include a corresponding soil sample when submitting a diagnostic tissue sample. This practice is particularly important when the sample taken is from an area where a nutrient deficiency is suspected. The soil sample may indicate other factors, such as pH or nematodes, that may have a negative effect on crop growth and nutrient availability.

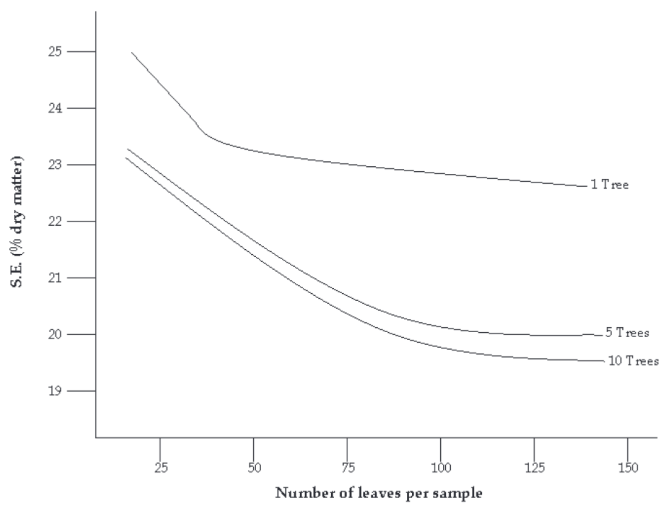

Figure 2. Nitrogen leaf sampling errors for different sampling sizes (Holland et al., 1967).

Contaminants

Samples are often contaminated by fungicides, nutrient sprays, soil, or dust. Data obtained from contaminated leaf samples will be misleading. Decontamination of some dust or soil is best accomplished by quickly rinsing in a dilute non-phosphate detergent solution (2%) followed by two distilled water rinses. Tap water should not be used because it can be high in certain nutrients such as Ca, Fe, Mg, or S. Leaf samples should be washed quickly to minimize the leaching of certain nutrients (especially K) from the leaves. When testing for Fe, it is always necessary to wash the tissue as described above. It is not likely that contamination from chemical or nutrient sprays can be effectively removed from the leaf surface.

Preparation for Shipping

Following rinsing, the sample should be blotted dry with absorbent paper. The samples should be air-dried for several hours before shipment. If a plant analysis mailing kit is not available, the samples should be wrapped in fresh absorbent paper and placed in a large envelope (plastic bags must not be used). The sample should be mailed immediately to the soil and plant analysis laboratory. An air-dried sample, if loosely packed to avoid rotting, will last two to three days before decomposition begins.

If the samples must be held for any length of time before shipping, they should be dried at 150°F in a ventilated oven (leave the door ajar) until dry weight is constant. Once dried, the sample can be placed in a plant analysis mailing kit or a large envelope. This ensures the integrity of the sample until shipping is possible.

Considerations for Choosing a Laboratory

Tissue testing can be a valuable tool for monitoring nutrients within a growing crop. Tissue samples must be collected from the field, shipped to the laboratory, and analytical results with appropriate interpretations returned to the grower. Armed with this information, the grower can make a knowledgeable decision regarding possible additions of fertilizers to the crop. The time for this cycle to be completed must be held to a minimum. A reasonable time frame for this process is 3 to 5 working days for most vegetables, for diagnostic samples. For some short season crops, and for deficiency diagnosis, next-day service is needed.

Laboratory Location

Because of the need for short turnaround from sampling to receipt of the results, the best approach is to select a reliable laboratory close to the production area. However, if the producer is equipped with electronic mail or FAX instruments, delays for return of results can be greatly reduced. Priority mailing of tissue samples can further reduce the turnaround time. Thus, the need for the laboratory to be located relatively close to the production site is somewhat reduced, but the grower should still consider the physical problems of mailing as a factor in selecting a laboratory for tissue testing.

Since several tissue samples will be needed throughout the season, it is often advisable to make prior arrangements with the laboratory for all of the expected samples. Some laboratories offer a "package" for selected crops that includes a discount for a specified number of sampling dates.

The Land Grant University laboratories in the southeast region have been exchanging standardized plant samples for many years [Southern Region Information Exchange Group (SRIEG) 18 Work Group] and have found good agreement among the participating university laboratories. However, both laboratory procedures and methodology can influence tissue results, so it is usually advisable to continue testing with the same laboratory throughout the season and years to avoid possibly significant differences among laboratories.

Interpretation of Laboratory Results

While many laboratories do an excellent job of reporting the concentrations of nutrients in plant tissue, a few laboratories also provide accurate interpretations and recommendations based upon those results. That interpretations and recommendations may be provided with the report is no indication of their value for efficient crop production. Information (such as that contained in this circular) must be based upon research in local field conditions to be of use in interpreting laboratory results. Some laboratories might report the tissue results, compared with the average value for that crop and nutrient, observed by the lab in previous years. This average value might not be the critical concentration the grower is looking for because the average value includes results from crops of variable nutrient status or varieties. In other words, one needs the true critical concentration. Sometime the lab's "low", "medium", and "high" interpretation are simply a placement of the results relative to what is observed on average by the laboratory. Interpretations of this sort are misleading and of little help when making nutrient management decisions. A discussion concerning the procedure used for interpreting concentrations can assist with laboratory selection.

Diagnostic Tissue Testing

By its very nature, diagnostic tissue testing is only undertaken after a problem has been recognized. Often, the grower will see some visual clue that the crop is not as it should be. At this point, information to help make a diagnosis is needed, one component of which may be tissue analysis. Other information, such as soil testing, climatic data, pesticide, and fertilizer records, will often be needed besides nutrient status of the crop before the problem is correctly identified.

All of the considerations discussed with respect to nutrient monitoring pertaining to laboratory selection and location apply equally to diagnostic sampling. However, sample turnaround time may be the most important, since prompt reaction to some nutrient deficiencies is needed to avoid loss of yield and/or fruit quality.

Interpretations and recommendations of diagnostic samples should be a two-step process. The first interpretation should be based solely on the concentrations of nutrients found in the tissue sample. In short, do the nutrient levels represent deficiency or toxicity? The information in this circular can help with the answer to this question.

Secondly, results of samples from the affected area should be compared with those taken from an unaffected area: so-called "normal" and "disorder" areas. The samples should be taken at the same time so that a valid comparison can be made. The distance between the two composite samples should also be as small as possible.

This comparison will greatly aid in proper diagnosis. Often, a nutrient may be found to be at the lower level of the sufficiency range in the "disorder" sample, immediately making that nutrient suspect. However, comparison between "normal" and "disorder" levels may reveal that the nutrient is of similar magnitude in both samples, indicating that the symptoms may be caused by other factors.

Plant-Analysis Methods

The method used by the laboratory may greatly affect the meaning of the reported results. Many laboratory procedures, all radically different in approach, have been developed for plant analysis. For example, tests for P, K, etc., range from exotic neutron magnetic resonance (NMR) techniques to field quick-test kits. However, growers should patronize laboratories offering agricultural tests. These methods usually require destructive sampling, either by dry ashing the sample or by dissolving the sample in one or more acids. For small sample sets, some laboratories may employ microwave digestion in acids, but most laboratories will digest samples using a controlled temperature oven or heating apparatus. Testing of the resulting solutions by specific ion electrode methods is usually considered less accurate than colorimetric or spectrophotometric methods.

Methods that analyze the plant sap are usually only semi-quantative measurements. Most field kits use this approach. While some of these kits are appropriate for field use by the grower for certain nutrients, the bulk of these procedures are not as precise as laboratory methods.

All reputable laboratories will monitor the accuracy and precision of test results. This process is usually referred to as a quality assurance program. It is this process that insures that numbers from the various tests are actually within acceptable accuracy ranges. A short discussion with the laboratory about their quality assurance program is good insurance against choosing the wrong laboratory. In all chemical and physical testing, it is agreed that an active quality assurance program has to be in place if any credence is to be given the results of the laboratory effort. Laboratories actively participating in the North American Proficiency Testing program meet or exceed plant tissue quality standards.

A common misconception is that two laboratories should be able to report the same, exact figures on split samples. Selection of methods and possibly different units of measure often cloud such expected agreement. For plant tissue analyses, the analytical results of split samples should be similar. For example, if one lab reports 4.8% N on one sample from a split-sample of tomato leaves, then the second lab results should be the same. In the final analysis however, the actual laboratory answer is but one step to making accurate interpretations and recommendations. It is the accuracy of the recommendation and subsequent positive crop response that is of value to the grower.

Listing of Commercial Laboratories for Agricultural Testing

The University of Florida (IFAS) Extension Soil Testing Laboratory (ESTL) offers only limited plant tissue testing to the public. Services for blueberry and pecan leaves are available. County extension faculty may request diagnostic testing of other plant samples, but this service is not offered directly to the public. Therefore, a discussion with the local county extension faculty is recommended before any samples are sent to the ESTL.

The listing in Table 3 of commercial laboratories may be of use to the reader. This listing is not exhaustive. http://www.naptprogram.org/

Plant-Sap Quick Test for Nutrient Analysis

Much of the diagnostic information presented in this publication deals with analysis of dried plant material (whole leaves, leaf blades, or petioles). The time period from sampling to recommendations for problem correction can be excessive for many situations involving deficiencies. Cost of routine sampling and analysis that involves many samples might be too high for many growers. However, the cost of tissue testing should be compared to the crop value at stake. Costs are often cited as hindrances to routine use of tissue testing in a fertilizer management program. Growers like the idea of tissue testing but may be reluctant to use it in a routine and timely fashion.

An alternative, for certain nutrients, to traditional laboratory analysis is a nutrient determination made on the fresh plant sap. Procedures for plant sap analysis have been available for years, but recently the techniques have been improved to make them more accurate and easier to use in the field. Most of these in-field plant sap "quick tests" should be used in conjunction with periodic laboratory analysis done on dried whole leaves.

Plant sap analysis kits are available in a range of sophistication from simple, hand-held "colorimeters" and ion-specific electrodes to sophisticated portable laboratory units that can test for a multitude of nutrients and chemicals. Growers interested in plant sap testing should evaluate their goals and purchase the equipment needed to meet the needs and avoid unneeded equipment. Often a $50 kit will suffice, but some growers who have the personnel, could benefit from larger, more diverse testing kits.

Plant sap kits can test for several plant nutrients but the user needs to evaluate the need for speed versus accuracy for the nutrients to be determined. For example, a sap test kit may not have the desired accuracy for certain micronutrients compared to traditional laboratory analyses using whole leaves.

Currently, plant sap test kits appear to have most utility for the mobile nutrients such as N, P, and K. These elements, particularly N and K, make up the bulk of nutrients applied as fertilizers to vegetable crops and also are the ones most often managed during the growing season, which makes plant sap testing particularly attractive for these elements. A good example is N management through the season with micro-irrigation. The routine use of a calibrated plant sap quick test could help a micro-irrigation manager make decisions regarding N scheduling for the crop. Proper management of N could reduce the overall fertilizer applications to that crop.

Recent studies in the University of Florida, Institute of Food and Agricultural Sciences (IFAS), have provided calibration data for commercially available nitrate and K quick tests. The kits, described below, have been adapted to determine nitrate and K concentrations of fresh plant sap from petioles of most-recently-matured leaves. The initial work was conducted for tomato, although some work also has been done for other crops (cantaloupe, broccoli, cucumber, squash, and collards). The kits calibrated for use in Florida are described in Table 4.

Plant sap test kits are easy to use and result in rapid evaluations of plant sap for nitrate and potassium.

For sap testing, petioles collected from MRML are used for analyses. Most-recently-matured leaves (MRML) are leaves that have essentially ceased to expand and have turned from a juvenile light-green color to a darker-green color. A random sample of a minimum of 25 petioles should be collected from each "management unit" or "irrigation zone." Management units larger than 20 acres should be subdivided into 20-acre blocks. Leaves with obvious defects or with diseases should be avoided. Sampling should be done on a uniform basis for time of day (best between 10 AM and 2 PM), and for interval after rainfall or fertilization.

For tomatoes, the sample is usually the fifth or sixth leaf from the tip. Whole leaves are collected from the plant and the leaf blade tissue and leaflets are then stripped from the petiole. For tomatoes, a petiole of six to eight inches in length remains. Petioles are chopped into about one-half inch segments. If analysis is not to be conducted immediately in the field, then whole petioles should be packed with ice and analyzed within a few hours of collecting. Given more extreme environmental field conditions (high temperature and bright sun), more dependable results are obtained by making measurement in the lab or office than outdoors.

Chopped petiole pieces are mixed and a random subsample (about 1/4 cup) is crushed in a garlic press, lemon press, or hydraulic press (obtainable from HACH Co., Table 4). Expressed sap is collected in a small beaker or juice glass and stirred.

Early in the season, when sap nitrate-N concentrations are high, the sap might need to be diluted. Dilution makes it possible to read the nitrate-N levels within the scales of some test kits. Dilution also will minimize the interference of the green chlorophyll color of the sap on the reading of colorimetric testing systems. Some users have reported success with charcoal-filtered sap. This procedure is particularly good for dark sap that does not need to be diluted. Slightly different results will be obtained with filtered and unfiltered sap and users should standardize procedures with one method. With tomatoes, a dilution of 50 or 60 parts deionized or distilled water to one part sap is needed. Later in the season, a dilution of 20 to 1 will usually suffice. Diluting can be accomplished by using a laboratory pipette and graduated cylinder or less precisely, with an eyedropper. The pipette method is recommended for highest accuracy. Diluted sap is stirred completely prior to use in the test kits.

For the Quant strip test, a test strip is removed from the container (keep strips cool when not in use) and dipped for a second into the diluted sap. Following 60 seconds, the pink or purple color developed on the test pad on the end of the strip is compared to the calibrated color chart provided with the kit. Interpolation will be needed for readings between any two color blocks on the chart. An alternative is to use a newly developed strip color reader. This reflectometer provides for more quantitative evaluation of the color on the strip. Readings are made in parts per million (ppm) nitrates which can be converted into ppm nitrate-N by dividing by 4.45.

For the HACH colorimeter, two viewing tubes are filled with diluted sap. One tube is placed in its slot in the "comparator." Contents of one powder reagent pillow are emptied into the second diluted sap sample and the tube mixed for one minute. After mixing, the tube is placed in its slot in the "comparator" and left for one minute. After one minute, the colors in the viewing slots are matched by rotating the color wheel, and the resulting ppm of nitrate-N read from the dial.

For the Cardy meters, plant sap is pressed from the petioles and a drop is placed on the Cardy meter, covering both electrode spots on the meter. The meter must be calibrated with standard ion solutions before measuring ion concentration in the sap and again between every 6 or 8 measurements. There are specific meters for nitrate-N and K.

Current interpretations for these test kits for several vegetables are presented in Table 5. Work is continuing to provide data for additional crops and for other nutrients. Details on use and care of these sap measuring systems are presented in the publication "Plant Petiole Sap-Testing Guide for Vegetable Crops". Fla. Coop. Ext. Circ. 1144. (http://edis.ifas.ufl.edu/cv004).

Correcting Nutrient Deficiencies

Nutrient deficiencies, if directly related to lack of fertilizer, must be corrected in timely fashion to avoid reduced yield and quality. It is best to avoid deficiencies by well executed soil-based nutrient programs, however, deficiencies if detected early enough can be corrected. Depending on the situation and cultural system used, several means of applying the needed fertilizer can be employed.

For open bare-ground culture, the deficient nutrient can be top dressed over the crop or banded along side of the row if the crop is not too large. Care must be taken to avoid soluble-salt damage to the crop or mechanical damage to the crop from the fertilizing equipment. For most macronutrients (N, P, K, Ca, Mg, S), a sidedressing of 30 to 40 lb. of element (P and K are in oxide form) per acre will correct a deficiency (Table 6).

Where polyethylene mulch is used, the nutrients must be applied to the root zone by manually punching holes in the mulch, with a liquid injection wheel, or through the micro-irrigation tubing, if that system is in place. Applying fertilizer in the alleys between the beds is not as effective as placing the fertilizer in the soil in the bed.

Foliar applications of macronutrients (N, P, K, Ca, Mg, or S) are not recommended due to inherent inefficiency. Too much nutrient is needed to overcome deficiencies in a short time period, which results in a high risk of foliar damage from soluble salt burn. Leaves are not well adapted for absorbing large amounts of nutrients in a short period due to the waxy cuticle and the inability to achieve uniform covering without soluble salt damage. These deficiencies are more effectively corrected by drenching or banding the needed nutrient in the root zone.

Micronutrient (Mn, Cu, Fe Zn, B, and Mo) deficiencies can be corrected by application of small amounts of the deficient nutrient (Table 6). Foliar application of the deficient micronutrient can be an effective means of correction if adequate leaf coverage is obtained. Micronutrients can be toxic in small amounts so care must be exercised to apply the recommended rates. For crops with waxy leaves, coverage can be improved by use of a spreader-sticker adjuvant in the spray tank.

Table of Deficient, Adequate, and Excessive Nutrient Concentrations for Vegetables

The following tables of nutrient concentrations were developed for vegetables from research conducted on vegetable nutrition. Tables 7 through 18 contain data for macronutrients N, P, K, Ca, Mg, and S and Tables 19 through 29 contain data on micronutrients Fe, Mn, Zn, B, Cu, and Mo. Much of these data were derived from fertilizer response research conducted in the United States with special emphasis on Florida. In these studies, researchers evaluated crop yield (and sometimes quality) response to varying rates of fertilizer nutrients on soils that contributed minimally to the crop nutrient requirement. Plant tissue nutrient concentrations from plants from those fertilizer treatments producing optimum yield and quality were selected as indicating adequate nutrition for a specific nutrient. Optimum fertilizer treatments were those fertilizer amounts above which no further increase in yields or quality resulted. Therefore, the corresponding tissue nutrient values would fall on the lower side of the sufficiency range.

Deficient nutrient values were those from fertilizer treatments that yielded significantly less than with the optimum treatments. These levels might not result in deficiency symptoms but are likely to result in reduced yields and quality.

In some situations, the dividing line between deficient and adequate values is not as clear as the table would indicate. For example, 2.0% and 2.1% might not be different from each other. For these “gray zone” values, one must use a common-sense approach to the interpretation.

The concentrations representing the adequate range (sufficiency range) are those nutrient concentrations to be found in plants that have adequate nutrients available to them. Plants with nutrient concentrations in the high range are indicative of over fertilization. Reduced yields and poor quality could result if the fertilizer rates are not reduced for these plants. For the micronutrients plant nutrient concentrations maintained in the high range could lead to phytotoxicity.

The reference tissues in Tables 5-29 are usually the MRML. This tissue is the whole leaf (blade plus petiole). This reference tissue is the most widely used plant part for most crops. However, for some crops, most of the interpretive research has been conducted for other plant parts (e.g., petioles).

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Table 1. Mobility of essential elements in plants. Mobility reflects the ability of an element to be relocated within the plant under deficient supply.

Relative Mobility in the Plant		
High	**Intermediate**	**Low**
Nitrogen (NO_3- or NH_4+)	Iron	Calcium
Phosphorus	Manganese	Boron
Potassium	Zinc	
Magnesium	Copper	
Sulfur	Molybdenum	
Chlorine		
Nickel		

Table 2. Key to Nutritional Disorders of Vegetable Crops.

	Symptoms of Nutritional Disorder	Diagnosis of Deficiency
A.	Symptoms on leaves, stems, or petioles	B
	Flowering or fruiting affected	M
	Storage organs affected	N
	Variable plant growth throughout the field. Some plants appear normal, some show severe marginal leaf necrosis, while others are stunted. Determine soil pH.	Acidic or Alkaline Soil Complex
B.	Youngest leaves affected first.	C
	Entire plant affected or oldest leaves affected first.	I
C.	Chlorosis appears on youngest leaves.	D
	Chlorosis is not a dominant symptom. Growing points eventually die and storage organs are affected.	H
D.	Leaves uniformly light green, followed by yellowing and poor, spindly growth. Most common in areas with acidic, highly leached, sandy soils low in organic matter.	Sulfur
	Uniform chlorosis does not occur.	E
E.	Leaves wilt, become chlorotic, then necrotic. Onion bulbs are undersize and outer scales are thin and lightly colored. May occur on acidic soils, on soils high in organic matter, or on alkaline soils.	Copper
	Wilting and necrosis are not dominant symptoms.	F
F.	Distinct yellow or white areas appear between veins, and veins eventually become chlorotic. Symptoms rare on mature leaves. Necrosis usually absent. Most common on calcareous soils ("lime induced chlorosis").	Iron
	Yellow/white areas are not so distinct, and veins remain green.	G
G.	Chlorosis is less marked near veins. Some mottling occurs in interveinal areas. Chlorotic areas eventually become brown, transparent, or necrotic. Symptoms may appear later on older leaves. In peas and beans, the radical and central tissue of cotyledons of ungerminated seeds become brown ("marsh spot"). Most common on soils with pH over 6.8	Manganese
	Leaves may be abnormally small and necrotic. Internodes are shortened. Beans, sweet corn ("white bud" of maize), and lima beans most affected; potatoes, tomatoes, and onion somewhat affected; uncommon with pea, asparagus, and carrots. Reduced availability in acidic, highly leached, sandy soils, in alkaline soils, and in organic soils.	Zinc
H.	Brittle tissues. Young, expanding leaves may be necrotic or may be short, especially at shoot terminals. Stems may be rough, cracked, or split along the vascular bundles (hollow stem or crucifers, cracked stem of celery). Most likely on highly leached, acidic soils and on organic soils with free lime.	Boron
	Brittle tissues not a dominant symptom. Growing points usually damaged or dead ("dieback"). Margins of leaves developing from the growing point are first to turn brown or necrotic, expanding corn leaf margins are gelatinous and necrotic, expanding cruciferous seedling leaves are cupped and have necrotic margins; old leaves remain green. Common on acidic, highly leached, sandy soils. May result from excess Na, K, or Mg from irrigation waters, fertilizer or dolomitic limestone. (Celery blackheart, brown heart of escarole, lettuce tipburn, internal tipburn of cabbage, internal browning of brussels sprouts, hypocotyl necrosis of snapbeans.)	Calcium
I.	Plant exhibits chlorosis.	J
	Chlorosis is not a dominant symptom.	L
J.	Interveinal or marginal chlorosis.	K

	Symptoms of Nutritional Disorder	Diagnosis of Deficiency
	General chlorosis. Chlorosis progresses from light green to yellow. Entire plant becomes yellow under prolonged stress. Growth is immediately restricted and plants soon become spindly and drop older leaves. Most common on highly leached soils or with high organic matter soils at low temperatures. Soil applications of N show dramatic improvements.	Nitrogen
K.	Marginal chlorosis or chlorotic blotches which later merge. Lower leaves show yellow chlorotic interveinal tissue on some species, reddish purple progressing to necrosis on others. Younger leaves affected with continued stress. Chlorotic areas may become necrotic, brittle, and curl upward. Symptoms usually occur late in growing season. Most common on acidic, highly leached, sandy soils or on soils with high K or high Ca.	Magnesium
	Interveinal chlorosis, with early symptoms resembling N deficiency (Mo is required for nitrate reduction); older leaves chlorotic or blotched with veins remaining pale green. Leaf margins become necrotic and may roll or curl. Symptoms appear on younger leaves as deficiency progresses. In Brassicas, leaf margins become necrotic and desintegrate, leaving behind a thin strip of leaf ("whiptail"), especially of cauliflower. Common on acidic soils or highly leached alkaline soils.	Molybdenum
L.	Leaf margins tanned, scorched, or have necrotic spots (may be small black dots which later coalesce). Margins become brown and cup downward. Growth is restricted and dieback may occur. Mild symptoms appear first on recently matured leaves, then become pronounced on older leaves, and finally on young leaves. Symptoms may be more common late in the growing season due to translocation of K to developing storage organs. Most common on highly leached, acidic soils and on organic soils due to fixation.	Potassium
	Leaves appear dull, dark green, blue-green, or red-purple, especially on the underside, and at the midrib and veins. Petioles may also exhibit purpling. Restriction in growth may be noticed. Availability reduced in acidic and alkaline soils, and in cold, dry, or organic soils.	Phosphorus
	Terminal leaflets wilt with slight water stress. Wilted areas later become bronzed, and finally necrotic. Very infrequently observed.	Chlorine
M.	Fruit appear rough, cracked, or spotted. Flowering is greatly reduced. Tomato fruits show open locule, internal browning, blotchy ripening, or stem-end russeting. Occurs on acidic soils, on organic soils with free lime, and on highly leached soils.	Boron
	Cracking and roughness are not dominant symptoms. Fruits exhibit water-soaked lesions on blossom end, later become sunken, dark or leathery (blossom end rot of tomato, pepper, and watermelon). Common on acidic, highly leached soils.	Calcium
N.	Internal or external necrotic or water soaked areas of irregular shape (hollow stem of crucifers, internal browning of turnip and rutabaga, canker or blackheart of beet, water core of turnip). May occur on acidic soils, on alkaline soils with free lime, or on highly leached soils.	Boron
	Cavities develop in the root phloem, followed by collapse of the epidermis, causing pitted lesions. (Cavity spot of carrots or parsnips.) Common on acidic, highly leached soils.	Calcium

Table 3. Partial listing of commercial laboratories offering agricultural testing services to Florida growers. Not all laboratories offer all services. Some laboratories do not provide interpretations or recommendations with test results. Clients should contact the laboratory before submitting samples. This listing does not imply a recommendation of these laboratories by the authors or IFAS.

ABC Research Corporation 3437 SW 24th Avenue Gainesville, FL 32607 (352) 372-0436	Thornton Laboratories 1145 E. Cass Street Tampa, FL 33602 (813) 223-9702
A & L Agricultural Laboratories 1301 W. Copans Road Bldg. D, Suite 8 Pompano Beach, FL 33064 (954) 972-3255	Bionomics Laboratory, Inc. 4310 Anderson Road Orlando, FL 32812 (407) 851-2560
Flowers Chemical Laboratory 481 Newberry Port Ave Winter Park, FL 32789 (407) 339-5984	Technical Services, Inc. 2901 Danese Street Jacksonville, FL 32206 (904) 353-5761
Agro Services International, Inc. 215 E. Michigan Avenue Orange City, FL 32763 (904) 775-6601	

Table 4. Nitrate-nitrogen (and potassium) quick-test kits for use in petiole sap nitrate-N (and potassium) determinations.

1.	**Hach colorimeter** - HACH Company, PO Box 389, Loveland, CO, 80539. Kit determines nitrate-N directly from a small hand-held "comparator" or colorimeter. There is a range in test-kit sophistication available from HACH and test kits for several other plant nutrients are available. http://www.environmental-expert.com/
2.	**Merckoquant test strips** - EMD Chemicals, Analytics & Reagents, 480 South Democrat Rd, Gibbstown, NJ 08027. Kit tests for total nitrates in test solution by comparison of color developed on test strip with a color chart. Available also is a "reflectometer" to assist in more quantitative reading of the color developed on the strips. http://www.emdchemicals.com/
3.	**Cardy Meters** - Spectrum Technologies, Inc. 12010 S. Aero Dr., Planfield IL 60544. Ion-specific, hand-held meters for nitrate-N or potassium ions. Measure ion concentrations in undiluted plant sap with digital read-out. http://www.specmeters.com/Nutrient_Management/Cardy_Plant_Nutrient_Meters.html

Table 5. Adequate nitrate-N and K concentrations in fresh petiole sap of most recently matured leaves for several vegetable crops at various periods in the season using the Hach or Quant-strip methods, or Cardy meter.

Crop	Stage of Growth	Fresh Petiole Sap Concentration (ppm)	
		K	NO_3-N conc.
Cucumber	First blossom	N/A	800 to 1000
	Fruits three inches		600 to 800
	First harvest		400 to 600
Broccoli and Collards	Six-leaf stage	N/A	800 to 1000
	Just prior to harvest		500 to 800
	At first harvest		300 to 500
Eggplant	First fruit (two-inches long)	4500 to 5000	1200 to 1600
	First harvest	4000 to 5000	1000 to 1200
	Mid harvest	3500 to 4000	800 to 600
Muskmelon (Cantaloupe)	First blossom	4000 to 5000	1000 to 1200
	Fruits 2 inches	3500 to 4000	800 to 1000
	First harvest	3000 to 3500	700 to 800
Pepper	First flower buds	3200 to 3500	1400 to 1600
	First open flowers	3000 to 3200	1400 to 1600
	Fruits half-grown	3000 to 3200	1200 to 1400
	First harvest	2400 to 3000	800 to 1000
	Second harvest	2000 to 2400	500 to 800
Potato	Plants 8 inches tall	4500 to 5000	1200 to 1400
	First open flowers	4500 to 5000	1000 to 1400
	50% flowers open	4000 to 4500	1000 to 1200
	100% flowers open	3500 to 4000	900 to 1200
	Tops falling over	2500 to 3000	600 to 900
Squash	First blossom	N/A	900 to 1000
	First harvest		800 to 900
Strawberry (in Florida)	November	3000 to 3500	800 to 900
	December	3000 to 3500	600 to 800
	January	2500 to 3000	600 to 800
	February	2000 to 2500	300 to 500
	March	1800 to 2500	200 to 500
	April	1500 to 2000	200 to 500
Tomato (Field)	First buds	3500 to 4000	1000 to 1200
	First open flowers	3500 to 4000	600 to 800
	Fruits one-inch diameter	3000 to 3500	400 to 600
	Fruits two-inch diameter	3000 to 3500	400 to 600
	First harvest	2500 to 3000	300 to 400
	Second harvest	2000 to 2500	200 to 400
Tomato (Greenhouse)	Transplant to 2nd fruit cluster	4500 to 5000	1000 to 1200
	2nd cluster to 5th cluster	4000 to 5000	800 to 1000
	Harvest season (Dec-Jun)	3500 to 4000	700 to 900
Watermelon	Vines 6-inches in length	4000 to 5000	1200 to 1500
	Fruits 2-inches in length	4000 to 5000	1000 to 1200
	Fruits one-half mature	3500 to 4000	800 to 1000
	At first harvest	3000 to 3500	600 to 800

Table 6. Recommendations for correction of crop nutrient deficiencies.

Nutrient	Fertilizer	Method	Application Rate (nutrient)lb. per acre
Nitrogen (N)	Ammonium nitrate	T,S,D,W[2]	30 to 40
	Calcium nitrate	T,S,D,W	30 to 40
Phosphorus (P_2O_5)	Ammonium phosphates	T,S,D,W	20
	Triple, normal superphosphate	T,S	20
	Phosphoric acid	S,D	20
Potassium (K_2O)	Potassium chloride	T,S,D,W	30
	Potassium nitrate	T,S,D,W	30
Calcium (Ca)	Calcium nitrate	T,S,D,W	30
	Calcium chloride	D,W	30
Magnesium (Mg)	Magnesium sulfate	T,S,D,W	20
	Magnesium nitrate	D,W	20
	Potassium magnesium sulfate	T,S	10
Boron (B)	Borax, Solubor[1]	D,F	0.1 to 0.2
Copper (Cu)	Copper sulfate	D,F	0.1 to 0.2
Iron (Fe)	Ferrous sulfate, chelated iron	D,F	0.2 to 0.5
Manganese (Mn)	Manganous sulfate	D,F	0.5 to 1.0
Molybdenum (Mo)	Sodium molybdate	D,F	0.01 to 0.05
Zinc (Zn)	Zinc sulfate, chelated zinc	D,F	0.1 to 0.2

[1] Mention of a trade name does not imply a recommendation compared to similar materials.

[2] T,S,D,W,F are topdress, sidedress, drip irrigation, injection wheel, and foliar, respectively.

Table 7. Critical (deficiency) values, adequate ranges, high values, and toxicity values for macronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of		------------ % -----------					
		Sampling	Status	N	P	K	Ca	Mg	S
Beets (Table)	Leaf blades	5 weeks after	Deficient	<3.0	0.2	2.0	1.5	0.25	-
		seeding	Adequate	3.0	0.3	2.0	1.5	0.25	0.6
			range	5.0	0.4	6.0	2.0	1.0	0.8
			High	>5.0	0.4	6.0	2.0	1.0	-
			Toxic (>)	-	-	-	-	-	-
	Leaf blades	9 weeks after	Deficient	<2.5	0.2	1.7	1.5	0.3	-
		seeding	Adequate	2.6	0.2	1.7	1.5	0.3	0.6
			range	4.0	0.3	4.0	3.0	1.0	0.8
			High	>4.0	0.3	4.0	3.0	1.0	-
			Toxic (>)	-	-	-	-	-	-
Brussel Sprouts	MRM leaf	At early sprouts	Deficient	<2.2	0.2	2.4	0.4	0.2	0.2
			Adequate	2.2	0.2	2.4	0.4	0.2	0.2
			range	5.0	0.6	3.5	2.0	0.4	0.8
			High	>5.0	0.6	3.5	2.0	0.4	0.8
Broccoli	MRM leaf	Heading	Deficient	<3.0	0.3	1.1	0.8	0.23	-
			Adequate	3.0	0.3	1.5	1.2	0.23	0.2
			range	4.5	0.5	4.0	2.5	0.4	-
			High	>4.5	0.5	4.0	2.5	0.4	-
Cabbage	MRM leaf	5 weeks after	Deficient	<3.2	0.3	2.8	0.5	0.25	-
		transplanting	Adequate	3.2	0.3	2.8	1.1	0.25	0.3
			range	6.0	0.6	5.0	2.0	0.6	-
			High	>6.0	0.6	5.0	2.0	0.6	-
			Toxic (>)	-	-	-	-	-	-
	MRM leaf	8 weeks after	Deficient	<3.0	0.3	2.0	0.5	0.2	-
		transplanting	Adequate	3.0	0.3	2.0	1.5	0.25	0.3
			range	6.0	0.6	4.0	2.0	0.6	-
			High	>6.0	0.6	4.0	2.0	0.6	-
	Wrapper leaf	Heads 1/2 grown	Deficient	<3.0	0.3	1.7	0.5	0.25	-
			Adequate	3.0	0.3	2.3	1.5	0.25	0.3
			range	4.0	0.5	4.0	2.0	0.45	-
			High	>4.0	0.5	4.0	2.0	0.45	-
	Wrapper leaf	At harvest	Deficient	<1.8	0.3	1.2	0.5	0.25	-
			Adequate	1.8	0.3	1.5	1.5	0.25	0.3
			range	3.0	0.4	1.5	1.5	0.25	0.3
			High	3.0	0.4	3.0	2.0	0.45	-

Table 8. Critical (deficiency) values, adequate ranges, high values, and toxicity values for macronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling	Status	N	P	K	Ca	Mg	S
				------------	%	-----------			
Collards	Tops	Young plants	Deficient	<4.0	0.3	3.0	1.0	0.4	-
			Adequate	4.0	0.3	3.0	1.0	0.4	-
			range	5.0	0.6	5.0	2.0	1.0	-
			High	>5.0	0.6	5.0	2.0	1.0	-
	MRM leaf	Harvest	Deficient	<3.0	0.3	2.5	1.0	0.35	-
			Adequate	3.0	0.3	2.5	1.0	0.35	-
			range	5.0	0.5	4.0	2.0	1.0	-
			High	>5.0	0.5	4.0	2.0	1.0	-
Carrots	MRM leaf	60 days after seeding	Deficient	<1.8	0.2	2.0	1.0	0.15	-
			Adequate	1.8	0.2	2.0	2.0	0.2	-
			range	2.5	0.4	4.0	3.5	0.5	-
			High	>2.5	0.4	4.0	3.5	0.5	-
	MRM leaf	Harvest	Deficient	<1.5	0.2	1.0	1.0	0.25	-
			Adequate	1.5	0.2	1.4	1.0	0.4	-
			range	2.5	0.4	4.0	1.5	0.5	-
			High	>2.5	0.4	4.0	1.5	0.5	-
Cauliflower	MRM leaf	Buttoning	Deficient	<3.0	0.4	2.0	0.8	0.25	0.6
			Adequate	3.0	0.4	2.0	0.8	0.25	0.6
			range	5.0	0.7	4.0	2.0	0.6	1.0
			High	>5.0	0.7	4.0	2.0	0.6	-
	MRM leaf	Heading	Deficient	<2.2	0.3	1.5	1.0	0.25	-
			Adequate	2.2	0.3	1.5	1.0	0.25	-
			range	4.0	0.7	3.0	2.0	0.6	-
			High	>4.0	0.7	3.0	2.0	0.6	-
Celery	Outer petiole	6 weeks after transplanting	Deficient	<1.5	0.3	6.0	1.3	0.3 -	-
			Adequate	1.5	0.3	6.0	1.3	0.3 -	-
			range	1.7	0.6	8.0	2.0	0.6 -	-
			High	>1.7	0.6	8.0	2.0	0.6 -	-
	Outer petiole	At maturity	Deficient	<1.5	0.3	5.0	1.3	0.3 -	-
			Adequate	1.5	0.3	5.0	1.3	0.3 -	-
			range	1.7	0.6	7.0	2.0	0.6 -	-
			High	>1.7	0.6	7.0	2.0	0.6 -	-
Chinese Cabbage (Heading)	Oldest undamaged leaf	8 leaf stage	Deficient	<4.5	0.5	7.5	4.5	0.35 -	-
			Adequate	4.5	0.5	7.5	4.5	0.35 -	-
			range	5.0	0.6	8.5	5.0	0.45	-
			High	>5.0	0.6	8.5	5.0	0.45	-
	Oldest undamaged leaf	At maturity	Deficient	<3.5	0.3	3.0	3.7	0.4	-
			Adequate	3.5	0.3	3.0	3.7	0.4	-
			range	4.0	0.6	6.5	6.0	0.5	-
			High	>4.0	0.6	6.5	6.0	0.5	-

Table 9. Critical (deficiency) values, adequate ranges, high values, and toxicity values for macronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling	Status	N	P	K	Ca	Mg	S
				%					
Cucumber	MRM leaf	Before bloom	Deficient	<3.5	0.3	1.6	2.0	0.58	0.3
			Adequate	3.5	0.3	1.6	2.0	0.58	0.3
			range	6.0	0.6	3.0	4.0	0.7	0.8
			High	>6.0	0.6	3.0	4.0	0.7	0.8
	MRM leaf	Early bloom	Deficient	<2.5	0.3	1.6	1.3	0.3	0.3
			Adequate	2.5	0.3	1.6	1.3	0.3	0.3
			range	5.0	0.6	3.0	3.5	0.6	0.8
			High	>5.0	0.6	3.0	3.5	0.6	0.8
			Toxic (>)	-	-	-	-	-	-
Eggplant	MRM leaf	Early fruit set	Deficient	<4.2	0.3	3.5	0.8	0.25	0.4
			Adequate	4.2	0.3	3.5	0.8	0.25	0.4
			range	5.0	0.6	5.0	1.5	0.6	0.6
			High	>6.0	0.6	5.0	1.5	0.6	0.6
Endive	Oldest undamaged leaf	8 leaf stage	Deficient	<4.5	0.5	4.5	2.0	0.25	-
			Adequate	4.5	0.5	4.5	2.0	0.25	-
			range	6.0	0.8	6.0	4.0	0.6	-
			High	>6.0	0.8	6.0	4.0	0.6	-
	Oldest undamaged leaf	Maturity	Deficient	<3.5	0.4	4.0	1.8	0.3	-
			Adequate	3.5	0.4	4.0	1.8	0.3	-
			range	4.0	0.6	6.0	3.0	0.4	-
			High	>4.0	0.6	6.0	3.0	0.4	-
Escarole	Oldest undamaged leaf	8 leaf stage	Deficient	<4.2	0.5	5.7	1.7	0.25	-
			Adequate	4.2	0.5	5.7	1.7	0.25	-
			range	5.0	0.6	6.5	2.2	0.35	-
			High	>5.0	0.6	6.5	2.2	0.35	-
	Oldest undamaged leaf	Maturity	Deficient	<3.0	0.4	5.5	2.0	0.25	-
			Adequate	3.0	0.4	5.5	2.0	0.25	-
			range	4.5	0.5	6.5	3.0	0.35	-
			High	>4.5	0.5	6.5	3.0	0.35	-
Romaine	Oldest undamaged leaf	8 leaf stage	Deficient	<5.0	0.4	5.0	2.0	0.25	-
			Adequate	5.0	0.4	5.0	2.0	0.25	-
			range	6.0	0.8	6.0	3.0	0.35	-
			High	>6.0	0.8	6.0	3.0	0.35	-
	Oldest undamaged leaf	Maturity	Deficient	<3.5	0.4	5.0	2.0	0.25	-
			Adequate	3.5	0.4	5.0	2.0	0.25	-
			range	4.5	0.6	6.0	3.0	0.4	-
			High	>4.5	0.6	6.0	3.0	0.4	-

Table 10. Critical (deficiency) values, adequate ranges, high values, and toxicity values for macronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling	Status	N	P	K	Ca	Mg	S
				- - - - - - - - - - - - % - - - - - - - - - - -					
Lettuce	MRM leaf	8 leaf stage	Deficient	<4.0	0.4	5.0	1.0	0.3	-
			Adequate	4.0	0.4	5.0	1.0	0.3	0.3
			range	5.0	0.6	7.0	2.0	0.5	-
			High	>5.0	0.6	7.0	2.0	0.5	-
	Wrapper leaf	Heads 1/2 size	Deficient	<2.5	0.4	4.5	1.4	0.3	-
			Adequate	2.5	0.4	4.5	1.4	0.3	0.3
			range	4.0	0.6	8.0	2.0	0.7	-
			High	>4.0	0.6	8.0	2.0	0.7	-
	Wrapper leaf		Deficient	>2.0	0.3	2.5	1.4	0.3	-
			Adequate	2.0	0.3	2.5	1.4	0.3	0.3
			range	3.0	0.5	5.0	2.0	0.7	-
			High	>3.0	0.5	5.0	2.0	0.7	-
Cos	Oldest undamaged leaf	8 leaf stage	Deficient	<4.0	0.5	4.0	1.7	0.3	-
			Adequate	4.0	0.5	4.0	1.7	0.3	-
			range	5.0	0.6	6.0	2.0	0.7	-
			High	>5.0	0.6	6.0	2.0	0.7	-
	Oldest undamaged leaf	Maturity	Deficient	<3.0	0.4	4.0	1.7	0.3	-
			Adequate	3.0	0.4	4.0	1.7	0.3	-
			range	4.0	0.6	6.0	2.0	0.7	-
			High	>4.0	0.6	6.0	2.0	0.7	-
Boston Lettuce	Oldest undamaged leaf	8 leaf stage	Deficient	<4.0	0.4	5.0	1.0	0.4	-
			Adequate	4.0	0.4	5.0	1.7	0.4	-
			range	6.0	0.6	6.0	2.0	0.6	-
			High	>6.0	0.6	6.0	2.0	0.6	-
			Toxic (>)	-	-	-	-	-	-
	Oldest	Maturity	Deficient	<3.0	0.4	5.0	1.0	0.3	-
			Adequate	3.0	0.4	5.0	1.7	0.3	-
			range	4.0	0.5	6.0	2.0	0.6	-
			High	>4.0	0.5	6.0	2.0	0.6	-
			Toxic (>)	-	-	-	-	-	-
Muskmelon (Cantaloupe)	MRM leaf	12 inch vines	Deficient	<4.0	0.4	5.0	3.0	0.35	-
			Adequate	4.0	0.4	5.0	3.0	0.35	0.2
			range	5.0	0.7	7.0	5.0	0.45	-
			High	>5.0	0.7	7.0	5.0	0.45	-
			Toxic (>)	-	-	-	-	-	-
	MRM leaf	Early fruit set	Deficient	<3.5	0.3	1.8	1.8	0.3	-
			Adequate	3.5	0.3	1.8	1.8	0.3	0.2
			range	4.5	0.4	4.0	5.0	0.4	-
			High	>4.5	0.4	4.0	5.0	0.4	-
			Toxic (>)	-	-	-	-	-	-

Table 11. Critical (deficiency) values, adequate ranges, high values, and toxicity values for macronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling		------------ % -----------					
			Status	**N**	**P**	**K**	**Ca**	**Mg**	**S**
Okra	MRM leaf	30 days after seeding	Deficient	<3.5	0.3	2.0	0.5	0.25	-
			Adequate	3.5	0.3	2.0	0.5	0.25	-
			range	5.0	0.6	3.0	0.8	0.5	-
			High	>5.0	0.6	3.0	0.8	0.5	-
	MRM leaf	Prior to harvest	Deficient	<2.5	0.3	2.0	1.0	0.25	-
			Adequate	2.5	0.3	2.0	1.0	0.25	-
			range	3.0	0.6	3.0	1.5	0.5	-
			High	>3.0	0.6	3.0	1.5	0.5	-
Sweet Onions	MRM leaf	Just prior to bulb initiation	Deficient	<2.0	0.2	1.5	0.6	0.15	0.2
			Adequate	2.0	0.2	1.5	0.6	0.15	0.2
			range	3.0	0.5	3.0	0.8	0.3	0.6
			High	>3.0	0.5	3.0	0.8	0.3	0.6
			Toxic (>)	-	-	-	-	-	-
Pepper	MRM leaf	Prior to blossoming	Deficient	<4.0	0.3	5.0	0.9	0.35	0.3
			Adequate	4.0	0.3	5.0	0.9	0.35	0.3
			range	5.0	0.5	6.0	1.5	0.6	0.6
			High	>5.0	0.5	6.0	1.5	0.6	0.6
			Toxic (>)	-	-	-	-	-	-
	MRM leaf	First blossoms open	Deficient	<3.0	0.3	2.5	0.9	0.3	0.3
			Adequate	3.0	0.3	2.5	0.9	0.3	0.3
			range	5.0	0.5	5.0	1.5	0.5	0.6
			High	>5.0	0.5	5.0	1.5	0.5	0.6
			Toxic (>)	-	-	-	-	-	-
	MRM leaf	Early fruit set	Deficient	<2.9	0.3	2.5	1.0	0.3	0.3
			Adequate	2.9	0.3	2.5	1.0	0.3	0.3
			range	4.0	0.4	4.0	1.5	0.4	0.4
			High	>4.0	0.4	4.0	1.5	0.4	0.4
			Toxic (>)	-	-	-	-	-	-
	MRM leaf	Early harvest	Deficient	<2.5	0.2	2.0	1.0	0.3	0.3
			Adequate	2.5	0.2	2.0	1.0	0.3	0.3
			range	3.0	0.4	3.0	1.5	0.4	0.4
			High	>3.0	0.4	3.0	1.5	0.4	0.4
			Toxic (>)	-	-	-	-	-	-

Table 12. Critical (deficiency) values, adequate ranges, high values, and toxicity values for macronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling	Status	N	P	K	Ca	Mg	S
				%					
Potato	MRM leaf	Plants 8 to 10 inches tall	Deficient	<3.0	0.2	3.5	0.6	0.3	0.3
			Adequate	3.0	0.2	3.5	0.6	0.3	0.3
			range	6.0	0.8	6.0	2.0	0.6	0.5
			High	>6.0	0.8	6.0	2.0	0.6	0.5
	MRM leaf	First blossom	Deficient	<3.0	0.2	3.0	0.6	0.25	0.2
			Adequate	3.0	0.2	3.0	0.6	0.25	0.2
			range	4.0	0.5	5.0	2.0	0.6	0.5
			High	>4.0	0.5	5.0	2.0	0.6	0.5
	MRM leaf	Tubers 1/2 grown	Deficient	<2.0	0.2	2.5	0.6	0.25	0.2
			Adequate	2.0	0.2	2.5	0.6	0.25	0.2
			range	4.0	0.4	4.0	2.0	0.6	0.5
			High	>4.0	0.4	4.0	2.0	0.6	0.5
	MRM leaf	At tops-down	Deficient	<2.0	0.2	1.5	0.6	0.2	0.2
			Adequate	2.0	0.2	1.5	0.6	0.2	0.2
			range	3.0	0.4	3.0	2.0	0.5	0.5
			High	>3.0	0.4	3.0	2.0	0.5	0.5
Radish	MRM leaf	At harvest	Deficient	<3.0	0.3	1.5	1.0	0.3	-
			Adequate	3.0	0.3	1.5	1.0	0.3	-
			range	4.5	0.4	3.0	2.0	0.5	-
			High	>4.5	0.4	3.0	2.0	0.5	-
			Toxic (>)	-	-	-	-	-	-
Snapbean	MRM trifoliate leaf	Before bloom	Deficient	<3.0	0.3	2.0	0.8	0.25	0.2
			Adequate	3.0	0.3	2.0	0.8	0.25	0.2
			range	4.0	0.5	3.0	1.5	0.45	0.4
			High	>4.1	0.5	3.1	1.6	0.45	0.4
			Toxic (>)	-	-	-	-	-	-
	MRM trifoliate leaf	Full bloom	Deficient	<3.0	0.3	2.0	0.8	0.25	0.2
			Adequate	3.0	0.3	2.0	0.8	0.26	0.2
			range	4.0	0.5	3.0	1.5	0.45	0.4
			High	>4.1	0.5	3.1	1.6	0.45	0.4
			Toxic (>)	-	-	-	-	-	-
	MRM trifoliate leaf	Full bloom	Deficient	<2.5	0.2	1.5	0.8	0.25	0.2
			Adequate	2.5	0.2	1.6	0.8	0.26	0.2
			range	4.0	0.4	2.5	1.5	0.45	0.4
			High	>4.1	0.4	2.5	1.6	0.45	0.4
			Toxic (>)	-	-	-	-	-	-
Squash (summer)	MRM leaf	Early fruit	Deficient	<3.0	0.3	2.0	1.0	0.3	0.2
			Adequate	3.0	0.3	2.0	1.0	0.3	0.2
			range	5.0	0.5	3.0	2.0	0.5	0.5
			High	>5.0	0.5	3.0	2.0	0.5	0.5

Table 13. Critical (deficiency) values, adequate ranges, high values, and toxicity values for macronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling	Status	N	P	K	Ca	Mg	S
				------------ % -----------					
Pumpkin	MRM leaf	5 weeks from seeding	Deficient	<3.0	0.3	2.3	0.9	0.35	0.2
			Adequate	3.0	0.3	2.3	0.9	0.35	0.2
			range	6.0	0.5	4.0	1.5	0.6	0.4
			High	>6.0	0.5	4.0	1.5	0.6	0.4
	MRM leaf	8 weeks from seeding	Deficient	<3.0	0.3	2.0	0.9	0.3	0.2
			Adequate	3.0	0.3	2.0	0.9	0.3	0.2
			range	4.0	0.4	3.0	1.5	0.5	0.4
			High	>4.0	0.4	3.0	1.5	0.5	0.4
Southern Pea	MRM leaf	Before bloom	Deficient	<3.5	0.3	2.0	1.0	0.3	-
			Adequate	3.5	0.3	2.0	1.0	0.3	-
			range	5.0	0.8	4.0	1.5	0.5	-
			High	>5.0	0.8	4.0	1.5	0.5	-
	MRM leaf	First bloom	Deficient	<2.5	0.2	2.0	1.0	0.3	-
			Adequate	2.5	0.2	2.0	1.0	0.3	-
			range	4.0	0.4	4.0	1.5	0.5	-
			High	>4.0	0.4	4.0	1.5	0.5	-
Spinach	MRM leaf	30 days after seeding	Deficient	<3.0	0.3	3.0	0.6	1.0	-
			Adequate	3.0	0.3	3.0	0.6	1.0	-
			range	4.5	0.5	4.0	1.0	1.6	-
			High	>5.0	0.5	4.0	1.0	1.6	-
	MRM leaf	Harvest	Deficient	<3.0	0.3	2.5	0.6	1.0	-
			Adequate	3.0	0.3	2.5	0.6	1.0	-
			range	4.0	0.5	3.5	1.0	1.6	-
			High	>4.0	0.5	4.0	1.0	1.6	-

Table 14. Critical (deficiency) values, adequate ranges, high values, and toxicity values for macronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling	Status	N	P	K	Ca	Mg	S
				------------		%	-----------		
Strawberry	MRM leaf	Tranplants	Deficient	<2.8	0.3	1.5	0.3	0.3	-
			Adequate	2.8	0.3	1.5	0.3	0.3	-
			range	3.5	0.4	3.0	1.5	0.6	-
			High	>3.5	0.4	3.0	1.5	0.6	-
	MRM leaf	Initial flower	Deficient	<3.0	0.2	1.5	0.4	0.25	-
			Adequate	3.0	0.2	1.5	0.4	0.25	-
			range	4.0	0.4	3.0	1.5	0.5	-
			High	>4.0	0.4	3.0	1.5	0.5	-
	MRM leaf	Initial flower	Deficient	<3.0	0.2	1.5	0.4	0.25	-
			Adequate	3.0	0.2	1.5	0.4	0.25	-
			range	3.5	0.4	2.5	1.5	0.5	-
			High	>3.5	0.4	2.5	1.5	0.5	-
			Toxic (>)	-	-	-	-	-	-
	MRM leaf	Midseason	Deficient	<2.8	0.2	1.1	0.4	0.2	0.8
			Adequate	2.8	0.2	1.1	0.4	0.2	0.8
			range	3.0	0.4	2.5	1.5	0.4	1.0
			High	>3.0	0.4	2.5	1.5	0.4	1.0
			Toxic (>)	-	-	-	-	-	-
	MRM leaf	End of season	Deficient	<2.5	0.2	1.1	0.4	0.2	-
			Adequate	2.5	0.2	1.1	0.4	0.2	-
			range	3.0	0.3	2.0	1.5	0.4	-
			High	>3.0	0.3	2.0	1.5	0.4	-

Table 15. Critical (deficiency) values, adequate ranges, high values, and toxicity values for macronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling	Status	N	P	K	Ca	Mg	S
				------------ % -----------					
Sweet Corn	Whole seedlings	3 leaf stage	Deficient	<3.0	0.4	2.5	0.6	0.25	0.4
			Adequate range	3.0	0.4	2.5	0.6	0.25	0.4
				4.0	0.5	4.0	0.8	0.5	0.6
			High	>4.0	0.5	4.0	0.8	0.5	0.6
			Toxic (>)	-	-	-	-	-	-
	Whole seedlings	6 leaf stage	Deficient	<3.0	0.3	2.5	0.5	0.25	0.4
			Adequate range	3.0	0.3	2.5	0.5	0.25	0.4
				4.0	0.5	4.0	0.8	0.5	0.6
			High	>4.0	0.5	4.0	0.8	0.5	0.6
			Toxic (>)	-	-	-	-	-	-
	MRM leaf	30 inches tall	Deficient	<2.5	0.2	2.5	0.5	0.2	0.2
			Adequate range	2.5	0.2	2.5	0.5	0.2	0.2
				4.0	0.4	4.0	0.8	0.4	0.4
			High	>4.0	0.4	4.0	0.8	0.4	0.4
			Toxic (>)	-	-	-	-	-	-
	MRM leaf	Just prior to tassel	Deficient	<2.5	0.2	2.0	0.3	0.15	0.2
			Adequate range	2.5	0.2	2.0	0.3	0.15	0.2
				4.0	0.4	3.5	0.6	0.4	0.4
			High	>4.0	0.4	3.5	0.6	0.4	0.4
			Toxic (>)	-	-	-	-	-	-
	MRM leaf (ear leaf)	Tasseling	Deficient	<1.5	0.2	1.2	0.3	0.15	0.2
			Adequate range	1.5	0.2	1.2	0.3	0.15	0.2
				2.5	0.4	2.0	0.6	0.4	0.4
			High	>2.5	0.4	2.0	0.6	0.4	0.4

Table 16. Critical (deficiency) values, adequate ranges, high values, and toxicity values for macronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling	Status	N	P	K	Ca	Mg	S
				------------ % -----------					
Sweet Potato	MRM leaf	Early vining	Deficient	<4.0	0.3	2.5	0.8	0.4	0.2
			Adequate	4.0	0.3	2.5	0.8	0.4	0.2
			range	5.0	0.5	4.0	1.6	0.8	0.6
			High	>5.0	0.5	4.0	1.6	0.8	0.6
	MRM leaf	Midseason -before root enlargment	Deficient	<3.0	0.2	2.0	0.8	0.25	0.2
			Adequate	3.0	0.2	2.0	0.8	0.25	0.2
			range	4.0	0.3	4.0	1.8	0.5	0.4
			High	>4.0	0.3	4.0	1.8	0.5	0.4
	MRM leaf	Root enlargement	Deficient	<3.0	0.2	2.0	0.8	0.25	0.2
			Adequate	3.0	0.2	2.0	0.8	0.25	0.2
			range	4.0	0.3	4.0	1.6	0.5	0.6
			High	>4.0	0.3	4.0	1.6	0.5	0.6
	MRM leaf	Just before harvest	Deficient	<2.8	0.2	2.0	0.8	0.25	0.2
			Adequate	2.8	0.2	2.0	0.8	0.25	0.2
			range	3.5	0.3	4.0	1.6	0.5	0.6
			High	>3.5	0.3	4.0	1.6	0.5	0.6

Table 17. Critical (deficiency) values, adequate ranges, high values, and toxicity values for macronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling	Status	N	P	K	Ca	Mg	S
				------------ % -----------					
Tomato	MRM leaf	5 leaf stage	Deficient	<3.0	0.3	3.0	1.0	0.3	0.3
			Adequate	3.0	0.3	3.0	1.0	0.3	0.3
			range	5.0	0.6	5.0	2.0	0.5	0.8
			High	>5.0	0.6	5.0	2.0	0.5	0.8
	MRM leaf	First flower	Deficient	<2.8	0.2	2.5	1.0	0.3	0.3
			Adequate	2.8	0.2	2.5	1.0	0.3	0.3
			range	4.0	0.4	4.0	2.0	0.5	0.8
			High	>4.0	0.4	4.0	2.0	0.5	0.8
			Toxic (>)	-	-	-	-	-	-
	MRM leaf	Early fruit set	Deficient	<2.5	0.2	2.5	1.0	0.25	0.3
			Adequate	2.5	0.2	2.5	1.0	0.25	0.3
			range	4.0	0.4	4.0	2.0	0.5	0.6
			High	>4.0	0.4	4.0	2.0	0.5	0.6
			Toxic (>)	-	-	-	-	-	-
	MRM leaf	First ripe fruit	Deficient	<2.0	0.2	2.0	1.0	0.25	0.3
			Adequate	2.0	0.2	2.0	1.0	0.25	0.3
			range	3.5	0.4	4.0	2.0	0.5	0.6
			High	>3.5	0.4	4.0	2.0	0.5	0.6
	MRM leaf	During harvest period	Deficient	<2.0	0.2	1.5	1.0	0.25	0.3
			Adequate	2.0	0.2	1.5	1.0	0.25	0.3
			range	3.0	0.4	2.5	2.0	0.5	0.6
			High	>3.0	0.4	2.5	2.0	0.5	0.6

Table 18. Critical (deficiency) values, adequate ranges, high values, and toxicity values for macronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling	Status	N	P	K	Ca	Mg	S
				------------ % -----------					
Turnip Greens	MRM leaf	Hypocotyl 1-inch diameter	Deficient	<3.0	0.3	2.5	0.8	0.25	0.2
			Adequate	3.0	0.3	2.5	0.8	0.25	0.2
			range	5.0	0.8	4.0	1.5	0.6	0.6
			High	>5.0	0.8	4.0	1.5	0.6	0.6
Watermelon	MRM leaf	Layby (last cultivation)	Deficient	<3.0	0.3	3.0	1.0	0.25	0.2
			Adequate	3.0	0.3	3.0	1.0	0.25	0.2
			range	4.0	0.5	4.0	2.0	0.5	0.4
			High	>4.0	0.5	4.0	2.0	0.5	0.4
			Toxic (>)	-	-	-	-	-	-
	MRM leaf	First flower	Deficient	<2.5	0.3	2.7	1.0	0.25	0.2
			Adequate	2.5	0.3	2.7	1.0	0.25	0.2
			range	3.5	0.5	3.5	2.0	0.5	0.4
			High	>3.5	0.5	3.5	2.0	0.5	0.4
	MRM leaf	First fruit	Deficient	<2.0	0.3	2.3	1.0	0.25	0.2
			Adequate	2.0	0.3	2.3	1.0	0.25	0.2
			range	3.0	0.5	3.5	2.0	0.5	0.4
			High	>3.0	0.5	3.5	2.0	0.5	0.4
	MRM leaf	Harvest period	Deficient	<2.0	0.3	2.0	1.0	0.25	0.2
			Adequate	2.0	0.3	2.0	1.0	0.25	0.2
			range	3.0	0.5	3.0	2.0	0.5	0.4
			High	>3.0	0.5	3.0	2.0	0.5	0.4

Table 19. Critical (deficiency) values, adequate ranges, high values, and toxicity values for micronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling	Status	ppm Fe	Mn	Zn	B	Cu	Mo
Table Beets	Leaf blades	5 weeks after seeding	Deficient	<40	30	15	30	5	0.05
			Adequate	40	30	15	30	5	0.2
			range	200	200	30	80	10	0.6
			High	-	-	-	80	10	-
			Toxic (>)	-	-	-	650	-	-
	Leaf blades	9 weeks after seeding	Deficient	-	-	15	30	5	0.1
			Adequate	-	70	15	60	5	0.6
			range	-	200	30	80	10	-
			High	-	-	-	80	10	-
			Toxic (>)	-	-	-	650	-	-
Brussel Sprouts	MRM leaf	At early sprouts	Deficient	<50	20	20	20	4	0.0
			Adequate	50	20	20	30	5	0.2
			range	150	200	80	70	10	0.2
			High	>150	200	80	70	-	-
Broccoli	MRM leaf	Heading	Deficient	<40	20	25	20	3	0.0
			Adequate	40	25	45	30	5	0.0
			range	300	150	95	50	10	0.2
			High	>300	150	100	100	10	-
Cabbage	MRM leaf	5 weeks after transplanting	Deficient	<30	20	30	20	3	0.3
			Adequate	30	20	30	20	3	0.3
			range	60	40	50	40	7	0.6
			High	>100	40	50	40	10	-
	MRM leaf	8 weeks after transplanting	Deficient	<30	20	30	20	3	0.3
			Adequate	30	20	30	20	3	0.3
			range	60	40	50	40	7	0.6
			High	>100	40	50	40	10	0.6
	Wrapper leaf	Heads 1/2 grown	Deficient	<20	20	20	30	4	0.3
			Adequate	20	20	20	30	4	0.3
			range	40	40	30	50	8	0.6
			High	>100	40	40	50	10	-
	Wrapper leaf	At harvest	Deficient	<20	20	20	30	4	0.3
			Adequate	20	20	20	30	4	0.3
			range	40	40	30	50	8	0.6
			High	>100	40	40	50	10	-

Table 20. Critical (deficiency) values, adequate ranges, high values, and toxicity values for micronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling	Status	ppm Fe	Mn	Zn	B	Cu	Mo
Collards	Tops	Young plants	Deficient	<40	40	25	25	5	-
			Adequate	40	40	25	25	5	-
			range	100	100	50	50	10	-
			High	>100	100	50	50	10	-
	MRM leaf	Harvest	Deficient	<40	40	20	25	5	-
			Adequate	40	40	20	25	5	-
			range	100	100	40	50	10	-
			High	>100	100	40	50	10	-
Carrots	MRM leaf	60 days after seeding	Deficient	<30	30	20	20	4	-
			Adequate	30	30	20	20	4	-
			range	60	60	60	40	10	-
			High	>60	100	60	40	10	-
	MRM leaf	Harvest	Deficient	<20	30	20	20	4	-
			Adequate	20	30	20	20	4	-
			range	30	60	60	40	10	-
			High	>60	100	60	40	10	-
Cauliflower	MRM leaf	Buttoning	Deficient	<30	30	30	30	5	-
			Adequate	30	30	30	30	5	-
			range	60	80	50	50	10	-
			High	>100	100	50	50	10	-
	MRM leaf	Heading	Deficient	<30	50	30	30	5	-
			Adequate	30	50	30	30	5	-
			range	60	80	50	50	10	-
			High	>100	100	50	50	10	-
Celery	Outer petiole	6 weeks after transplanting	Deficient	<20	5	20	15	4	-
			Adequate	20	5	20	15	4	-
			range	30	10	40	25	6	-
			High	>100	20	60	25	-	-
	Outer petiole	At maturity	Deficient	<20	5	20	20	1	-
			Adequate	20	5	20	20	1	-
			range	30	10	40	40	3	-
			High	>100	20	60	40	3	-
Chinese Cabbage (Heading)	Oldest undamaged leaf	8 leaf stage	Deficient	<-	8	30	15	5	-
			Adequate	-	14	30	15	5	-
			range	-	20	50	25	10	-
			High	>-	20	50	25	10	-
	Oldest undamaged leaf	At maturity	Deficient	<-	7	20	30	4	-
			Adequate	-	13	20	30	4	-
			range	-	19	40	50	6	-
			High	>-	20	40	50	6	-

Table 21. Critical (deficiency) values, adequate ranges, high values, and toxicity values for micronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling	Status	------------ ppm -----------					
				Fe	Mn	Zn	B	Cu	Mo
Cucumber	MRM leaf	Before bloom	Deficient	<40	30	20	20	5	0.2
			Adequate	40	30	20	20	5	0.3
			range	100	100	50	60	20	1.0
			High	>100	100	50	60	20	2.0
	MRM leaf	Early bloom	Deficient	<40	30	20	20	5	0.2
			Adequate	40	30	20	20	5	0.3
			range	100	100	50	60	20	1.0
			High	>100	100	50	60	20	2.0
			Toxic (>)	-	900	950	150	-	-
Eggplant	MRM leaf	Early fruit set	Deficient	<50	50	20	20	5	0.5
			Adequate	50	50	20	20	5	0.5
			range	100	100	40	40	10	0.8
			High	>100	100	40	40	10	0.8
Endive	Oldest undamaged leaf	8 leaf stage	Deficient	<-	15	30	25	5	-
			Adequate	-	15	30	25	5	-
			range	-	25	50	35	10	-
			High	>-	25	50	35	10	-
	Oldest undamaged leaf	Maturity	Deficient	<-	15	20	30	5	-
			Adequate	-	15	20	30	5	-
			range	-	20	40	40	10	-
			High	>-	20	40	40	10	-
Escarole	Oldest undamaged leaf	8 leaf stage	Deficient	<-	15	30	20	4	-
			Adequate	-	15	30	20	4	-
			range	-	25	50	30	6	-
			High	>-	25	50	30	6	-
	Oldest undamaged leaf	Maturity	Deficient	<-	15	20	30	4	-
			Adequate	-	15	20	30	4	-
			range	-	25	50	45	6	-
			High	>-	25	50	45	6	-
Romaine	Oldest undamaged leaf	8 leaf stage	Deficient	<-	15	20	30	5	-
			Adequate	-	15	20	30	5	-
			range	-	25	50	45	10	-
			High	>-	25	50	45	10	-
	Oldest undamaged leaf	Maturity	Deficient	<-	15	20	30	5	0.1
			Adequate	-	15	20	30	5	0.1
			range	-	25	50	45	10	0.4
			High	>-	25	50	45	10	-

Table 22. Critical (deficiency) values, adequate ranges, high values, and toxicity values for micronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling	Status	Fe	Mn	Zn	B	Cu	Mo
				ppm					
Lettuce	MRM leaf	8 leaf stage	Deficient	<50	20	25	15	5	-
			Adequate	50	20	25	15	5	-
			range	150	40	50	30	10	-
			High	>150	40	50	30	10	-
	Wrapper leaf	Heads 1/2 size	Deficient	<50	20	25	15	5	-
			Adequate	50	20	25	15	5	-
			range	150	40	50	30	10	-
			High	>150	40	50	30	10	-
	Wrapper leaf	Maturity	Deficient	<50	20	25	15	5	-
			Adequate	50	20	25	15	5	-
			range	150	40	50	30	10	-
			High	>150	40	50	30	10	-
Cos	Oldest undamaged leaf	8 leaf stage	Deficient	<40	10	40	20	5	-
			Adequate	40	10	40	20	5	-
			range	100	20	60	40	10	-
			High	>100	20	60	40	10	-
	Oldest undamaged leaf	Maturity	Deficient	<20	10	20	20	5	-
			Adequate	20	10	20	20	5	-
			range	50	20	40	40	10	-
			High	>50	20	40	40	10	-
Boston Lettuce	Oldest undamaged leaf	8 leaf stage	Deficient	<50	10	40	15	5	0.1
			Adequate	50	10	40	15	5	0.1
			range	100	20	60	25	10	0.2
			High	>100	20	60	25	10	0.4
			Toxic (>)	-	250	-	100	-	-
	Oldest undamaged leaf	Maturity	Deficient	<50	10	20	15	5	0.1
			Adequate	50	10	20	15	5	0.1
			range	100	20	40	25	10	0.2
			High	>100	20	40	25	10	0.4
			Toxic (>)	-	250	-	100	-	-
Muskmelon	MRM leaf	12 inch vines	Deficient	<40	20	20	20	5	0.6
			Adequate	40	20	20	20	5	0.6
			range	100	100	60	80	10	1.0
			High	>100	100	60	80	10	1.0
			Toxic (>)	-	900	-	150	-	-
	MRM leaf	Early fruit set	Deficient	<40	20	20	20	5	0.6
			Adequate	40	20	20	20	5	0.6
			range	100	100	60	80	10	1.0
			High	>100	100	60	80	10	1.0
			Toxic (>)	-	900	-	150	-	-

Table 23. Critical (deficiency) values, adequate ranges, high values, and toxicity values for micronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling		------------ ppm -----------					
			Status	Fe	Mn	Zn	B	Cu	Mo
Okra	MRM leaf	30 days after seeding	Deficient	<50	30	30	25	5	-
			Adequate	50	30	30	25	5	-
			range	100	100	50	50	10	-
			High	>100	100	50	50	10	-
	MRM leaf	Prior to harvest	Deficient	<50	30	30	25	5	-
			Adequate	50	30	30	25	5	-
			range	100	100	50	50	10	-
			High	>100	100	50	50	10	-
Sweet Onions	MRM leaf	Just prior to bulb initiation	Deficient	<-	10	15	10	5	-
			Adequate	-	10	15	10	5	-
			range	-	20	20	25	10	-
			High	>-	20	20	25	10	-
			Toxic (>)	-	-	-	100	-	-
Pepper	MRM leaf	Prior to blossoming	Deficient	<30	30	25	20	5	-
			Adequate	30	30	25	20	5	-
			range	150	100	80	50	10	-
			High	>150	100	80	50	10	-
			Toxic (>)	-	-	-	350	-	-
	MRM leaf	First blossoms open	Deficient	<30	30	25	20	5	-
			Adequate	30	30	25	20	5	-
			range	150	100	80	50	10	-
			High	>150	100	80	50	10	-
			Toxic (>)	-	1000	-	350	-	-
	MRM leaf	Early fruit set	Deficient	<30	30	25	20	5	-
			Adequate	30	30	25	20	5	-
			range	150	100	80	50	10	-
			High	>150	100	80	50	10	-
			Toxic (>)	-	-	-	350	-	-
	MRM leaf	Early harvest	Deficient	<30	30	25	20	50	0.1
			Adequate	30	30	25	20	5	0.1
			range	150	100	80	50	10	0.2
			High	>150	100	80	50	10	-
			Toxic (>)	-	-	-	350	-	-

Table 24. Critical (deficiency) values, adequate ranges, high values, and toxicity values for micronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling	Status	ppm					
				Fe	Mn	Zn	B	Cu	Mo
Potato	MRM leaf	Plants 8 to 10 inches tall	Deficient	<40	30	30	20	5	0.1
			Adequate	40	30	30	20	5	0.1
			range	150	60	60	60	10	0.2
			High	>150	60	60	30	10	-
	MRM leaf	First blossom	Deficient	<40	30	30	20	5	0.1
			Adequate	40	30	30	20	5	0.1
			range	150	100	60	30	10	0.2
			High	>150	100	60	30	10	-
	MRM leaf	Tubers 1/2 grown	Deficient	<40	20	30	20	5	0.1
			Adequate	40	20	30	20	5	0.1
			range	150	100	60	30	10	0.2
			High	>150	100	60	30	10	-
	MRM leaf	At tops-down	Deficient	<40	20	30	20	5	0.1
			Adequate	40	20	30	20	5	0.1
			range	150	100	60	30	10	0.2
			High	>150	100	60	30	10	-
Radish	MRM leaf	At harvest	Deficient	<30	20	30	15	3	0.1
			Adequate	30	20	30	15	3	0.1
			range	50	40	50	30	10	2.0
			High	>50	40	50	30	10	2.0
			Toxic (>)	-	-	-	85	-	-
Snapbean	MRM trifoliate leaf	Before bloom	Deficient	<25	20	20	15	5	-
			Adequate	25	20	20	15	5	0.4
			range	200	100	40	40	10	-
			High	>200	100	40	40	10	-
			Toxic (>)	-	1000	-	150	-	-
	MRM trifoliate leaf	First bloom	Deficient	<25	20	20	15	5	-
			Adequate	25	20	20	15	5	-
			range	200	100	40	40	10	0.4
			High	>200	100	40	40	10	-
			Toxic (>)	-	1000	-	150	-	-
	MRM trifoliate leaf	Full bloom	Deficient	<25	20	20	15	5	-
			Adequate	25	20	20	15	5	-
			range	200	100	40	40	10	0.4
			High	>200	100	40	40	10	-
			Toxic (>)	-	1000	-	150	-	-
Squash (summer)	MRM leaf	Early fruit	Deficient	<40	40	20	25	5	0.3
			Adequate	40	40	20	25	5	0.3
			range	100	100	50	40	20	0.5
			High	>100	100	50	40	20	0.5

Table 25. Critical (deficiency) values, adequate ranges, high values, and toxicity values for micronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling	Status	ppm Fe	ppm Mn	ppm Zn	ppm B	ppm Cu	ppm Mo
Pumpkin	MRM leaf	5 weeks from seeding	Deficient	<40	40	20	25	5	0.3
			Adequate	40	40	20	25	5	0.3
			range	100	100	50	40	10	0.5
			High	>100	100	50	40	10	-
	MRM leaf	8 weeks from seeding	Deficient	<40	40	20	20	5	0.3
			Adequate	40	40	20	20	5	0.3
			range	100	100	50	40	10	0.5
			High	>100	100	50	40	10	-
Southern Pea	MRM leaf	Before bloom	Deficient	<30	30	20	15	5	-
			Adequate	30	30	20	15	5	-
			range	100	100	40	25	10	-
			High	>100	100	40	25	10	-
	MRM leaf	First bloom	Deficient	<30	30	20	15	5	4.0
			Adequate	30	30	20	15	5	4.0
			range	100	100	40	25	10	6.0
			High	>100	100	40	25	10	6.0
Spinach	MRM leaf	30 days after seeding	Deficient	<-	50	50	20	5	0.1
			Adequate	-	50	50	20	5	0.1
			range	-	100	70	40	7	1.0
			High	>-	100	70	40	7	1.0
	MRM leaf	Harvest	Deficient	<-	30	50	20	5	0.1
			Adequate	-	30	50	20	5	0.1
			range	-	50	70	40	7	1.0
			High	>-	80	70	40	7	1.0

Table 26. Critical (deficiency) values, adequate ranges, high values, and toxicity values for micronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling	Status	ppm					
				Fe	Mn	Zn	B	Cu	Mo
Strawberry	MRM leaf	Transplants	Deficient	<50	30	25	25	5	-
			Adequate	50	30	25	25	5	-
			range	100	100	40	40	10	-
			High	>100	100	40	40	10	-
	MRM leaf	Initial flower	Deficient	<50	30	20	20	5	-
			Adequate	50	30	20	20	5	-
			range	100	100	40	40	10	-
			High	>100	100	40	20	10	-
	MRM leaf	Initial harvest	Deficient	<50	30	20	20	5	-
			Adequate	50	30	20	20	5	-
			range	100	100	40	40	10	-
			High	>100	100	40	40	10	-
			Toxic (>)	-	800	-	-	-	-
	MRM leaf	Midseason	Deficient	<50	25	20	20	5	0.5
			Adequate	50	25	20	20	5	0.5
			range	100	100	40	40	10	0.8
			High	>100	100	40	40	10	0.8
			Toxic (>)	-	800	-	-	-	-
	MRM leaf	End of season	Deficient	<50	25	20	20	5	-
			Adequate	50	25	20	20	5	-
			range	100	100	40	40	10	-
			High	>100	100	40	40	10	-

Table 27. Critical (deficiency) values, adequate ranges, high values, and toxicity values for micronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling	Status	Fe	Mn	Zn	B	Cu	Mo
				ppm					
Sweet Corn	Whole seedlings	3 leaf stage	Deficient	<50	40	30	10	5	0.1
			Adequate	50	40	30	10	5	0.1
			range	100	100	40	30	10	0.2
			High	>100	100	40	30	10	0.2
			Toxic (>)	-	-	-	100	-	-
	Whole seedlings	6 leaf stage	Deficient	<50	40	30	10	5	0.1
			Adequate	50	40	30	10	5	0.1
			range	100	100	40	30	10	0.2
			High	>100	100	40	30	10	0.2
			Toxic (>)	-	-	-	100	-	-
	MRM leaf	30 inches tall	Deficient	<40	40	25	10	4	0.1
			Adequate	40	40	25	10	4	0.1
			range	100	100	40	30	10	0.2
			High	>100	100	40	30	10	0.2
			Toxic (>)	-	-	-	100	-	-
	MRM leaf	Just prior to tassel	Deficient	<30	30	20	10	4	0.1
			Adequate	30	30	20	10	4	0.1
			range	100	100	40	20	10	0.2
			High	>100	100	40	20	10	0.2
			Toxic (>)	-	-	-	100	-	-
	MRM leaf (ear leaf)	Tasseling	Deficient	<30	20	20	10	4	0.1
			Adequate	30	20	20	10	4	0.1
			range	100	100	40	20	10	0.2
			High	>100	100	40	20	10	0.2

Table 28. Critical (deficiency) values, adequate ranges, high values, and toxicity values for micronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling	Status	ppm Fe	Mn	Zn	B	Cu	Mo
Sweet Potato	MRM leaf	Early vining	Deficient	<40	40	25	20	5	-
			Adequate	40	40	25	20	5	-
			range	100	100	50	50	10	-
			High	>100	100	50	50	10	-
	MRM leaf	Midseason -before root enlargment	Deficient	<40	40	25	25	5	-
			Adequate	40	40	25	25	5	-
			range	100	100	40	40	10	-
			High	>100	100	40	40	10	-
	MRM leaf	Root enlargment	Deficient	<40	40	25	20	5	-
			Adequate	40	40	25	20	5	-
			range	100	100	50	50	10	-
			High	>100	100	50	50	10	-
	MRM leaf	Just before harvest	Deficient	<40	40	25	20	5	-
			Adequate	40	40	25	20	5	-
			range	100	100	50	50	10	-
			High	>100	100	50	50	10	-
Tomato	MRM leaf	5 leaf stage	Deficient	<40	30	25	20	5	0.3
			Adequate	40	30	25	20	5	0.2
			range	100	100	40	40	15	0.6
			High	>100	100	40	40	15	0.6
	MRM leaf	First flower	Deficient	<40	30	25	20	5	0.2
			Adequate	40	30	25	20	5	0.2
			range	100	100	40	40	15	0.6
			High	>100	100	40	40	15	0.2
			Toxic (>)	-	1500	300	250	-	-
	MRM leaf	Early fruit set	Deficient	<40	30	20	20	5	0.2
			Adequate	40	30	20	20	5	0.2
			range	100	100	40	40	10	0.6
			High	>100	100	40	40	10	0.6
			Toxic (>)	-	-	-	250	-	-
	MRM leaf	First ripe fruit	Deficient	<40	30	20	20	5	0.2
			Adequate	40	30	20	20	5	0.2
			range	100	100	40	40	10	0.6
			High	>100	100	40	40	10	0.6
	MRM leaf	During harvest period	Deficient	<40	30	20	20	5	0.2
			Adequate	40	30	20	20	5	0.2
			range	100	100	40	40	10	0.6
			High	>100	100	40	40	10	0.6

Table 29. Critical (deficiency) values, adequate ranges, high values, and toxicity values for micronutrients for vegetables (most-recently-matured whole leaf plus petiole (MRM leaf) unless otherwise noted).

Crop	Plant Part	Time of Sampling	Status	ppm Fe	Mn	Zn	B	Cu	Mo
Turnip Greens	MRM leaf	Hypocotyl 1-inch diameter	Deficient	<30	30	20	20	5	-
			Adequate	30	30	20	20	5	-
			range	100	100	40	40	10	-
			High	>100	100	40	40	10	-
Watermelon	MRM leaf	Layby (last cultivation)	Deficient	<30	20	20	20	5	-
			Adequate	30	20	20	20	5	-
			range	100	100	40	40	10	-
			High	>100	100	40	40	10	-
			Toxic (>)	-	800	-	-	-	-
	MRM leaf	First flower	Deficient	<30	20	20	20	5	-
			Adequate	30	20	20	20	5	-
			range	100	100	40	40	10	-
			High	>100	100	40	40	10	-
	MRM leaf	First fruit	Deficient	<30	20	20	20	5	-
			Adequate	30	20	20	20	5	-
			range	100	100	40	40	10	-
			High	>100	100	40	40	10	-
	MRM leaf	Harvest period	Deficient	<30	20	20	20	3	-
			Adequate	30	20	20	20	3	-
			range	100	100	40	40	10	-
			High	>100	100	40	40	10	-

UF IFAS Extension
UNIVERSITY of FLORIDA

SL129

UF/IFAS Standardized Fertilization Recommendations for Agronomic Crops [1]

R. Mylavarapu, D. Wright, and G. Kidder[2]

Introduction

This publication presents in abbreviated form the fertilization recommendations for agronomic crops based on soil tests performed by the UF/IFAS Extension Soil Testing Laboratory (ESTL). It contains the basic information from which ESTL soil-test reports and fertilization recommendations are generated.

General Background

Soil testing is a tool in crop fertilization management. Its successful use requires that: (1) you send the lab soil samples that best represent your field or management unit; (2) the laboratory uses legitimate methods for predicting fertility; and (3) the fertilizer recommendations are based on measured crop responses.

The ESTL extracts phosphorus (P), potassium (K), magnesium (Mg), and calcium (Ca) with the Mehlich-3 extractant and bases fertilization recommendations for those nutrients on the test results. Current interpretation of test results are presented in Table 1. Nitrogen (N) fertilization is **not** based on soil tests but rather is based on crop needs as documented in research literature.

Liming recommendations are based on the Adams-Evans lime requirement test, a calibration equation developed for Florida soils, and on the target pH for the crop for which the recommendation is being made.

Soil test reports from the ESTL are computer-generated from lab data and crop codes. If a cropping situation is not in the list of crop codes, routine soil tests may not be appropriate. In such instances, the local county agent should be consulted **before** soil samples are sent for testing. Reports contain the results of the tests (soil pH, ppm extractable P, K, Mg, and Ca), a rating of the P, K, and Mg (high to low), and the fertilization recommendation for the specified crop. The recommendation is composed of two parts: (1) the rates of N, P_2O_5, and K_2O fertilizer to apply; and (2) footnotes that give important information about fertilization management such as application timing, special crop requirements, etc.

Table 2 of this document contains crop codes, crop descriptions, target pH, N recommendation, P_2O_5 and K_2O recommendations for each of the three soil-test rating levels, the footnotes printed for each of the crop codes, and the references for these recommendations.

The text of the footnotes referred to in Table 2 is given below.

1. This document is SL129, one of a series of the Soil and Water Science Department, UF/IFAS Extension. Original publication date June 1997 as "Notes in Soil Science #35,". Revised September 2013.Visit the EDIS website at http://edis.ifas.ufl.edu.

2. R. Mylavarapu, professor, nutrient management specialist and director of Soil Testing Laboratory, Soil and Water Science Department; D. Wright, professor, Agronomy Department; and G. Kidder, professor emeritus, Soil and Water Science Department, UF/IFAS Extension, Gainesville, FL 32611.

Text of Footnotes

102. Apply all of the P_2O_5, 30% of the K_2O, and 30 lb N/A in a preplant or at-planting application. Four weeks after planting, sidedress the remaining 70% of the K_20. Apply the remaining 120 lb N/A in two or more sidedressings, one of which should be at 4 weeks after planting.

104. Apply all of the P_2O_5, 30% of the K_2O, and 30 lb N/A in a preplant or at-planting application. Four weeks after planting, sidedress the remaining 70% of the K_2O. Apply the remaining 180 lb N/A in three or more sidedressings, one of which should be at 4 weeks.

106. Apply all of the P_2O_5 and 30% of the K_2O and N in a preplant or at-planting application. Topdress or sidedress the remaining 70% of the K_2O and N. For small grains grown for grain, silage, or hay, topdress during late January or early February. For grain sorghum or forage sorghum, sidedress before plants are too tall to cultivate or approximately 4 weeks after planting.

107. Apply all of the P_2O_5 and 30% of the K_2O and N in a preplant or at-planting application. Apply the remaining 70% of the K_2O and N in one sidedressing.

108. Application of 20–30 lb N/A may give vegetative response but is unlikely to increase harvested yield.

109. If peanuts are grown for seed or if they are Virginia type, regardless of soil test, apply gypsum in a band over the potential pegging zone at early flower. Apply 400 lb gypsum/A for runner types and 800 lb gypsum/A for Virginia types. Double these rates if broadcasting granular or phosphogypsum (bulk wet). For peanuts not grown for seed, apply gypsum as recommended above only if the calcium soil-test level is below 250 ppm Ca.

110. Apply 50% of the fertilizer at or before transplanting and the other half within 3 weeks of transplanting.

111. Apply 30 lb N/A, 50% of the K_2O, and all of the P_2O_5 fertilizer in a preplant or at-planting application. Apply 50 lb N/A and the remaining K_2O after the first grazing period. Apply an additional 50 lb N/A after each subsequent grazing period.

112. When planting on a prepared seed bed, apply 30 lb N/A, 50% of the K_2O, and all of the P_2O_5 fertilizer in a preplant or at-planting application. Apply 50 lb N/A and the remaining K_2O after the first grazing period. Apply an additional 50 lb N/A after each subsequent grazing period. When overseeding established perennial grasses with cool-season annual grasses, apply 50 lb N/A plus all of the P_2O_5 and K_2O after emergence. Apply an additional 50 lb N/A after each subsequent grazing period.

115. Apply all of the P_2O_5 and K_2O fertilizer in late fall. If legumes are planted in combination with oats, rye, wheat, and/or ryegrass, apply 30 lb N/A in a preplant or at-planting application plus one additional 50 lb N/A application after the grass is well established.

118. Apply 0.75 lb boron/A in the fertilizer or 0.5 lb boron/A as a foliar spray with the first fungicide application.

120. Fertilizer should contain 15–20 lb sulfur/A. Apply as a sulfate (e.g., gypsum, ammonium sulfate, magnesium sulfate, potassium sulfate, potassium magnesium sulfate), because elemental sulfur will react too slowly to supply the sulfur needs of the current crop.

121. Apply all of the P_2O_5 and K_2O in spring or early summer when seedlings or regrowth are 3–4 inches tall. Species included are aeschynomene, alyceclover, desmodiums, hairy indigo, perennial peanut, and other tropical legumes.

122. Species included are all true clovers (white, red, arrowleaf, crimson, subterranean), vetches, lupines, and sweet clover.

123. Apply all of the P_2O_5 and 50% of the K_2O fertilizer in late fall. Apply the remaining K_2O in early spring. If the alfalfa is mechanically harvested rather than grazed, apply an additional 30 lb P_2O_5/A and 60 lb K_2O/A after each harvest. An additional application of 100 lb K_2O/A in June or July may increase summer survival of alfalfa. Apply 3 lb boron/A per year to alfalfa in three 1 lb/A applications. Copper and zinc fertilizer may be needed if soil pH is above 6.5. The lime requirement shown is adequate for established alfalfa. However if the alfalfa has not yet been planted, apply and incorporate one ton of lime/A if the soil pH is below 6.6. Lime is especially important for establishment of alfalfa. It is not practical to incorporate lime once the alfalfa is planted.

124. UF/IFAS fertilization and liming recommendations are advisory in nature and emphasize efficient fertilizer use and environmentally sound nutrient management without losses of yield or crop quality. It is generally assumed the nutrients will be supplied from purchased, commercial fertilizer and the expected crop yields and quality will be typical of economically viable production. Growers should consider UF/IFAS recommendations in the context of their entire management strategy, such as return on investment in fertilizer and the benefits of applying manure or biosolids (sewage sludge) to their land.

There is insufficient research available to support the use of UF/IFAS soil test results for environmental nutrient management purposes. Such use is discouraged until correlation is proven.

125. Grass species included are bermuda, star, digit, and rhodesgrass.

126. *FERTILIZATION MANAGEMENT NOTES FOR BERMUDAGRASS, STARGRASS, DIGITGRASS, AND RHODESGRASS*

Establishment of New Plantings

For establishment of new plantings, apply 100 lb N/A and split as follows: apply 30 lb N/A, all of the P_2O_5, and 50% of the K_2O as soon as plants have emerged. Apply the remaining K_2O and 70 lb N/A 30–50 days later.

Maintenance Fertilization of Established Pastures

For grazed, established stands, apply 80 lb N/A, all of the P_2O_5, and 50% of the K_2O in early spring. Apply 80 lb N and the remaining K_2O at mid-season.

Under intensive management in central and south Florida, up to 200 lb N/A may be economically viable for stargrass and bermudagrass. In that situation, apply 80 lb N/A, all of the P_2O_5 and 50% of the K_2O in early spring, follow with 50 lb N/A in mid-season, and 70 lb N/A and the remaining K_2O in mid- to late September.

Making Hay, Silage, or Green Chop

Apply 80 lb N/A and all of the recommended P_2O_5 and K_2O in early spring. Apply an additional 80 lb N and 40 lb K_2O/A after each cutting, except the last in the fall. Include 20 lb of P_2O_5 in the supplemental fertilizer if the soil tested low or medium in P.

Special Note if Applying Manure or Biosolids

A different set of economic factors are usually considered when waste materials rather than purchased fertilizer are supplying the nutrients. Additionally, it is often impractical to follow the application timings discussed above when using waste materials from other operations.

127. Apply all of the P_2O_5, 50% of the K_2O, and 40 lb N/A at planting. Topdress the remaining N and K_2O in late January. On land which lacks clayey soil within the top 6 to 8 inches of the surface, apply 5 to 10 lb sulfate-sulfur/A at planting and 10 lb sulfate-sulfur/A in the topdressing. Wettable or other elemental forms of sulfur will react too slowly to supply the sulfur needs of the current crop. On flatwoods soils with pH above 6.1, apply 10 lb manganese/A. On better-drained sands with pH above 6.5, apply 6 to 10 lb manganese/A.

128. The recommended rates of fertilizer are sufficient to produce soybean yields in the 60 bu/A range. If yields from this field have never exceeded 40 bu/A under current management, reduce P_2O_5 and K_2O recommendations by 20 lb/A. If yields from this field have never exceeded 25 bu/A, reduce P_2O_5 and K_2O recommendations by 40 lb/A. Often this adjustment will mean that you will achieve your yield potential without any P or K fertilizer additions.

129. These recommendations are made assuming adequate soil moisture will be available either from rainfall or irrigation. In south Florida, lack of adequate rainfall during the cool season frequently causes stand failure or limits growth. Under nonirrigated conditions in south Florida, the probability of inadequate moisture is high, and the likelihood that the crop will benefit from applied fertilizer is low, especially on the drier soils.

130. For grazing or hay production of perennial peanuts, apply all of the P_2O_5 and K_2O in early spring. For hay production, make an annual application of 20 to 30 lb sulfur/A. Apply as a sulfate (e.g., gypsum, ammonium sulfate, magnesium sulfate, potassium sulfate, potassium magnesium sulfate). After each hay harvest, apply an additional 15 pounds of P_2O_5 and 40 pounds of K_2O per ton of hay removed, unless the soil tested high.

131. *FERTILIZATION MANAGEMENT NOTES FOR GRAZED BAHIAGRASS*

Bahiagrass is probably the most widely-used planted forage grass in Florida. It responds well to grazing management and inputs such as fertilization. However, it also can persist and give satisfactory yields under low inputs. Because of the wide range of possible use and management levels, recommendations for bahiagrass fertilization differ with the level of management and the economic inputs. Management decisions concerning liming and fertilization of bahiagrass pastures are very sensitive to cattle productivity and prices.

Liming

In order to obtain maximum fertilization efficiency, soil pH should be maintained at 5.5 or higher. If soil pH tests below 5.3 or lower, a lime requirement test will be conducted and a recommendation for lime application will be made. Optimal use of lime is to apply at least 3–6 months prior to fertilization to provide adequate time for the lime reaction to occur and the soil pH to adjust to the desired level. Soils should be tested for pH every 2–3 years.

Phosphorus Fertilization

In order to receive phosphorus fertilizer recommendations for established bahiagrass, soil AND tissue samples should be submitted to the ESTL at the same time. As per the preliminary research findings, soil tests alone were not found to be adequate to determine bahiagrass P needs. A companion tissue test has therefore been added to the testing procedures along with the soil test to determine the P fertilization needs. Producers are strongly encouraged to simultaneously test soil and tissue samples if bahiagrass pastures have not received P fertilization for long periods. Phosphorus should not be applied if tissue P concentrations are at or above 0.15%, even if soil tested Low in P. For Medium and High soil P levels, P application is not recommended since there is no added benefit of P fertilization on bahiagrass yields.

If P recommendations are not desired and the producer is only interested in either the test for soil pH and lime requirement recommendations, or the test for soil pH, lime requirement, K, Mg, and Ca recommendations, the soil sample alone can be submitted to the ESTL. In this case, the soil test report **will not** include P fertilizer recommendations.

Both the consolidated representative soil and the tissue samples should be collected simultaneously from each field of **up to** 40 acres.

The testing procedures and the recommendations for P for bahiagrass may be adjusted as field research data become available.

Maintenance Fertilization of Established Bahiagrass Pasture

Four fertilization options are presented below for bahiagrass pastures. Choose the option that most closely fits your fertilizer budget, management objectives, and land capability. If you will only be grazing your bahiagrass, you should carefully consider the potential for economical return on your investment in fertilizer before using the Medium-Nitrogen or High-Nitrogen options described below. The added forage produced for grazing animals may not be worth the added cost.

Low-Nitrogen Option. Do not use this option if you cut hay because nutrient removal by hay is much greater than by grazing animals. This option results in the lowest cost of purchased fertilizer. Apply 50 to 60 lb N/A in the early spring to maximize much-needed forage. Do not apply K recognizing that N will be the limiting nutrient in this low-cost option. Apply 25 lb P_2O_5/A if your soil tests Low in P and tissue P concentration is below 0.15%. Do not apply P if tissue P concentration is at or above 0.15%, even if the soil tests Low in P. For Medium and High soil P levels, neither P application nor tissue analysis is recommended because there will be no added benefit of P fertilization on bahiagrass yields.

Medium-Nitrogen Option. Apply 100 lb N/A in the early spring. Apply 25 lb P_2O_5/A if your soil tests Low in P and tissue P concentration is below 0.15%. Do not apply P if tissue P concentration is at or above 0.15%, even if the soil tests Low in P. For Medium and High soil P levels, neither P application nor tissue analysis is recommended because there will be no added benefit of P fertilization on bahiagrass yields. Apply 50 lb K_2O/A if your soil tests Low in K and none if it tests Medium or High.

High-Nitrogen Option. Apply 160 lb N/A in two applications of 80 lb N/A in early spring and early summer. Apply 40 lb P_2O_5/A if your soil tests Low in P and tissue P concentration is below 0.15%. Do not apply P if tissue P concentration is at or above 0.15%, even if the soil tests Low in P. For Medium and High soil P levels, neither P application nor tissue analysis is recommended since there will be no added benefit of P fertilization on bahiagrass yields. Apply 80 lb K_2O/A if your soil tests Low in K and 40 lb K_2O/A if it tests Medium. No K should be applied if your soil tests High in K. The fertilization rates suggested in this option are high enough to allow bahiagrass pasture to achieve well above average production. Management and environmental factors will determine how much of the potential production is achieved and how much of the forage is utilized. A single cutting of hay can be made without need for additional fertilization.

Bahiagrass Cut Sometimes for Hay

For a Single Cut Per Year from Pastures. If you used the **Low-N option** of pasture fertilization, apply 80 lb N/A no later than six weeks before the growing season ends. Apply

50 lb K_2O/A if your soil tests Low in K and none if it tests Medium or High. Apply 25 lb P_2O_5/A if your soil tests Low in P and tissue P concentration is below 0.15%. Do not apply P if tissue P concentration is at or above 0.15%, even if the soil tests Low in P. If you used the **Medium-N option** of pasture fertilization, apply an additional 80 lb N no later than six weeks before the growing season ends. Apply 50 lb K_2O/A if your soil tests Low in K and none if it tests Medium or High. Apply 25 lb P_2O_5/A if your soil tests Low in P and tissue P concentration is below 0.15%. If you used the **High-N option** of pasture fertilization, you do not need any additional N fertilization to make one cut of hay. Apply 80 lb K_2O/A if your soil tests Low in K and 40 lb K_2O/A if it tests Medium. Apply 40 lb P_2O_5/A if your soil tests Low in P and tissue P concentration is below 0.15%.

Bahiagrass Grown Only for Hay

For Multiple Cuts of Hay. Apply 80 lb N/A in early spring. Also in spring, apply 80 lb K_2O/A if your soil tests Low in K and 40 lb K_2O/A if it tests Medium. Apply 40 lb P_2O_5/A if your soil tests Low in P and tissue P concentration is below 0.15%. Apply an additional 80 lb N and 40 lb K_2O/A after each cutting, except the last in the fall. Include 20 lb of P_2O_5/A after each cutting if the soil tested Low in P.

Bahiagrass for Seed Production

Apply 60–80 lb N/A in February or March. At the same time, apply 80 lb K_2O/A if your soil tests Low in K and 40 lb K_2O/A if it tests Medium. Apply 40 lb P_2O_5/A if your soil tests Low in P and tissue P concentration is below 0.15%. Graze until May, June, or July, depending on variety. Remove cattle before seed heads start to emerge and apply an additional 60–80 lb N/A.

If the bahiagrass is not grazed, do not apply fertilizer in February or March because this may stimulate excessive top growth. Mowing from February to April may be needed to remove excessive top growth. Apply 60–80 lb N/A before seed heads first appear. Apply 25 lb P_2O_5/A if your soil tests Low in P and tissue P concentration is below 0.15%. Do not apply P if tissue P concentration is at or above 0.15%, even if the soil tests Low in P. For Medium and High soil P levels, neither P application nor tissue analysis is recommended. Apply 50 lb K_2O/A if your soil tests Low in K and none if it tests Medium or High. Fertilize Pensacola in March/April and Argentine and Paraguay in May/June.

132. *HAY OR SILAGE (PERENNIAL GRASS)*

For Multiple Cuts

Apply 80 lb N/A and all of the recommended P_2O_5 and K_2O in early spring. Apply an additional 80 lb N and 40 lb K_2O/A after each cutting, except the last in the fall. Include 20 lb of P_2O_5/A in the supplemental fertilizer if the soil tested low or medium in P.

For a Single, Late Season Cut from Pastures:

If you have not applied N in the past two months, apply 80 lb N/A and the soil-test recommended amount of P_2O_5 and K_2O. If you have applied N in the past two months, do not apply any N now, but do apply the soil-test recommended amount of P_2O_5 and K_2O. Any application of fertilizer should be made no later than six weeks before the growing season ends.

Special Note if Applying Manure or Biosolids:

A different set of economic factors is usually considered when waste materials rather than purchased fertilizer are supplying the nutrients. Additionally, it is often impractical to follow the application timings discussed in this footnote when using waste materials from other operations.

133. *FERTILIZATION MANAGEMENT NOTES FOR LIMPOGRASS (*Hemarthria*)*

Establishment of New Plantings

For establishment of new plantings, apply 100 lb N/A and split as follows: apply 30 lb N/A, all of the P_2O_5, and 50% of the K_2O as soon as plants have emerged. Apply the remaining K_2O and 70 lb N/A 30–50 days later.

Maintenance Fertilization of Established Pastures

For grazed, established stands, apply 60 lb N/A and all of the P_2O_5 and K_2O in late winter or early spring. Apply an additional 60 lb N in late summer or early fall. For a minimum fertilization alternative, ignore the P and K recommendation and apply only 60 lb N per year.

Making Hay, Silage, or Green Chop

Apply 80 lb N/A and all of the recommended P_2O_5 and K_2O in late winter or early spring. Apply an additional 80 lb N and 40 lb K_2O/ A after each cutting, except the last in the fall. If the soil tested Low in P, then include 20 lb P_20_5/A in the fertilizer applied after each cutting, except the last in the fall.

Special Note if Applying Manure or Biosolids:

A different set of economic factors is usually considered when waste materials rather than purchased fertilizer are supplying the nutrients. Additionally, it is often impractical to follow the application timings discussed above when using waste materials from other operations.

134. BAHIAGRASS, ESTABLISHMENT OF NEW PLANTINGS

Apply 80 lbs N/A for establishment of new bahiagrass plantings in two split applications. Apply 30 lb N/A and all of the recommended P_2O_5 and 50% of the recommended K_2O as soon as the plants have emerged. Apply the remaining 50 lbs N/A and the remaining K_2O between 30 and 50 days after the initial application. If manure or biosolids are used as the main source of nutrients, apply the entire annual application once the plants are large enough to withstand physical damage from the application.

Table 1. Current Mehlich-3 soil test interpretations used for agronomic crops.

Element	Low	Medium	High
	-------- parts per million soil ----------		
P	≤ 25	26–40	41+
K	≤ 25	26–40	41+
Mg	≤ 10	11–23	24+

Table 2. Target pH, and recommended annual N, P_2O_5, and K_2O fertilizer rates for agronomic crops. Phosphorus and K rates are based on interpretation of a Mehlich-3 soil test.

Crop Code	Crop Description	Target pH	----------------------lb/A/year----------------------							Footnotes	References*
			N	---------P_2O_5---------			--------K_2O--------				
			lb/A	LO	MED	HI	LO	MED	HI		
2	Non-irrigated corn	6.5	150	125	50	0	120	60	0	102, 120, 124	AF70
5	Irrigated corn	6.5	210	175	70	0	175	70	0	104, 120, 124	AF70
7	Grain sorghum or forage sorghum for silage	6.5	150	125	50	0	125	50	0	106, 124	AF70
8	Triticale, oats, or rye for grain or silage	6.0	70	100	40	0	100	40	0	106, 124	SSAGR45 & SSAGR46
9	Cotton	6.5	60	120	60	0	125	70	0	107, 124	AF111
10	Peanuts	6.0	0	100	40	0	100	40	0	108	AF70
11	Soybeans	6.5	0	60	20	0	60	20	0	108, 124, 128	NSS23
12	Flue-cured tobacco	5.8	80	100	60	0	200	120	0	110, 124	AF70
13	Sugarcane for syrup	6.0	90	100	40	0	100	40	0	106, 124	AF70
14	Summer annual grasses	6.0	**	80	40	0	80	40	0	111, 124	AF70
21	Warm-season legumes or legume-grass mixtures	6.0	0	30	30	0	60	30	0	121, 124	SSAGR46
22	Cool-season legumes or legume-grass mixtures	6.5	0	100	60	0	160	120	0	115, 122, 124, 129	SSAGR46
23	Alfalfa	7.0	0	125	80	0	160	120	0	120, 123, 124	SSAGR46
25	Improved perennial grass (excluding bahia and limpo)	5.5	160	40	0	0	80	40	0	124, 125, 126	AF70 & SSAGR46
26	Cool-season annual grasses	6.0	**	80	40	0	80	40	0	112, 124	AF70 & SSAGR46
27	Wheat for grain	6.0	80	100	40	0	100	40	0	124, 127	SSAGR45 & SSAGR46
28	Perennial peanuts	6.0	0	30	30	0	60	60	0	124, 130	CIR S275 & RWR
32	Hay or silage (perennial grass)	5.5	**	80	60	0	80	60	0	124, 132	SP253
33	Limpograss (Hemarthria)	5.0	120	20	0	0	40	20	0	124, 133	MBA
35	Bahiagrass, establishment of new plantings	5.5	80	40	25	0	80	50	0	124, 134	
36	Bahiagrass, grazed										
	High-N option	5.5	160	***	0	0	***	***	0	124, 131	AF70 & SSAGR46
	Medium-N option	5.5	100	***	0	0	***	0	0	124, 131	AF70 & SSAGR46
	Low-N option	5.5	50	***	0	0	0	0	0	124, 131	----------------

*AF refers to Agronomy Facts; SSAGR refers to the special series of the Agronomy Department; NSS refers to Notes in Soil Science; RWR refers to R.W. Rice's dissertation, 1993.
**The N recommendation for this crop is discussed in Footnote 111, 112, or 132.
***The P and K recommendations for this crop are discussed in Footnote 131.

Table 3. Interpretation for Bahiagrass Soil and Tissue Test

Soil Test	Tissue Test	Recommendations
P Med / High	No Tissue Test	0
P Low	P $\geq$ 0.15%	0
P Low	P < 0.15%	25 or 40 lbs P_2O_5/acre†

†Recommended amount of P_20_5 depends upon nitrogen option chosen.

Soil and Fertilizer Management for Vegetable Production in Florida[1]

G. D. Liu, E. H. Simonne, K. T. Morgan, and G.J. Hochmuth[2]

Best Management Practices

With the passage of the Federal Clean Water Act (FCWA) in 1972, states were required to assess the impacts of non-point sources of pollution on surface and ground waters, and establish programs to minimize the pollutants. Section 303(d) of the FCWA also requires states to identify impaired water bodies and establish total maximum daily loads (TMDLs) for pollutants entering these water bodies. Water quality parameters targeted by the TMDLs and involving vegetable production are concentrations of nitrate, phosphate, and total dissolved solids in these water bodies. A TMDL establishes the maximum amount of pollutant a water body can receive and still keep its water quality parameters consistent with its intended use (swimming, fishing, or potable uses). The establishment of the TMDLs is currently underway and they will be implemented through a combination of regulatory, non-regulatory, and incentive-based measures. Best Management Practices (BMPs) are specific cultural practices aimed at reducing the load of a specific compound, while maintaining or increasing economical yields. They are tools available to vegetable growers to achieve the TMDLs. BMPs are intended to be educational, economically sound, environmentally effective, and based on science. It is important to recognize that BMPs do not aim at becoming an obstacle to vegetable production. Instead, they should be viewed as a means to balance economical vegetable production with environmental responsibility.

The BMPs that will apply to vegetable production in Florida are described in the *Agronomic and Vegetable Crop Water Quality/Water Quantity BMP Manual for Florida*. This manual was developed between 2000 and 2005 through a cooperative effort between state agencies, water management districts and commodity groups, and under the scientific leadership of the University of Florida's Institute of Food and Agricultural Sciences (UF/IFAS). The manual has undergone a thorough scientific review in 2003 and was presented to stakeholders and state commodity groups for feed back in 2004. The manual was adopted by reference in 2006 and by rule in Florida Statutes (5M-8 Florida Administrative Code). The manual was revised in 2015, adopted by rule, and may be consulted online at http://www.floridaagwaterpolicy.com/ PDFs/BMPs/ vegetable&agronomicCrops.pdf. Vegetable growers may get one-on-one information on 1) the benefits for joining the BMP program, 2) how to join it, 3) how to select the BMPs that apply to their operation, and 4) record keeping requirements by getting in contact with their county extension agent or their local implementation team (see the vegetable

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BMP website at http://swfrec.ifas.ufl.edu/programs/veg-hort/research/veg-bmp.php for more information).

The vegetable BMPs have adopted all current UF/IFAS recommendations; including those for fertilizer and irrigation management (see the new BMP manual *Optimum Fertilizer Management* which will be published soon). Through the implementation of a series of targeted cultural practices (the BMPs), growers should be able to reconcile economic profitability and responsible use of water and fertilizer. At the field level, adequate fertilizer rates should be used together with irrigation scheduling techniques and crop nutritional status monitoring tools (leaf analysis, petiole sap testing). In the BMP manual, adequate fertilizer rates may be achieved by combinations of UF/IFAS recommended base rates and supplemental fertilizer applications added after leaching rainfall, when tissue analyses suggest a need for more fertilizer, or when the harvesting season is prolonged.

Soils

Vegetables are grown on more than 300,000 acres in various soil types throughout the state. These soil types include sandy soils, sandy loam soils, histosols (organic muck), and calcareous marl soils. Each soil group is described below.

Sands

Sandy soils (Figure 1) make up the dominant soil type for vegetable production in Florida. Vegetables are produced on sandy soils throughout the Florida peninsula and on sandy soils and sandy loams in the panhandle. Sandy soils have the advantage of ease of tillage and they can produce the earliest vegetable crops for a particular region. Sandy soils allow timely production operations such as planting and harvesting. Sandy soils, however, have the disadvantage that mobile nutrients such as nitrogen, potassium, and even phosphorus can be leached by heavy rain or over irrigation. Therefore, sands must be managed carefully with regard to fertility programs. Sands hold very little water; therefore, irrigation management is more critical compared to other soil types used for vegetable production in Florida. Nearly all vegetable crops produced in Florida can be successfully grown on sandy soils. The major vegetable crops such as tomatoes, peppers, potatoes, watermelons, strawberries, and cabbage are grown commonly on sandy soils.

Histosols

Histosols (Figure 2) are organic soils which occur in areas throughout the peninsula, especially in southern and central Florida. Large organic deposits used for vegetable production occur south of Lake Okeechobee. Smaller pockets of muck occur throughout central and northern Florida.

Figure 1. Sandy soils used for commercial potato production in northeast Florida.

Figure 2. Sanyd soils in Hastings (northeast FL), Live Oak (north FL). Parrish (southwest FL), and Belle Glade (south FL).

Histosols consist largely of decomposing plant material and are largely underlain by calcareous deposits. Muck soils have large water and nutrient holding capacities and are used to produce crops such as the leafy vegetables (leaf lettuce, and various greens), celery, sweet corn, and radishes. With time, the organic matter decomposes and the muck subsides. Thus the pH of the muck can increase because of increasing proximity to the underlying calcareous material.

Muck subsidence causes problems for water and nutrient management. The increase in pH due to subsidence and also to the practice of flooding the histosols to reduce oxidation can result in increased requirements of phosphorus and micronutrients. These nutrients can be fixed by the high pH of the soil. Nutrient management in these situations should involve banding rather than increased rates of nutrients.

Calcareous Rock and Marl

The calcareous soils (Figure 3) in southern Florida (Miami-Dade County) consist of two phases, rockland and marl. Rockland soils are calcium carbonate soils consisting of particles that range from sand-like in size to pebble and gravel. The rockland soils are extremely shallow, about 4 to 6 inches deep. The marl is the fine-textured, clay-like phase of the calcium carbonate soils. Tomatoes, beans, summer squash, okra, sweet corn, boniato, and strawberries can be produced in the winter months on the rockland soils of Miami-Dade County. Potatoes, malanga, snap beans, and sweet corn are produced on the marl. Both soils have extremely high pH, therefore, nutrients such as phosphorus and micronutrients must be banded to ensure availability.

Figure 3. Tomatoes growing on plastic mulch on rockland soil in Miami-Dade County.

Soil Testing

Plants require 17 elements for normal growth and reproduction (Table 1). American Association of Plant Food Control officials added nickel (Ni) to the list of essential elements in 2004. Nickel is the seventeenth element recognized as essential for plant growth and development (see *Nickel Nutrition in Plants*, http://edis.ifas.ufl.edu/hs1191). The crop nutrient requirement (CNR) for a particular element is defined as the total amount in lb/A of that element needed by the crop to produce economic optimum yield. This concept of economic optimum yields is important for vegetables because a certain amount of nutrients might produce a moderate amount of biomass, but produce negligible marketable product due to small fruit size. Fruit size and quality must be considered in the CNR concept for vegetables.

The CNR can be satisfied from many sources, including soil, water, air, organic matter, or fertilizer. For example, the CNR of potassium (K) can be supplied from K-containing minerals in the soil, from K retained by soil organic matter, or from K fertilizers.

The CNR for a crop is determined from field experiments that test the yield response to levels of added fertilizer. For example, a watermelon study involving K might be conducted on a soil which tests very low in extractable K. In this situation, the soil can be expected to contribute only a small amount of K for optimum watermelon growth and yield, and K must be supplied largely from fertilizer. The researcher plots the relationship between crop yield and fertilizer rate.

The CNR is equivalent to the fertilizer rate above which no significant increases in yield are expected. The CNR values derived from such experiments take into account factors such as fertilizer efficiencies of the soils. These efficiencies include fertilizer leaching or fertilizer nutrient fixing capability of the soil. If data are available from several experiments, then reliable estimates of CNR values can be made. Using the CNR concept will ensure optimum, economic yields when developing a fertilizer program while minimizing both pollution from overfertilization and loss of yield due to underfertilization.

The CNR values are those amounts of nutrients needed to produce optimum, economic yields from a fertilization standpoint. It is important to remember that these nutrient amounts are supplied to the crop from both the soil and the fertilizer. The amounts are applied as fertilizers only when a properly calibrated soil test indicates very small extractable amounts of these nutrients to be present in the soil. Therefore, soil testing must be conducted to determine the exact contribution from the soil to the overall CNR. Based on such tests, the amount of fertilizer that is needed to supplement the nutrition component of the native soil can be calculated (Tables 2 and 3).

It is important that soil samples represent the field or management unit to be fertilized. A competent soil testing laboratory that uses calibrated methodologies should analyze the samples. Not all laboratories can provide accurate fertilizer recommendations for Florida soils. The BMP program for vegetables requires the importance of calibrated soil test. More information about soil testing can be found in *Developing a Soil Test Extractant: The Correlation and Calibration Processes*, http://edis.ifas.ufl.edu/ss622, and *Soil Testing for Plant-Available Nutrients—What Is It and Why Do We Use It?* http://edis.ifas.ufl.edu/ss621.

Liming

Current University of Florida standardized recommendations call for maintaining soil pH between 6.0 and 6.5 (Table 4). However, some vegetables, such as watermelon, will perform normally at lower soil pH as long as large amounts of micronutrients are not present in the soil. A common problem in Florida has been overliming, resulting in high soil pH. Overliming and resulting high soil pH can tie up micronutrients and phosphorus and restrict their bioavailability to the crop. Overliming also can reduce the accuracy with which a soil test can predict the fertilizer component of the CNR.

It is important, however, not to allow soil pH to drop below approximately 5.5 for most vegetable production, especially where micronutrient levels in the soil may be high due to a history of micronutrient fertilizer and micronutrient-containing pesticide applications. When soil pH decreases in such soils, the solubility of micronutrients and probably aluminum (Al) can increase to levels that may become toxic to plants.

Irrigation water from wells in limestone aquifers is an additional source of liming material usually not considered in many liming programs. The combination of routine additions of lime and use of alkaline irrigation water has resulted in soil pH greater than 8.0 for many sandy soils in south Florida. To measure the liming effect of irrigation, have a water sample analyzed for total bicarbonates and carbonates annually, and the results converted to pounds of calcium carbonate per acre. Include this information in your decisions concerning lime.

It should be evident that liming (Table 5), fertilization (Table 6), and irrigation programs are closely related to each other. An adjustment in one program will often influence the other. To maximize overall production efficiency, soil and water testing must be made a part of any fertilizer management program.

Choosing ammoniacal fertilizers as nitrogen (N) source can neutralize alkalinity in rootzone due to selective uptake of plants to different ions. Fertigation with ammonium-N is effective for neutralization. If nitrification inhibitors are also used with the fertilizers together, the neutralization can last much longer. Ammonium sulfate is one of the most effective fertilizers to lower rootzone pH. Similarly, sulfate of potash or muriate of potash also can reduce rootzone pH.

For more information about liming see *Liming of Agronomic Crops*, https://edis.ifas.ufl.edu/aa128.

Manures

Waste organic products, including animal manures and composted organic matter, contain nutrients (Table 7) that can enhance plant growth. These materials decompose when applied to the soil, releasing nutrients that vegetable crops can absorb and utilize in plant growth. The key to proper use of organic materials as fertilizers comes in the knowledge of the nutrient content and the decomposition rate of the material. Many laboratories offer organic material analyses to determine specific nutrient contents. Growers contemplating using organic materials as fertilizers should have an analysis of the material before determining the rate of application. In the case of materials such as sludges, it is important to have knowledge about the type of sludge to be used. Certain classes of sludge are not appropriate for vegetable production, and in fact may not be permitted for land application. Decomposition rates of organic materials in warm sandy soils in Florida are rapid. Therefore, there will be relatively small amounts of residual nutrients remaining for succeeding crops. Organic materials are generally similar to mixed chemical fertilizers in that the organic waste supplies an array of nutrients, some of which may not be required on a particular soil. For example, the P in poultry manure would not be required on a soil already testing high in phosphate. Usually application rates of organic wastes are determined largely by the N content. Organic waste materials can con tribute to groundwater or surface water pollution if applied in rates in excess of the crop nutrient requirement for a particular vegetable crop. Therefore, it is important to understand the nutrient content and the decomposition rate of the organic waste material as well as the P-holding capacity of the soil.

For more information about using manure for vegetable production see *Using Composted Poultry Manure (Litter) in Mulched Vegetable Production*, https://edis.ifas.ufl.edu/ss506.

N, P, K Nutrient Sources

Nitrogen often is the most limiting nutrient in Florida's sandy soils. The amount of nitrogen required by vegetable plants must be applied each growing season because it leaches rapidly. Therefore crop nitrogen requirements vary among crops and are not dependent on soil test results (Table 8). Fertilizer rates of other nutrients must be applied based on soil test results (see soil test above) to follow BMPs (Table 9). The soil test extractant used in UF/IFAS recommendations recently has changed from Mehlich 1 to Mehlich 3. More information on the Change to Mehlich-3 can be found in *Extraction of Soil Nutrients Using Mehlich-3 Reagent for Acid-Mineral Soils of Florida*, http://edis.ifas.ufl.edu/ss620.

The range of soil nutrients found in soil at three ranges (low, medium, and high) also have changed (Table 9). The recommendations found in Tables 8 and 9 were determined in field rate studies considering a wide range of nutrient applications and various soil pH levels. Crop plant development, crop yield, and vegetable quality were considered in determining the optimum nutrient levels for UF/IFAS recommendations.

Nitrogen (N) can be supplied in both nitrate and ammoniacal forms (Table 10). Nitrate-nitrogen is generally the preferred form for plant uptake in most situations, but ammoniacal N can be absorbed directly or after conversion to nitrate-N by soil microbes. Since this rate of conversion is reduced in cold, fumigated, or strongly acidic soils, it is recommended that under such conditions 25% to 50% of the N be supplied from nitrate sources. This ratio is not critical for unfumigated or warm soils.

Phosphorus (P) can be supplied from several sources, including single and triple superphosphate, diammonium phosphate and mono ammonium phosphate, and monopotassium phosphate. All sources can be effective for plant nutrition on sandy soil. However, on soils that test very low in native micronutrient levels, diammonium phosphate in mixtures containing micronutrients reduces yields when banded in large amounts. Availability of P also can be reduced with use of diammonium phosphate compared to use of triple superphosphate. Negative effects of diammonium phosphate can be eliminated by using it for only a portion of the P requirement and by broadcasting this material in the bed.

Potassium (K) can also be supplied from several sources, including potassium chloride, potassium sulfate, potassium nitrate, and potassium-magnesium sulfate. If soil-test-predicted amounts of K fertilizer are adhered to, there should be no concern about the K source or its relative salt index.

Ca, S, and Mg

The secondary nutrients calcium (Ca), sulfur (S), and magnesium (Mg) have not been a common problem in Florida. Calcium usually occurs in adequate supply for most vegetables when the soil is limed. Since there is not yet an interpretation for Mehlich-3 soil Ca, we will use the Mehlich-1 soil Ca intepretation. If the Mehlich-1 soil Ca index is above 300 ppm, it is unlikely that there will be a response to added Ca. Maintaining correct moisture levels in the soil by irrigation will aid in Ca supply to the roots. Calcium is not mobile in the plant; therefore, foliar sprays of Ca are not likely to correct deficiencies. It is difficult to place enough foliar-applied Ca at the growing point of the plant on a timely basis.

Sulfur deficiencies have seldom been documented for Florida vegetables. Sulfur deficiency would most likely occur on deep, sandy soils low in organic matter after leaching rains. If S deficiency has been diagnosed, it can be corrected by using S-containing fertilizers such as magnesium sulfate, ammonium sulfate, potassium sulfate, normal superphosphate, or potassium-magnesium sulfate. Using one of these materials in the fertilizer blends at levels sufficient to supply 30 to 40 lb S/A should prevent S deficiencies.

Magnesium deficiency may be a problem for vegetable production; however, when the Mehlich-3 soil-test index for Mg is below 21 ppm, 30–40 lb Mg/A will satisfy the Mg CNR. If lime is also needed, Mg can be added by using dolomite as the liming material. If no lime is needed, then the Mg requirement can be satisfied through use of magnesium sulfate or potassium-magnesium sulfate. Blending of the Mg source with other fertilizer(s) to be applied to the soil is an excellent way of ensuring uniform application of Mg to the soil.

Micronutrients

It has been common in Florida vegetable production to routinely apply a micronutrient package. This practice has been justified on the basis that these nutrients were inexpensive and their application appeared to be insurance for high yields. In addition, there was little research data and a lack of soil-test calibrations to guide judicious application of micronutrient fertilizers. Compounding the problem has been the vegetable industry's use of micronutrient-containing pesticides for disease control. Copper (Cu), manganese (Mn), and zinc (Zn) from pesticides have tended to accumulate in the soil.

This situation has forced some vegetable producers to overlime in an effort to avoid micronutrient toxicities. Data have now been accumulated which permit a more accurate assessment of micronutrient requirements (Table 3). Growers are encouraged to have a calibrated micronutrient soil test conducted and to refrain from shotgun micronutrient fertilizer applications. It is unlikely that micronutrient fertilizers will be needed on old vegetable land, especially where micronutrients are being applied regularly via recommended pesticides. A micronutrient soil test every 2 to 3 years will provide recommendations for micronutrient levels for crop production.

Foliar Fertilization

Foliar fertilization should be thought of as a last resort for correcting a nutrient deficiency (Table 11). The plant leaf is structured in such a way that it naturally resists easy infiltration by fertilizer salts. Foliar fertilization most appropriately applies to micronutrients and not to macronutrients such as N, P, and K. Foliar applications of N, P, and/or K are not needed where proper soil-directed fertilizer programs are in use. Leaves cannot absorb sufficient macronutrients (without burning the leaves) to correct any related deficiency. Some benefit from macronutrient foliar sprays probably results when nutrients are washed by rain or irrigation water off the leaf surface into the soil. The nutrient then may enter the plant via the roots. Amounts of macronutrients recommended on the label of most commercial foliar products are so minuscule compared to nutrition derived from the soil that benefit to the plant is highly unlikely. Additionally, fertilizer should only be added if additional yield results and research with foliar-nutrient applications has not clearly documented a yield increase for vegetables.

In certain situations, temporary deficiencies of Mn, Fe, Cu, or Zn can be corrected by foliar application. Examples include vegetable production in winter months when soils are cool and roots cannot extract adequate amounts of micronutrients and in cases where high pH (marl and rockland soils) fixes broadcast micronutrients into unavailable forms. Micronutrients are so termed because small, or micro, amounts are required to satisfy the CNR. Such micro amounts may be supplied adequately through foliar applications to correct a temporary deficiency.

Boron is highly immobile in the plant. To correct boron deficiencies, small amounts of boron must be applied frequently to the young tissue or buds.

Any micronutrient should be applied only when a specific deficiency has been clearly diagnosed. Do not make unneeded applications of micronutrients. There is a fine line between adequate and toxic amounts of these nutrients. Indiscriminate application of micronutrients may reduce plant growth and restrict yields because of toxicity. Compounding the problem is the fact that the micro-nutrients can accumulate in the soil to levels which may threaten crop production on that soil. An important part of any micronutrient program involves careful calculations of all micronutrients being applied, from all sources.

Liquid vs. Dry Fertilizer

There is no difference in response of crops to similar amounts of nutrients when applied in either liquid or dry form. Certain situations (use of drip irrigation or injection wheel) require clear or true solutions. However, sidedress applications of fertilizer can be made equally well with dry or liquid forms of nutrients.

The decision to use liquid or dry fertilizer sources should depend largely on economics and on the type of application equipment available. The cost per unit of nutrient (e.g., dollars per unit of actual N) and the combination of nutrients provided should be used in any decision-making process.

Conversion from liquid fertilizer to dry fertilizer is critical for using the proper fertilizer rate in fertigation for commercial vegetable production (see *How to Convert Liquid Fertilizer into Dry Fertilizer in Fertigation for Commercial Vegetable and Fruit Crop Production*, http://edis.ifas.ufl.edu/hs1200).

Figure 4. Applying liquid fertilizer to second-cropped squash with a liquid fertilizer injection wheel.

Controlled-Release Fertilizers

Several brands of controlled-release fertilizers (CRFs) are available for supplying N. Some vegetables increase in yield when controlled-release fertilizers, such as polymer-coated or sulfur-coated urea, or , are used to supply a portion of the N requirement. Although more expensive, these materials may be useful in reducing fertilizer losses through leaching and possible N loss through ammonia volatilization in high pH soils, in decreasing soluble salt damage, and in supplying adequate fertilizer for long-term crops such as strawberry or pepper. Controlled-release potassium fertilizers also have been demonstrated to be beneficial for several vegetables. It is essential to match the nutrient release pattern of the CRF with the crop's uptake pattern.

Controlled-release fertilizers as nutrient management tools are important for BMPs (see *Controlled-Release and Slow-Release Fertilizers as Nutrient Management Tools*, http://edis.ifas.ufl.edu/hs1255).

Soluble Salts

Overfertilization or placement of fertilizer too close to the seed or root leads to soluble salt injury or "fertilizer burn." Fertilizer sources differ in their capacity to cause soluble salt injury. Therefore, where there is a history of soluble salt problems, or where irrigation water is high in soluble salts, choose low-salt index fertilizer sources, and broadcast or split-apply the fertilizer.

Starter Fertilizer

A true starter fertilizer is a soluble fertilizer, generally high in P, used for establishment of young seedlings and transplants. Starter fertilizers generally work best if a small amount of N and K is present along with the P. Starters represent a very small percentage of the overall fertilizer amount but are very important in establishing crops in cool, damp soils. They can be applied with the planter at 2 inches to the side of the seed and 2 inches deep or can be dissolved in the transplant water and applied in the furrow.

Fertilizer Placement

Management of fertilizer consists of the proper combination of what may be referred to as the "4Rs": right rate, right source, right placement, and the right timing. Fertilizer rate and placement must be considered together. Banding low amounts of fertilizer too close to plants can result in the same amount of damage as broadcasting excessive amounts of fertilizer in the bed.

Because P movement in most soils is minimal, it should be placed in the root zone. Banding is generally considered to provide more efficient utilization of P by plants than broadcasting. This is especially true on the high P-fixing calcareous soils. Where only small amounts of fertilizer P are to be used, it is best to band. If broadcasting P, a small additional amount of starter P near the seed or transplant may improve early growth, especially in cool soils. The modified broadcast method where fertilizer is broadcast only in the bed area provides more efficient use of fertilizer than complete broadcasting.

Micronutrients can be broadcast with the P and incorporated in the bed area. On the calcareous soils, micronutrients, such as Fe, Mn, and B, should be banded or applied foliarly.

Since N and, to a lesser extent, K are mobile in sandy soils, they must be managed properly to maximize crop uptake. Plastic mulch helps retain these nutrients in the soil. Under non-mulched systems, split applications of these nutrients must be used to reduce losses to leaching. Here, up to one-half of the N and K may be applied to the soil at planting or shortly after that time. The remaining fertilizer is applied in one or two applications during the early part of the growing season. Splitting the fertilizer applications also will help reduce the potential for soluble salt damage to the plants.

When using plastic mulch, fertilizer placement depends on the type of irrigation system (seep or drip) and on whether drip tubing or the liquid fertilizer injection wheels are to be used.

With seep irrigation, all P and micronutrients should be incorporated in the bed. Apply 10 to 20 percent (but not more) of the N and K with the P. The remaining N and K should be placed in narrow bands on the bed shoulders, the number of which depends on the crop and number of rows per bed. These bands should be placed in shallow (2- to 2 1/2-inch- deep) grooves. This placement requires that adequate bed moisture be maintained so that capillarity is not broken. Otherwise, fertilizer will not move to the root zone.

Excess moisture can result in fertilizer leaching. Fertilizer and water management programs are linked. Maximum fertilizer efficiency is achieved only with close attention to water management.

Under either system above, fertilizing with drip irrigation or with a liquid fertilizer injection wheel might be suitable alternatives to the placement of all N and K in or on the bed prior to mulching.

In cases where supplemental sidedressing of mulched crops is needed, applications of liquid fertilizer can be made through the mulch with a liquid fertilizer injection wheel. This implement is mounted on a tool bar and, using 30 to 40 psi pressure, injects fertilizer through a hole pierced in the mulch.

The 4Rs are described in *The Four Rs of Fertilizer Management*, http://edis.ifas.ufl.edu/ss624.

Supplemental Fertilizer Applications and BMPS

In practice, supplemental fertilizer applications allow vegetable growers to numerically apply fertilizer rates higher than the standard UF/IFAS recommended rates when growing conditions require doing so. The two main growing conditions that may require supplemental fertilizer applications are leaching rains and extended harvest periods. Applying additional fertilizer under the following three circumstances is part of the current UF/IFAS fertilizer recommendations. Supplemental N and K fertilizer applications may be made under these three circumstances:

1. For vegetable crops grown on bare ground with seepage irrigation and without drip irrigation, a 30 lbs / acre of N and /or 20 lbs /acre of K_2O supplemental application is allowed after a leaching rain. A leaching rain occurs when it rains at least 3 inches in 3 days, or 4 inches in 7 days.

2. For all vegetable crops grown on any production system with one of the IFAS recommended irrigation scheduling methods, a supplemental fertilizer application is allowed when nutrient levels in the leaf or in the petiole fall below the sufficiency ranges. For bare ground production, the supplemental amount allowed is 30 lbs /acre of N and/or 20 lbs /acre of K_2O. For drip irrigated crops, the supplemental amount allowed is 1.5 to 2.0 lbs /A/day for N and/or K_2O for one week.

3. Supplemental fertilizer applications are allowed when, for economical reasons, the harvest period has to be longer than the typical harvest period. When the results of tissue analysis and/or petiole testing are below the sufficiency ranges, a supplemental 30 lbs /acre N and/or 20 lbs / acre of K_2O may be made for each additional harvest for bare ground production. For drip-irrigated crops, the supplemental fertilizer application is 1.5 to 2.0 lbs/A/ day for N and/or K_2O until the next harvest. A new leaf analysis and/or petiole analysis is required to document the need for additional fertilizer application for each additional harvest.

Double-Cropping

Successive cropping of existing mulched beds is a good practice in order to make effective use of the polyethylene mulch and fumigant. Double-cropping also can make use of residual fertilizer in the beds. If fertilizer-N applications and amounts were properly managed for the first crop, then there should be negligible amounts of N-fertilizer remaining in the beds. The practice of adding extra fertilizer to the beds when planting the first crop, thinking that this fertilizer will aid growth of the second crop is strongly discouraged. The extra fertilizer could contribute to soluble-salt damage to the first crop, and might still be leached from the root zone before the second crop is established.

Figure 5. Second-crop cucumbers following tomato.

A drip-irrigation system can be used to supply adequate nutrients to each crop in a double crop system. In most cases, only N and K may be needed for the second crop. Amounts of P and micronutrients (if any) used for the first crop will likely remain adequate for the second crop as well. Soil testing of a sample taken from the bed away from any fertilizer bands will help determine P or micro-nutrient needs, assuming that these nutrients were broad-cast in the bed prior to planting the first crop.

If N for the first crop was not applied in excess of the CNR, then the second crop should receive an amount of N equal to its own CNR. Potassium requirements of the second crop can be determined as for P in cases where the K for the first crop was incorporated in the bed. Potassium requirements for the second crop are more difficult to determine in cases where K for the first crop was banded. A moderate amount of residual K will probably remain in the bed from the application to the first crop. Therefore, K requirements for the second crop will likely be slightly less than the CNR value for the chosen crop.

Once the crop fertilizer requirements have been ascertained, the needed nutrition may be applied through the drip system. Where drip irrigation is not being used, a liquid injection wheel can be used to place fertilizer in the bed for the second crop.

Linear Bed Foot (LBF) system for Fertilizer Application

The UF/IFAS Extension Soil Testing Laboratory (ESTL) employs the Standardized Fertilizer Recommendation System in which all recommendations are expressed in lb/A. These fertilizer rates are based upon typical distances between bed centers for each crop. Use of lb/100 LBF as a fertilizer rate assures that an appropriate rate of fertilizer will be applied, regardless of the total number LBF in the cropped area. In other words, use of lb/A to express the fertilizer rate requires an adjustment based upon actual cropped area.

In reality, the goal is to provide a specific concentration of nutrients to plant roots; that is, a specific amount of fertilizer within a certain volume of soil. This conceptual approach makes sense because most plant roots are con-fined within the volume of soil comprising the bed, especially under the polyethylene in the full-bed mulch system.

The LBF system is described in *Calculating Recommended Fertilizer Rates for Vegetables Grown in Raised-Bed, Mulched Cultural Systems*, http://edis.ifas.ufl.edu/ss516.

Irrigation Management

Water management and fertilizer management are linked. Changes in one program will affect the efficiency of the other program. Leaching potential is high for the mobile nutrients such as N and K; therefore, over irrigation can result in movement of these nutrients out of the root zone. This could result in groundwater pollution in the case of N. The goal of water management is to keep the irrigation water and the fertilizer in the root zone. Therefore, growers need knowledge of the root zone of the particular crop so that water and fertilizer inputs can be managed in the root zone throughout the season.

With increased pressure on growers to conserve water and to minimize the potential for nutrient pollution, it becomes extremely important to learn as much as possible about irrigation management.

Plant Tissue Analysis

Analysis of plants for nutrient concentration provides a good tool to monitor nutrient management programs. There are basically two approaches to plant tissue testing: standard laboratory analyses based on dried plant parts; and the plant sap testing procedures. Both procedures have value in nutrient management programs for vegetable crops, each having its own advantages and disadvantages.

Standard laboratory analyses can be very accurate and are the most quantitative procedures. However, they can be time consuming for most diagnostic situations in the field. Standard laboratory analysis involves analyzing the most-recently-matured leaf of the plant for an array of nutrients. The resulting analyses are compared against published adequate ranges for that particular crop. Laboratory results that fall outside the adequate range for that nutrient may indicate either a deficiency or possibly toxicity (especially in the case of micronutrients). The most-recently- matured leaf serves well for routine crop monitoring and diagnostic procedures for most nutrients. However, for the immobile nutrients such as Ca, B, and certain other micro-nutrients, younger leaves are generally preferred.

Figure 6. Ion-specific electrodes for measuring concentrations of nitrate-N and potassium in vegetable leaf petiole sap.

Several plant sap quick test kits have been calibrated for N and K for several vegetables in Florida. These testing kits analyze fresh plant sap for N and K. Quick test kits offer speed of analysis but are less quantitative than standard laboratory procedures. However, quick tests are accurate enough and if properly calibrated are a valuable tool for on-the-spot monitoring of plant nutrient status with the goal of making fine adjustments in fertilizer application programs, especially for those involving drip irrigation.

Diagnostic information for leaf and petiole sap testing can be found in *Plant Tissue Analysis and Interpretation for Vegetable Crops in Florida*, http://edis.ifas.ufl.edu/ep081 and *Petiole Sap Testing for Vegetable Crops*, http://edis.ifas.ufl.edu/cv004.

Drip Irrigation/Fertigation

Drip irrigation has become a very important water management tool for Florida vegetable growers. Approximately 60,000 acres of vegetables are produced with drip irrigation yearly in Florida. Many drip irrigation users have turned to fertigation (applying nutrients through the irrigation tube) to gain better fertilizer management capability. In most situations, N and K are the nutrients injected through the irrigation tube. Split applications of N and K through irrigation systems offers a means to capture management potential and reduce leaching losses. Other nutrients, such as P and micronutrients, are usually applied to the soil rather than by injection. This is because chemical precipitation can occur with these nutrients and the high calcium carbonate content of our irrigation water in Florida.

Figure 7. Media filters for filtering water used for drip irrigation of vegetables.

Nutrient management through irrigation tubes involves precise scheduling of N and K applications. Application rates are determined by crop growth and resulting nutrient demand. Demand early in the season is small and thus rates of application are small, usually on the order of ½ to ¾ lb of N or K_2O per acre per day. As the crop grows, nutrient demand increases rapidly so that for some vegetable crops such as tomato the demand might be as high as 2 lb of N or K_2O per day. Schedules of N and K application have been developed for most vegetables produced with drip irrigation in Florida. Schedules for these crops are presented in the crop chapters in this book.

Fertigation management such as reduction of clogging problems is key for efficient use of fertilizers and BMPs. For information about reducing clogging problems in fertigation for commercial vegetable production see *How to Reduce Clogging Problems in Fertigation*, http://edis.ifas.ufl.edu/hs1202).

Soil Preparation

A well-prepared seed or planting bed is important for uniform stand establishment of vegetable crops. Old crop residues should be plowed down well in advance of crop establishment. A 6- to 8-week period between plowing down of green cover crops and crop establishment is recommended to allow the decay of the refuse. Freshly incorporated plant material promotes high levels of damping-off organisms such as *Pythium* spp. and *Rhizoctonia* spp. Turning under plant refuse well in advance of cropping reduces damping-off disease organisms. Land should be kept disked if necessary to keep new weed cover from developing prior to cropping.

Chisel plowing is beneficial in penetrating and breaking tillage pan layers in fields. If plastic mulch culture is practiced, debris and large undecayed roots will create problems in preparing good beds over which mulch will be applied. For information about soil preparation for commercial vegetable production see *Soil preparation and Liming for Vegetable Gardens*, http://edis.ifas.ufl.edu/vh024.

Bedding

Fields, where seepage irrigation is used or fields prone to flooding, should be cropped using raised beds. Beds generally range from 3 to 8 inches in height, with high beds of 6 to 8 inches preferred where risk of flooding is greatest. Raised beds dry faster than if the soil was not bedded, requiring closer attention to irrigation management especially early in the season when root systems are limited. Raised beds promote early season soil warming resulting in somewhat earlier crops during cool seasons. Many raised beds covered with mulch in north Florida in sandy, well drained soils do not need to be as high as 6 to 8 inches as they do in poorly drained soils.

Bedding equipment may include single or double bedding discs, and curved bedding blades. After the soil is cut and thrown into a loose bed the soil is usually firmed with a bed press. In unmulched production the loosely formed bed may be leveled off at the top by dragging a board or bar across the bed top. Boarding-off the raised beds is common in unmulched watermelon production in central and northern Florida. Mulching requires a smooth, well-pressed bed for efficient heat transfer from black mulch to the soil. Adequate soil moisture is essential in forming a good bed for mulching. Dry sandy soils will not form a good bed for a tight mulch application. Overhead irrigation is sometimes needed to supply adequate moisture to dry soils before bedding.

Cover Crops

Cover crops between vegetable cropping seasons can provide several benefits. The use of cover crops as green manure can slightly increase soil organic matter during the growing season. Properties of soil tilth can also be improved with turning under good cover crops. The cover can reduce soil losses due to erosion from both wind and water. Many crops are effective at recycling nutrients left from previous crops. Recycling of nutrients is becoming an increasingly important issue in protecting groundwater quality.

The selection of a cover crop is based on the seasonal adaptation and intended use for the crops. Vegetable production in south Florida results in cover crops needed during the late spring and summer months. Summer grasses like sorghum or sudan/sorghum hybrids have been popular among Florida producers as a summer cover. Pearl millet is another grass crop providing excellent cover but is not as popular as sudan/sorghum. Both pearl millet and sudan/sorghum provide a vigorous tall crop with high biomass production and are excellent at competing with weeds. The cover crop selected should have resistance to nematodes or at least serve as a relatively poor nematode host. Warm-season legumes such as sunn hemp, velvet bean, and hairy indigo have been noted for their resistance to nematodes. Hairy indigo has been unpopular because of its habit of reseeding. It also has hard seed and produces volunteers in later years. Alyce clover is another warm season legume with one variety, F1-3, having nematode resistance

Alyce clover produces excellent quality hay for producers that can utilize hay from a cover crop.

In north Florida, vegetable crops are established in the spring and early fall. Cover crops are generally utilized during the winter months of November through March. Popular cool season grasses have included rye, wheat, oats, or ryegrass. The traditional crop rotation for water-melon growers has included the use of well-established bahiagrass pastures followed by a crop of watermelon. The acreage of available bahiagrass pastures for rotation has been reduced and these pastures are difficult to find for many growers. As a result, growers are being forced to more intensively crop fields. Cover crops would be helpful in managing the land. When bahiagrass sod is used for production, the extensive root system must be very well tilled well in advance of the cropping season to break up the clumps, especially if plastic mulch will be used. Deep plowing is best to facilitate decomposition of the grass roots and stems. For information about cover crops for commercial vegetable production see *Cover Crops*, http://edis.ifas.ufl.edu/aa217.

Figure 8. Rye windbreaks provide wind protection for early spring crops in central and north Florida.

Windbreaks

The use of windbreaks is an important cultural practice consideration in many vegetable crops and in most states in the United States. Windbreaks used in agriculture are barriers, either constructed or vegetative, of sufficient height to create a windless zone to their leeward or protected side. Strong winds, even if a few hours in duration, can cause injury to vegetable crops by: whipping plants around, abrasion with solid particles (“sand blasting”), cold damage, and plant desiccation. Windbreaks are especially important to protect young plants that are most susceptible to wind damage. Abrasion to plants from wind-blown sand is of concern in most of Florida where sandy soils are commonly used for production. Spring winds in Florida are expected each year. Many of the vegetable crops produced in central and north Florida are at a young and very susceptible stage during these windy spring periods. Strips of planted rye are generally recommended for temporary windbreaks in those areas. Sugarcane can also serve as a more permanent windbreak in South Florida.

Figure 9. Sugarcane windbreaks provide wind protection in south Florida.

The primary reasons windbreaks have been used in vegetable crops have been to reduce the physical damage to the crop from the whipping action of the wind and to reduce sand blasting. Young, unprotected vegetable crop stands can be totally lost from these two actions. Many Florida vegetable crops are grown using plastic mulch culture. Young cucurbit crops, such as watermelon and cantaloupe grown on plastic are especially susceptible to the whipping action of the wind. Vines of these crops eventually become anchored to the soil between mulched beds, however, young vines can be whipped around in circles for several days until they become anchored. The physical damage by whipping and sandblasting can reduce stand, break or weaken plants, open wounds which can increase disease, and reduce flowering and fruit set.

Windbreaks can also help conserve moisture for the crop. Effective windbreaks reduce the wind speed reaching the crops. This reduces both direct evaporations from the soil and transpiration losses from the plant. Improved moisture conditions can help in early season stand establishment and crop growth. Air temperatures around the crop can also be slightly modified by windbreaks.

Temperature on the leeward side of the windbreaks can be slightly higher than if no windbreak were present. Early season crop growth is also greater when windbreaks are utilized. Workers in several states reported increased earliness when rye strips were effectively used as windbreaks.

A field layout to include windbreaks must be properly designed to achieve the maximum benefit. The windbreaks should be positioned perpendicular to the prevailing winds. This determination is perhaps more difficult in Florida than most other states, however, windbreaks planned for protection in the spring should generally protect against winds from the west or northwest. Wind protection is achieved as long as the barrier is a least three feet high, the vegetation is sufficiently dense, and is positioned perpendicular to the prevailing wind.

The height of the windbreak is the most important factor in determining how far apart the strips must be located. Research on windbreaks has been conducted indicating wind protection is afforded to a distance of 6 to 20 times the height of the barrier. Field research with rye strips showed protection was afforded up to a distance of 10 times the height of the barrier. For example, a healthy crop of rye planted in a 5 to 8 ft wide strip using a grain drill and reaching a height of 3 ft would afford wind protection up to 30 ft from the rye strip. If the same rye strip reached a height of 4 ft it would afford protection up to 40 ft from the rye strip. These examples use the calculation of protection afforded up to 10 times the height of an adequate rye strip.

Crops such as small grains, trees, shrubs, or sugarcane are "permeable" barriers in comparison to solid barriers such as smooth constructed walls. Solid barriers are less effective windbreaks than permeable barriers. Wind passing over a solid barrier is deflected over and creates an area of turbulence on the protected side and returns to the ground quickly.

Another type of technology that can provide excellent protection from high winds is the use of plastic row tunnels. Polyethylene or polypropylene materials are place over the plants in a row and held in place. Tunnels are popular for many vegetable crops, especially cucurbits such as cantaloupes. The cover is removed from cucurbits when the first female blooms appear to allow honeybees to pollinate the crops. Tunnels are generally used in conjunction with rye strips because the tunnels have to be removed and once removed the crop is susceptible to wind.

The most widely used windbreak in vegetable crops across the United States is the rye strip method. Winter or cereal rye (*Secale cereale*) is the preferred small grain for this use because the seed is usually cheaper; it provides more growth under cold temperatures and results in the highest plant habit. In some cases the field is solid seeded and later tilled in only the narrow strips where the plastic mulch bed is applied. This leaves a narrow strip of rye between each bed and row and is generally a very effective windbreak design. This design can result in more difficulties in weed management if weeds emerge in the rye strips, however, the rye can be managed with herbicide in certain crops.

The most common use of rye as a windbreak is planting it into strips. Seeding rye should be done in the fall (October–December) for protection in a spring crop. The strips are typically 5-8 ft wide and planted with a grain drill. The windbreak is a valuable component of the cropping system and should be treated as such. A top dressing or two of a fertilizer (at least nitrogen) will promote sufficient early spring growth of the rye to maximize effectiveness as a windbreak. Unfertilized rye strips on low fertility soil will often result in poor, thin, short strips of rye that will be less effective as a windbreak.

The spacing of the rye strips every 30 to 40 feet also allows them to be used as drive roads or spray roads in the field. These are generally necessary in managing most vegetable crops and therefore the rye strips are not taking away cropped areas of the field.

When the rye strips have served their purpose, they can be removed by mowing, rototilling, or disking. If mowing is used in a plastic mulched field, the mower should not throw the rye stems into the plastic area because holes will be pierced in the mulch. One insect management concern in using rye strips in Florida is their attractiveness to thrips. Rye strips also seem to be an excellent environment for beneficial insects, especially lady beetles. If thrips need to be managed in the rye strips, the strips could be sprayed just before the rye is mowed or tilled out. Once the rye is destroyed, the thrips migrate to the crops so control would be more effective while they are still on the rye strips. For more information see *The Benefits of Windbreaks for Florida Growers* at http://edis.ifas.ufl.edu/fr253; *Management of Field Windbreaks* at http://edis.ifas.ufl.edu/fr290; and *Windbreak Designs and Planting for Florida Agricultural Fields* at http://edis.ifas.ufl.edu/fr289.

Table 1. Nutrient elements required by plants.

Nutrient	Deficiency symptoms	Occurrence
Nitrogen (N)	Stems thin, erect, hard. Leaves small, yellow; on some crops (tomatoes) undersides are reddish. Lower leaves affected first.	On sandy soils especially after heavy rain or after overirrigation. Also on organic soils during cool growing seasons.
Phosphorus (P)	Stems thin and shortened. Leaves develop purple color. Older leaves affected first. Plants stunted and maturity delayed.	On acidic soils or very basic soils. Also when soils are cool and wet.
Potassium (K)	Older leaves develop gray or tan areas on leaf margins. Eventually a scorch appears on the entire margin.	On sandy soils following leaching rains or overirrigation.
Boron (B)	Growing tips die and leaves are distorted. Specific diseases caused by boron deficiency include brown curd and hollow stem of cauliflower, cracked stem of celery, blackheart of beet, and internal browning of turnip.	On soils with pH above 6.8 or on sandy, leached soils, or on crops with very high demand such as cole crops.
Calcium (Ca)	Growing-point growth restricted on shoots and roots. Specific deficiencies include blossom-end rot of tomato, pepper and watermelon, brownheart of escarole, celery blackheart, and cauliflower or cabbage tipburn.	On strongly acidic soils, or during severe droughts.
Copper (Cu)	Yellowing of young leaves, stunting of plants. Onion bulbs are soft with thin, pale scales.	On organic soils or occasionally new mineral soils.
Iron (Fe)	Distinct yellow or white areas between veins on youngest leaves.	On soils with pH above 6.8.
Magnesium (Mg)	Initially older leaves show yellowing between veins, followed by yellowing of young leaves. Older leaves soon fall.	On strongly acidic soils, or on leached sandy soils.
Manganese (Mn)	Yellow mottled areas between veins on youngest leaves, not as intense as iron deficiency.	On soils with pH above 6.4.
Molybdenum (Mo)	Pale, distorted, narrow leaves with some interveinal yellowing of older leaves, e.g. whiptail disease of cauliflower. Rare.	On very acidic soils.
Zinc (Zn)	Small reddish spots on cotyledon leaves of beans; light areas (white bud) of corn leaves.	On wet, cold soils in early spring or where excessive phosphorus is present.
Sulfur (S)	General yellowing of younger leaves and growth.	On very sandy soils, low in organic matter, reduced especially following continued use of sulfur-free fertilizers and especially in areas that receive little atmospheric sulfur.
Chlorine (Cl)	Deficiencies very rare.	Usually only under laboratory conditions.

Table 2. Mehlich-1 (double-acid) and Mehlich-3 interpretations for vegetable crops in Florida.

	Mehlich-1 (double-acid) interpretations				
	Very low	**Low**	**Medium**	**High**	**Very high**
Element	**Parts per million soil**				
P	<10	10–15	16–30	31–60	>60
K	<20	20–35	36–60	61–125	>125
Mg[1]	<10	10–20	21–40	41–60	>60
Ca[2]	<100	100–200	201–300	301–400	>400

[1] Up to 40 lbs/a may be needed when soil test results are medium or lower
[2] Ca levels are typically adequate when > 300 ppm

	Mehlich-3 interpretations		
	Parts per million soil		
Nutrient	**Low**	**Medium**	**High**
P	<25	26–45	>45
K	<35	36–60	>60
Mg	<20	21–40	>40

Table 3. Interpretations of Mehlich-1 soil tests for micronutrients.

Soil pH (mineral soils only)			
	5.5–5.9	**6.0–6.4 parts per million**	**6.5–7.0**
Test level below which there may be a crop response to applied copper.	0.1–0.3	0.3–0.5	0.5
Test level above which copper toxicity may occur.	2.0–3.0	3.0–5.0	5.0
Test level below which there may be a crop response to applied manganese.	3.0–5.0	5.0–7.0	7.0–9.0
Test level below which there may be a crop response to applied zinc.	0.5	0.5–1.0	1.0–3.0

When soil tests are low or known deficiencies exists, apply per acre 5 lbs Mn, 2 lbs Zn, 4 lbs Fe, 3 lb Cu and 1.5 lbs B (higher rate needed for cole crops).

Table 4. A general guideline to crop tolerance of mineral soil acidity.[1]

Slightly tolerant (pH 6.8–6.0)		**Moderately tolerant (pH 6.8-–-5.5)**		**Very tolerant (pH 6.8–5.0)**
Beet	Leek	Bean, snap	Mustard	Endive
Broccoli	Lettuce	Bean, lima	Pea	Potato
Cabbage	Muskmelon	Brussels sprouts	Pepper	Shallot
Cauliflower	Okra	Carrot	Pumpkin	Sweet potato
Celery	Onion	Collard	Radish	Watermelon
Chard	Spinach	Corn	Squash	
		Cucumber	Strawberry	
		Eggplant	Tomato	
		Kale	Turnip	

[1] From Donald N. Maynard and George J. Hochmuth, *Knott's Handbook For Vegetable Growers*, 4th edition (1997). Reprinted by permission of John Wiley & Sons, Inc.

Table 5. Liming materials.

Material	Formula	Amount of Material to be used to equal 1 ton of Calcium Carbonate[1]	Neutralizing value[2] (%)
Calcium carbonate, calcite, hi-cal lime	$CaCO_3$	2,000 lbs	100
Calcium-magnesium carbonate, dolomite	$CaCO_3$, $MgCO_3$	1,850 lbs	109
Calcium oxide, burnt lime	CaO	1,100 lbs	179
Calcium hydroxide, hydrated lime	$Ca(OH)_2$	1,500 lbs	136
Calcium silicate, slag	$CaSiO_3$	2,350 lbs	86
Magnesium carbonate	$MgCO_3$	1,680 lbs	119

[1] Calcutated as (2000 x 100) / neutralizing value (%).
[2] The higher the neutralizing value, the greater the amount of acidity that is neutralized per unit weight of material.

Table 6. Effect of some fertilizer materials on soil pH.

Fertilizer material	Approximate calcium carbonate equivalent (lb)[1]
Ammonium nitrate	-1200
Ammonium sulfate	-2200
Anhydrous ammonia	-3000
Diammonium phosphate	-1250 to -1550
Potassium chloride	0
Sodium-potassium nitrate	+550
Nitrogen solutions	-759 to -1800
Normal (ordinary) superphosphate	0
Potassium nitrate	+520
Potassium sulfate	0
Potassium-magnesium sulfate	0
Triple (concentrated) superphosphate	0
Urea	-1700

[1] A minus sign indicates the number of pounds of calcium carbonate needed to neutralize the acid formed when one ton of fertilizer is added to the soil.

Table 7. Average nutrient concentration of selected organic fertilizers.

	N	P_2O_5	K_2O
Product		% dry weight	
Blood	13	2	1
Fish meal	10	6	0
Bone meal	3	22	0
Cotton seed meal	6	3	1.5
Peanut meal	7	1.5	1.2
Soybean meal	71	1.2	1.5
Dried commercial manure products			
Stockyard	1	1	2
Cattle	2	3	3
Chicken	1.5	1.5	2

Table 8. Target pH and nitrogen (N) fertilization recommendations for selected vegetable crops in mineral soils of Florida.

Target pH	N (lb/acre)	Target pH	N (lb/acre)
Tomato, pepper, potato, celery, sweet corn, crisphead lettuce, endive, escarole, romaine lettuce, and eggplant		Snapbean, lima bean, and pole bean	
6.0 (potato) and 6.5	200	6.5	100
Broccoli, cauliflower, Brussels sprouts, cabbage, collards, Chinese cabbage, and carrots		Radish and spinach	
6.5	175	6.5	90
Cucumber, squash, pumpkin, muskmelon, leaf lettuce, sweet bulb onion, watermelon, and strawberry		Southernpea, snowpea, English pea, and sweet potato	
6.0 (watermelon) and 6.5	150	6.5	60
Kale, turnip, mustard, parsley, okra, bunching onion, leek, and beet			
6.5	120		

Table 9. Phosphorus (P; expressed as P_2O_5) and potassium (K; expressed as K_2O) fertilization recommendations for selected vegetable crops in mineral soils of Florida, using Mehlich 1 soil extractant method. VL, L, M, H, and VH = very low, low, medium, high, and very high, respectively.

P_2O_5 (lb/acre/crop season) K_2O									
VL	L	M	H	VH	VL	L	M	H	VH
Celery									
200	150	100	0	0	250	150	100	0	0
Eggplant									
160	130	100	0	0	160	130	100	0	0
Broccoli, cauliflower, Brussels sprouts, cabbage, collards, Chinese cabbage, carrots, kale, turnip, mustard, parsley, okra, muskmelon, leaf lettuce, sweet bulb onion, watermelon, pepper, sweet corn, crisphead lettuce, endive, escarole, strawberry, and romaine lettuce									
150	120	100	0	0	150	120	100	0	0
Tomato									
150	120	100	0	0	225	150	100	0	0
Cucumber, squash, pumpkin, snapbean, lima bean, pole bean, beet, radish, spinach, and sweet potato									
120	100	80	0	0	120	100	80	0	0
Bunching onion and leek									
120	100	100	0	0	120	100	100	0	0
Potato									
120	120	60	0	0	150	--	--	--	--
Southern pea, snowpea, and English pea									
80	80	60	0	0	80	80	60	0	0

Table 10. Some commonly used fertilizer sources.

Nutrient	Fertilizer source	Nutrient content (%)
Nitrogen (N)	Ammonium nitrate	34
	Ammonium sulfate	21
	Calcium nitrate	15.5
	Diammonium phosphate	18
	Potassium nitrate (nitrate of potash)	13
	Urea	46
	Sodium-potassium nitrate (nitrate of soda-potash)	13
Phosphorus (P_2O_5)	Normal (ordinary) superphosphate	20
	Triple (concentrated) superphosphate	46
	Diammonium phosphate	46
	Monopotassium phosphate	53
Potassium (K_2O)	Potassium chloride (muriate of potash)	60
	Potassium nitrate	44
	Potassium sulfate (sulfate of potash)	50
	Potassium-magnesium sulfate (sulfate of potash-magnesia)	22
	Sodium-potassium nitrate	14
	Monopotassium phosphate	34
Calcium (Ca)	Calcic limestone	32
	Dolomite	22
	Gypsum	23
	Calcium nitrate	19
	Normal superphosphate	20
	Triple superphosphate	14
Magnesium (Mg)	Dolomite	11
	Magnesium sulfate	10
	Magnesium oxide	55
	Potassium-magnesium sulfate	11
Sulfur (S)	Elemental sulfur	97
	Ammonium sulfate	24
	Gypsum	18
	Normal superphosphate	12
	Magnesium sulfate	14
	Potassium-magnesium sulfate	22
	Potassium sulfate	18
Boron (B)	Borax	11
	Fertibor[1]	14.9
	Granubor[1]	14.3
	Solubor[1]	20.5
Copper (Cu)	Copper sulfate, monohydrate	35
	Copper sulfate, pentahydrate	25
	Cupric oxide	75
	Cuprous oxide	89
	Copper chloride	17
	Chelates (CuEDTA)	13
	(CuHEDTA)	6
Iron (Fe)	Ferrous sulfate	20
	Ferric sulfate	20
	Chelates (FeHEDTA)	5 to 12
Manganese (Mn)	Manganous sulfate	28
	Manganous oxide	68
	Chelates (MnEDTA)	5 to 12
Molybdenum (Mo)	Ammonium molybdate	54
	Sodium molybdate	39

Nutrient	Fertilizer source	Nutrient content (%)
Zinc (Zn)	Zinc sulfate Zinc oxide Zinc chloride Chelates (ZnEDTA) (ZnHEDTA)	36 80 50 6 to 14 6 to 10
[1]Mention of a trade name does not imply a recommendation over similar materials.		

Table 11. Some nutrients and fertilizer management for vegetable production in Florida.

Nutrient	Source	Foliar application (lb product per acre)
Boron	Borax Solubor[1]	2 to 5 1 to 1.5
Copper	Copper sulfate	2 to 5
Iron	Ferrous sulfate Chelated iron	2 to 3 0.75 to 1
Manganese	Manganous sulfate	2 to 4
Molybdenum	Sodium molybdate	0.25 to 0.50
Zinc	Zinc sulfate Chelated zinc	2 to 4 0.75 to 1
Calcium	Calcium chloride Calcium nitrate	5 to 10 5 to 10
Magnesium	Magnesium sulfate	10 to 15
[1] Mention of a trade name does not imply a recommendation over similar materials.		

Calculating Recommended Fertilizer Rates for Vegetables Grown in Raised-Bed, Mulched Cultural Systems[1]

George Hochmuth and Edward Hanlon[2]

Figure 1. Tomatoes growing in a mulched, raised bed system using a drive-road irrigation/drainage ditch system.

Introduction

There is increased awareness in Florida about the impact of excess fertilizer nutrients in the environment. The Florida Department of Agriculture and Consumer Services (FDACS) encourages the use of Best Management Practices (BMPs) to minimize the possibility of fertilizer losses from agricultural operations. BMPs are crop production practices that are practical and economical to implement on the farm, which also protect environmental water quality. Many vegetable crops, such as tomato, pepper, eggplant, watermelon, cucumber, strawberry, and others are grown on polyethylene-mulched raised beds. This mulched cultural system typically includes drip irrigation for providing water and fertilizer to the crops; however, for some crops in certain areas in the state, subsurface irrigation systems are still being used to supply water. The mulched system is considered a BMP because it helps protect losses of fertilizer from leaching by rainfall when the fertilizer is placed beneath the mulch. More information on vegetable BMPs can be found at http://www.floridaagwaterpolicy.com/PDF/Bmps/Bmp_VeggieAgroCrops2005.pdf

Farmers are advised to base their fertilizer rates on Cooperative Extension Service recommendations that are themselves based on many years of research and field demonstration. Extension recommendations embody the Crop Nutrient Requirement (CNR) method. In the CNR approach to fertilization, the fertilizer supplements the nutrient levels already in the soil (and available to the crop) to achieve a positive crop response. Not only is a crop response to fertilization desired, but the fertilizer rate recommendation must also take into account any possible negative impact on the environment, due to leaching or runoff. Certain recommended fertilizer management practices, such as timing, placement, form of fertilizer, etc., also play a role in the environmental aspects of a fertilizer

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2. George Hochmuth, professor, Department of Soil and Water Science; and Edward Hanlon, professor, Department of Soil and Water Science; UF/IFAS Extension, Gainesville, FL 32611.

recommendation. Mulching and drip irrigation contribute directly to improving nutrient use by the crop and reduced leaching.

Fertilizer recommendations from UF/IFAS Extension present the CNRs in terms of the amount of a nutrient needed for the crop. Some growers ask about the "ratio" of nutrients needed in a fertilizer material, such as a N:K ratio. A required ratio cannot be proven scientifically because to conduct the study, one needs to change the ratios. In changing the ratio you will necessarily change the rates of one or both of the nutrients. Therefore, the rate effect cannot be separated from the ratio effect. Further, once you apply a certain "ratio" to the ground, you lose the ratio because the special ratio fertilizer has now been mixed with the same nutrients already in the soil. The LBF and CNR systems focus on fertilizing the crop, not the soil.

Most public (including Extension) and private soil testing laboratories in the country express fertilizer rates as the amount, e.g., pounds, of a particular nutrient per real estate acre. This rate expression describes an amount (pounds) applied over a surface area (acre), and could be said to be a "fertilize the soil" approach. Today, growers must think more of a "fertilize the crop" approach which the CNR method takes.

What is a Fertilizer "Recommendation"?

A fertilizer "recommendation" is the research-based set of guidelines, or management practices for supplying fertilizer to the crop to achieve yield and quality goals (economic) of the farmer while doing so in a manner that minimizes nutrient losses to the environment. The amount of a nutrient, e.g., pounds per acre, is only a part of a recommendation. Rate must not be considered alone. For the rate part of the recommendation to work, the other parts of the recommendation must be included in the overall fertilizer management practice set. Other important parts of a recommendation include:

- Optimum irrigation management so nutrients are not leached or subject to runoff. Irrigation and fertilizer must be managed together to keep the water and nutrients in the root zone;
- Best timing of fertilizer application-matching applications to the crop growth pattern and crop nutrient needs in the season;
- Best placement of fertilizer so it is as close as possible to the roots for absorption;
- Application of fertilizer only when the plants are present and are most likely to absorb the nutrients(e.g., do not apply fertilizer far ahead of crop establishment, unless using a production practice such as mulch to protect the fertilizer from leaching);
- Use of appropriate split applications in the growing season so that fertilizer is more likely to be used by the crop (e. g., split side-dressings, fertigation); and
- Where economical and practical, consideration of fertilizer materials that release nutrients throughout a period of time and are less "soluble," such as controlled-release fertilizers.

Fertilizer BMPs allow the use of seasonal amounts of fertilizer greater than the recommended amount 1) when leaching rains occur, 2) when you have a diagnosed nutrient deficiency, or 3) when you are extending your typical harvesting period due to a continued favorable market.

Usually, application of fertilizer late in the season, or shortly before harvest, does not result in additional yield or quality and is not a part of appropriate fertilizer recommendations. Remember that the nutrient must be taken up by the plant, transferred to the fruit, and incorporated into the fruit/vegetable tissue before late season fertilizer will be of any benefit to the crop. All of this process takes time, and that's why late season or just before harvest fertilizer applications are unlikely to improve yield or quality.

The "Per Acre" Expression

Considering the "per acre" expression in the context of fertilizing the crop growing in a mulched bed system can lead to some confusion. For example, there would be no reason to fertilize the soil in the alleys between mulched beds because there are no vegetable plants growing there. Additional confusion arises in the mulched bed system, because the cropped portion of an acre is often less than the total acre. It is this confusion that this publication addresses. For example, tomato production on one farm using beds spaced 5 feet apart (bed center to bed center) and another farm using beds on 6-foot centers would require the same fertilizer in the row but different total amounts on an acre basis. Another problem arises where a drainage ditch is used between groups of beds, but the area of the acre adjacent to the ditch is not used for crop production. If you provide the same surface-area rate of fertilizer in these examples, then there would be differing amounts of fertilizer applied to the crop because there would be differing amounts of bedded crop in each surface acre of land. There needs to be a method for expressing fertilizer rates that ensures the same crop, growing in differing bed spacing arrangements, will receive the same amount of fertilizer in the root zone. This approach ensures that we fertilize the crop and not the soil. There are examples provided below to illustrate fertilizer calculations in these situations.

The University of Florida Cooperative Extension Service and the Extension Soil Testing Laboratory (ESTL) have chosen to use the Linear Bed Foot (LBF) system to further define fertilizer rates for crops grown in mulched-bed culture. The LBF system has been incorporated into the ESTL's Standardized Fertilizer Recommendations System where fertilizer rates are expressed on a per acre basis and LBF. The LBF system automatically standardizes the fertilizer rate applied across varying bed arrangements.

The LBF system can be used to express fertilizer rates for any fertilizer delivery method with mulched beds, including production systems still using the seepage irrigation/fertilization system. Here, a "starter" or "cold" mix (often containing N, P if needed, and K) is incorporated in the soil that forms the bed, and the N and K fertilizers are placed in narrow grooves in the bed surface. In the production systems that rely on the drip irrigation system to deliver water and fertilizers, the LBF fits closely because growers already know the total length of drip tubing in an acre. In addition, the LBF system can be used for crops such as potato or sweet corn grown in rows without mulch. This publication focuses on the use of the LBF system with crops grown on mulched beds.

Using The LBF System with the IFAS Standardized Fertilizer Recommendations

Step 1

The first step is to determine the standardized fertilizer recommendation for the crop of interest. This recommendation will be comprised of two parts: the typical bed spacing (and numbers of rows per bed) for the crop and the rate of fertilizer on a per (real-estate) acre, from the soil testing lab report. The typical bed spacing is that bed spacing that is used by most farmers and for which much of the fertilization research was conducted. The bed arrangements for several vegetable crops are summarized in Table 1.

Step 2

Use the information in Step1 to enter Table 2. Using Table 2, go down the left-most column to the row with your crop's typical bed spacing. Go across that row until you come to the column with the recommended fertilizer rate for your crop. The number you find is the amount of fertilizer (N, P_2O_5, K_2O) you will apply per 100 LBF. Divide that number by the % of N, P_2O_5, or K_2O in your fertilizer to get the resulting amount of the fertilizer material to apply per 100 LBF. If your recommended fertilizer rate is greater than the maximum number in the table (e.g., greater than 180) then select the column with half your recommended rate and double your half-rate answer for the final answer.

Examples

1. Tomato on 6-foot Bed Centers

Your nitrogen (N) fertilizer recommendation is 200 pounds per acre. Using Table 2, you would go down the left-most column to the row with 6-foot typical bed spacing. Go across that row until you come to the column with the recommended fertilizer rate of 100 pounds per acre. Come down that column to meet the 6-foot bed spacing row, and find the number 1.38 pounds of N per 100 LBF. You will want to double this amount because we used the 100 pound column, and your recommended rate was 200 pounds per acre. So you will need to apply 2.76 pounds of N per 100 LBF. You can check your math by noting that there are 72.6 100-LBF in an acre of beds on 6-foot centers (Table 1). Then you will note than 72.6 times 2.76 equals 200.

If your fertilizer is 25% N then you will apply 11.04 pounds of fertilizer per 100 LBF. This calculation is 2.76 / 0.25 = 11.04. Please keep in mind this is the amount for the seasonal CNR and you might be planning on split-applications or applying in weekly amounts through the drip irrigation system.

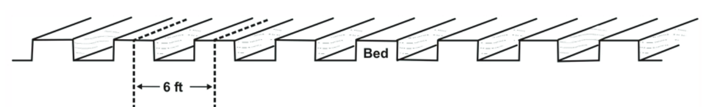

Figure 2. Uniform bed spacing pattern across a field.

2. Tomato on 5-foot Centers

Your nitrogen (N) fertilizer recommendation is 200 pounds per acre. Using Table 2, proceed down the left-most column to the row with 6-foot typical bed spacing. Go across that row until you come to the column with the recommended fertilizer rate of 100 pounds per acre. Come down that column to meet the 6-foot bed spacing row, and find the number 1.38 pounds of N per 100 LBF. You will want to double this amount because we used the 100 pound column and your recommended rate was 200 pounds per acre. So you will need to apply 2.76 pounds of N per 100 LBF. If your fertilizer is 25% N then you will apply 11.04 pounds of fertilizer per 100 LBF.

This is the same answer you saw in example 1. Why? Remember our objective is to standardize our fertilizer rate under the mulched bed and to "fertilize the crop." Both examples use tomato as the crop. Example 1 fits exactly the typical bed arrangement. The farmer in example 2 has a higher plant density (more rows) in a real-estate acre by using beds on 5-foot centers. The goal is the same fertilizer rate per 100 LBF, but since the farmer in example 2 has more LBF of beds, there will be a corresponding increase in the total amount of fertilizer per real-estate acre, **but the same rate per 100 LBF**, which is the goal of the fertilization program, to fertilize the crop.

The fertilizer for Farmer 1 works out to be 200 lbs/acre because he is growing tomatoes on the typical bed spacing of 6 feet. The fertilizer rate for Farmer 2 works out to be 240 lbs/acre because she is growing tomatoes on 5-ft centers. Both are using the research-developed recommended rate per 100 LBF/acre. Farmer 2 has more plants per acre, and therefore needs more fertilizer per acre, but each plant has been supplied the same amount of nutrition in both cases.

3. Tomatoes on 6-foot Centers with a 12-ft Wide Ditch/Access Road Every 6 Beds

In this example, neither the crop, bed spacing, nor fertilizer rate has changed. The bed spacing is 6-feet and the recommended N rate is still 200 pounds per acre. Therefore, the recommended N rate is still 2.76 pounds per 100 LBF. The difference in this example compared with the examples discussed above is the loss of cropped area to the ditches and access roads. The cropped area is 75% of the real-estate acre. The farmer will apply the same rate of N under the mulch, which is our goal, to fertilize the crop, but will purchase less fertilizer for the real-estate acre compared with examples 1 or 2. Example 3 is the more typical situation, with ditches or drive roads, compared to examples 1 or 2 (also, please see the cover photo). There may be production systems that result in cropped areas different from 75%, but the same calculation principles hold.

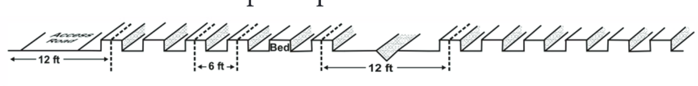

Figure 3. Bed spacing pattern of 6-foot bed centers depicting either a 12-foot wide ditch/road or access road every 6 beds.

4. Watermelons on 8-foot Centers with a 12-ft Drive Road Every 5 Beds

The recommended N rate for watermelon is 150 pounds per acre for the typical bed spacing of 8 feet (Figure 3). From Tables 1 and 2, you must read down the 100 pound per acre column until you come to the 8-foot spacing row in Table 2. You will get 1.84 pounds per 100 LBF. Since the recommendation is 150 pounds per acre, you need to add 50% more to 1.84, and will get 2.76 pounds per 100 LBF. You also could have interpolated between the columns for 140 and 160 pounds per acre. If your fertilizer contains 25% N, then you apply 11.04 pounds of fertilizer per 100 LBF. If you grew watermelons on 9-ft. beds, then you would use the same fertilizer rate per 100 LBF, but you would need a little less fertilizer per real estate acre.

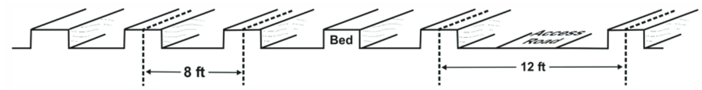

Figure 4. An example of five 8-foot beds plus one 8-foot drive road.

Summary

Growers need to fertilize the crop and not the soil; therefore, you are interested in applying the fertilizer in a manner that is consistent with maximized crop use. The linear bed foot (LBF) system allows you to standardize the amounts of fertilizer for the crop even if you are growing crops in varying bed spacing among farmers. This publication explains the LBF concept and provides easy-to-use tables for converting a fertilizer recommendation from pounds per acre to pounds per 100 LBF. Examples are provided to illustrate the concept in several situations in Florida vegetables.

Definitions of Terms

Real-estate acre: Farm land (land area) that occupies 43,560 square feet. This term also may be called "gross acre" and refers to the land area used for crop production, including the cropped land plus the land used for access roads and irrigation/drainage ditches.

Cropped area: The portion of the real-estate acre used solely for crop production. Alternatively, the cropped area is the land remaining after uncropped land, such as access roads, and irrigation/drainage ditches have been subtracted from the real-estate area. If the entire area is used for crop production, then the cropped area is equal to the real-estate area. Otherwise the cropped area is less than the real-estate area.

Recommended fertilizer rate: This is the amount of fertilizer determined by field research to be needed for normal and economical crop production. This amount will satisfy the crop needs for the season under good growing conditions: where leaching rain does not occur, or where other problems do not limit the plant's access to nutrients. Consistent with the BMPs, a grower might end up using more than the recommended rates, for example when tissue tests indicate a low nutrient level, when there is a leaching rain event, or when the harvesting season will be extended due to favorable prices.

Linear bed foot (LBF): The LBF is the linear distance of 1 foot measured along a raised, mulched bed. The total number of LBF in a particular planting system or bed arrangement system that is the cropped area of real-estate acre is expressed as the LBF per acre (LBF/acre). For simplicity, it is preferred to express the rate per 100 LBF per acre. Growers easily adapt to the LBF system for expressing fertilizer rates because they already know how many linear feet of plastic mulch and drip tubing they use per real estate acre. Also, a similar linear foot system is used to calibrate their fertilizer spreading equipment.

Table 1. Typical bed spacing and number of rows per bed for some vegetable crops grown in mulched bed culture.

Vegetable crop	Typical bed spacing (ft)[z]	No. of 100-LBF per acre	Number of rows of plants on a bed	Vegetable crop	Typical bed spacing (ft)[z]	No. of 100-LBF per acre	Number of rows of plants on a bed
Broccoli	6	72.6	2	Muskmelon	5	87.1	1
Cabbage	6	72.6	2	Pepper	6	72.6	2
Cauliflower	6	72.6	2	Squash-summer	6	72.6	2
Cucumber	6	72.6	2	Squash-winter	6	72.6	2
Eggplant	6	72.6	1	Strawberry	4	108.9	2
Lettuce	4	108.9	2	Tomato	6	72.6	1
Leafy greens	6	72.6	2	Watermelon	8	54.6	1

[z] The bed spacing is measured from the center of one bed to the center of the adjacent bed.

Table 2. Conversion of fertilizer rates in pounds per acre to pounds per 100 LBF[z].

Typical bed spacing (ft)	Recommended fertilizer rate (N, P_2O_5, K_2O) (pounds per acre)								
	20	40	60	80	100	120	140	160	180
	Resulting fertilizer rate (N, P_2O_5, K_2O) (pounds per 100 LBF)								
3	0.14	0.28	0.41	0.55	0.69	0.83	0.96	1.10	1.24
4	0.18	0.37	0.55	0.73	0.92	1.10	1.29	1.47	1.65
5	0.23	0.46	0.69	0.92	1.15	1.38	1.61	1.84	2.07
6	0.28	0.55	0.83	1.10	1.38	1.65	1.93	2.20	2.48
8	0.37	0.73	1.10	1.47	1.84	2.20	2.57	2.94	3.31

[z] This table is used correctly by (1) determining the typical bed spacing from Table 1 for the crop; (2) locating the column containing the recommended fertilizer rate in pounds per acre; and (3) reading down the column until reaching the row containing the typical bed spacing. The resulting number in pounds per 100 LBF should be used even in situations where the farmer's bed spacing differs from the typical bed spacing. Use of the table will involve doubling the rate, for example where the column for 100 pounds per acre was used in the calculation of pounds per 100 LBF for a recommended rate of 200 pounds per acre.

Soil pH Range for Optimum Commercial Vegetable Production[1]

Guodong Liu and Edward Hanlon[2]

Introduction

Soil pH is a measure of soil acidity or basicity, and it is defined as the negative logarithm of the proton (H^+) activity. The pH ranges from 0 to 14. A pH of 7.0 is defined as neutral, while a pH of less than 7.0 is described as acidic, and a pH of greater than 7.0 is described as basic (Figure 1). According to the USDA Natural Resources Conservation Service (1993), soil pH ranges roughly from acidic (pH < 3.5) to very strongly alkaline (pH > 9.0). Soil pH is a master characteristic in soil chemical properties because it governs many chemical processes. The pH specifically affects nutrient bioavailability by controlling the chemical forms of nutrients. For example, ferrous iron is a bioavailable form of iron for most crop species, but ferric iron is not. At a relatively high pH, ferric iron is the primary form of the nutrient, and crop plants may experience iron deficiency.

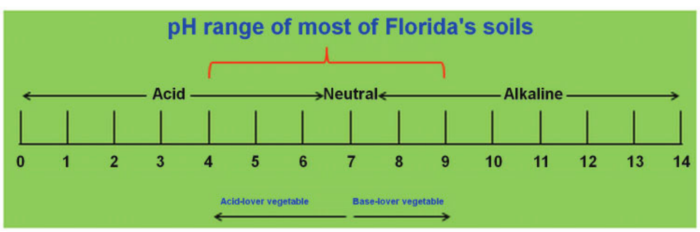

Figure 1. The pH scale and vegetable categories. The pH is measured on a logarithm scale from 0 to 14.
Credits: Guodong Liu

As one of the most important soil chemical properties for optimal crop production, soil pH determines nutrient sufficiency, deficiency, toxicity, and need for liming (Fageria and Zimmermann 1998) or addition of sulfur. The pH range of most of the Florida's soils is approximately between 4.0 and 9.0 (Figure 1; Tables 1–4). Because nutrient solubility is highly pH dependent, soil pH near 4.0 or 9.0 is usually not suitable for commercial vegetable production. A pH range from 5.5 to 7.0 is suitable for most vegetable crops (Figure 2). This pH range can assure high bioavailability of most nutrients essential for vegetable growth and development (Ronen 2007). For example, at soil pH 8.0 or higher, iron and/or manganese bioavailability can not satisfy most vegetable crops' requirements. However, when soil pH reaches 5.0 or lower, aluminum, iron, manganese, and/or zinc solubility in soil solution becomes toxic to most vegetable crops (Osakia, Watanabe, and Tadano 1997).

This publication is intended to provide information about soil pH basics to commercial growers, county Extension agents, and college students specializing in vegetable production.

Effects of Soil pH on Vegetable Crop Growth and Development

Effects on cation and anion nutrients: Soil pH determines the solubility and bioavailability of nutrients essential for crop production. There are seventeen elements essential for normal growth and development of vegetable crops. Based on the source, the seventeen nutrient elements can be

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roughly categorized into two groups: three nutrients from air and water, which are carbon (C), hydrogen (H), and oxygen (O), and fourteen soil nutrients, which are nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), iron (Fe), zinc (Zn), copper (Cu), manganese (Mn), boron (B), chlorine (Cl), molybdenum (Mo), and nickel (Ni). The bioavailable forms of all the soil nutrients are ionic—some are anionic (negatively charged, such as nitrate ions), some cationic (positively charged, such as ammonium ions), and some are both. For example, P, S, Cl, and Mo are typical anion nutrients, and K, Ca, Mg, Fe, Zn, Cu, Mn, and Ni are typical cation nutrients, but N can be either anions or cations. Boron is predominately undissociated boric acid (H_3BO_3 or $B(OH)_3$), but less than 2% of B is in the form of an anion $B(OH)_{4-}$ at pH 7.5 or lower. The solubility (i.e., bioavailability) of each of these fourteen nutrient elements is closely related to soil pH. At pH lower than 5.0, Fe, Cu, Mn, and Zn are highly soluble. These micronutrients can form precipitates with phosphate at this low pH, and P becomes unavailable accordingly. However, at pH greater than 7.0, Ca and Mg have high solubility, and they can fix P as well. Thus, comprehensively speaking, in the pH range from 5.5 to 7.0, all of the nutrients have favorable usability to vegetable plants (Figure 3).

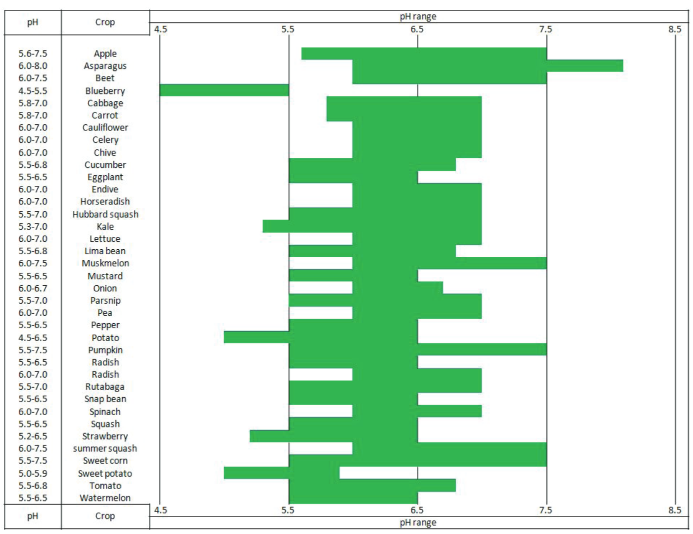

Figure 2. Soil pH range for optimal growth of selected vegetable crops (*Source*: Havlin et al. 2005; Splittstoesser 1990)

Effects on nutrient uptake near the root zone: Soil pH also affects nutrient uptake by vegetable plants because it can change soil particle property. For example, if soil pH is unfavorably low, the positive charges on soil particle surfaces can tightly hold up nutrients like P, potentially causing P deficiency in vegetable plants. However, if soil pH is adversely high, then Fe, Mn, and Zn will become difficult for vegetable plants to use. In one study, bean (*Phaseolus vulgaris* L.) absorbed 93.3% more P, 53.8%, more Fe, and 44.1% more Zn at pH 5.4 than at pH 7.3, respectively (Thomson, Marschner, and Römheld 1993). The lower pH favors P, Fe, and Zn uptake because the bioavailability of P, Fe, and Zn is greater at pH 5.4 than at pH 7.3 (Figure 3).

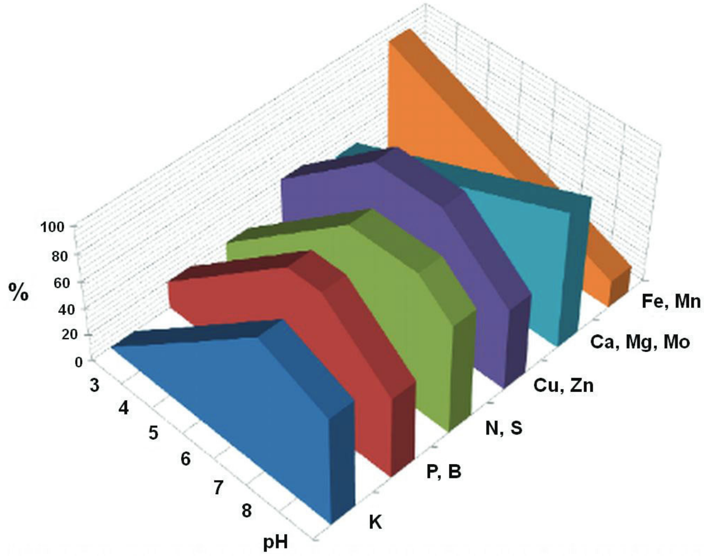

Figure 3. The pH and bioavailability (%) of listed nutrients in soil solution (*Source*: Finck 1976)

Effects on metal toxicity: Basically, metal toxicity occurs at soil pH lower than 5.0 when elements such as Al, Fe, Mn, and Cu have much greater solubility than plants need. To avoid this problem, lime is needed to increase soil pH and decrease the potential for toxicity.

Effects on plant pathogens: Some soilborne diseases are closely associated with soil pH. For example, clubroot disease of mustard, cabbage, or other crucifers caused by *Plasmodiophora brassicae* is a major epidemic disease when soil pH is lower than 5.7 but is dramatically reduced in a pH range from 5.7 to 6.2. This disease is virtually eliminated when the soil pH is greater than 7.3. Similarly, common scab of potato is favored when the pH is greater than 5.2 but significantly reduced at less than 5.2 (Kioke et al. 2003).

Statewide Overview of Soil pH

Florida is a unique state in terms of soil diversity. Its soil pH significantly differs in the entire state from north to south and east to west. Even in the same county, soil pH can differ by as much as 6 pH units, according to the USDA soil survey (USDA 1976, 1979, 1983, 1996). For example, soil pH ranges from 3.6 to 9.0, from 3.6 to 9.0, from 3.3 to 9.0, and from 3.6 to 8.4 for Dade County, Palm Beach County, St. Johns County, and Jackson County, respectively (Tables 1 through 4). These extremes are all unfavorable for vegetable production.

Nutrients and Soil pH

Nutrient bioavailability: Nutrient bioavailability is usually a limiting factor in commercial crop production because of solubility limitation or immobilization of plant nutrients by soil colloids. A nutrient's bioavailability is the proportion of that particular nutrient that is soluble or mobilized by root exudates, including protons (directly related to soil pH), chelates, mucilage and mucigel, or microbial products (Neumann and Römheld 2012). For instance, in the Everglades Agricultural Area, total P in cultivated soil is up to 1227 parts per million (ppm), but bioavailable P is only 1.3 ppm (Wright, Hanlon, and McCray 2009). The bioavailability of that particular soil is only 0.1% of the total P. Thus, P deficiency does not mean lack of P in that particular soil, but it does mean lack of absorbable or usable P for crop plants. In fact, the bioavailability of most nutrients is controlled by soil pH. As soil pH increases, the bioavailability decreases for P, Fe, Mn, B, Zn, and Cu. As soil pH decreases, the bioavailability decreases for Ca, Mg, and Mo (Figure 3).

Nutrients needed in large amounts by vegetable plants are called macronutrients, such as N, P, K, Ca, Mg, and S, whereas those needed in trace amounts are referred to as micronutrients or trace nutrients, such as Fe, Mn, B, Zn, Cu, Cl, Mo, and Ni. Soil pH affects both macronutrient and micronutrient solubility (Figure 3) and bioavailability. For example, the primary form of iron in dry soil is ferric hydroxide ($Fe(OH)_3$) because ferrous iron is easily oxidized and little ferrous iron exists in dry soil, particularly at soil pH 7.3 or higher. The solubility of ferric hydroxide is only 6.3×10^{-20} mol/L (i.e., only 1.34×10^{-11} mg Fe per 1000 gallons of water at pH 7.3). However, its solubility is 1.34×10^{-5} mg Fe per 1000 gallons of water at pH 5.3. The solubility increases one million times when soil pH is lowered just three pH units. This dramatic change in solubility can explain why iron deficiency symptoms often occur when soil pH is 7.3 or higher. If the soil is appropriately wet and soil pH is neutral or slightly acidic, a considerable proportion of iron exists in the form of ferrous iron, usually enough to satisfy crop nutrient requirements for Fe.

Soil pH influence on uptake of cation and anion nutrients: In low-pH soils, the hydrogen ion exists as a hydrated proton and may become a toxicant if soil pH is lower than 3.0 (Liu et al. 2007). However, the effects of soil pH on nutrient intake are mainly indirect, caused by increasing the solubility of toxic metals, such as aluminum (Al). Aluminum solubility is also a function of soil pH. The solubility of Al increases as soil pH decreases. At pH 5.5 or lower, the solubility of Al increases 1000-fold for every pH unit decrease. For example, at pH 5.0, Al solubility is only 0.05 ppm, but at pH 4.0, Al solubility increases to a toxic 51 ppm.

Such high concentrations of Al can damage root morphology and induce P deficiency in soil (Figure 3). The root system of corn can be seriously damaged or its growth retarded when Al concentration is greater than 9 ppm (Lidon and Barreiro 1998). This negative effect on plants is evidence of Al toxicity. Aluminum and phosphate precipitate in low-pH soil. Both Al and P have a reciprocal relationship. As mentioned above, Al solubility is 1000-fold greater at pH 4.0 than at pH 5.0. Because of the Al concentration increase, the bioavailability of P at pH 4.0 reduces to one thousandth of the concentration present at pH 5.0, having been precipitated by the increase in Al. Similar effects for other elements can be seen in Figure 3.

Low pH exacerbates nutrient leaching problems because cation nutrients adsorbed by soil particles may be replaced by protons in soil solution. The nutrient leaching reduces nutrient uptake and nutrient use efficiency of vegetable crops.

Effects on nutrient uptake near the root zone: In the presence of toxic concentrations of elements such as Al at low pH, root growth and water uptake are inhibited and plants may show symptoms of P deficiency and drought stress. Aluminum-stressed plants cannot efficiently absorb nutrients from soil solution. There are two other reasons for inhibition of cation nutrient uptake and induction of nutrient deficiency: (a) impairment of net excretion of protons and (b) decrease of bioavailable cation nutrients, such as Ca, Mg, Zn, and Mn in soil solution.

Effects of Soil pH on Microbial Activity

The pH affects microbial activities, which in turn can affect the bioavailability of both macronutrients and micronutrients. Most soil microbes thrive in a range of slightly acidic pH (6–7) because of the high bioavailability of most nutrients in that pH range (Sylvia et al. 2005). Because microbes can increase nutrient bioavailability and promote plant nutrient uptake, vegetable crops can also thrive in such environments (Das et al. 2010).

Nutrient Sources Affect Soil pH in Root Zones

Acid-forming or basic-forming fertilizers: Acid-forming fertilizers are defined as those that lower rhizosphere pH after being absorbed by plants. All fertilizers containing cation nutrients, such as ammoniacal-N, K, Ca, and Mg, are acid forming, whereas those having anion nutrients, such as nitrate N, P, and S, are basic forming. For instance, ammonium chloride, potassium chloride, calcium chloride, and magnesium chloride are acid-forming fertilizers. However, sodium nitrate, sodium dihydrogen phosphate, and sodium sulfate are basic-forming fertilizers.

Acid- or basic-forming fertilizer is *NOT* related to the acidity or basicity of the applied fertilizer itself. The acidity or basicity results from the selective uptake of nutrients by crop plants. For example, potassium chloride is chemically neutral. Potassium and chlorine (Cl) are both essential for vegetable crop growth and development. However, the ratio of plants' K requirement to Cl requirement is greater than 80. This ratio shows that plants need to absorb more than 80 K^+ ions when they take up one Cl^- ion. These two nutrients are either positively or negatively charged. If plants take these two kinds of cation and anion ions without electrical neutralization, plant cells would accumulate tremendous positive charges. These unbalanced charges can kill the cells immediately. To avoid this, plant cells have developed two strategies. In the first strategy, they stoichiometrically release the same type of charges, such as protons (H^+), when they intake K. In the second strategy, the cells can also neutralize the unbalanced charges by absorbing the same amount of other ions with counter charges, such as OH^- or HCO_3^-, in this case when they take up K^+ ions. Regardless of strategy, the net consequence is the same: The pH in the growth medium, particularly in the root zone, is decreased. Similarly, sodium nitrate is chemically neutral, but the pH in the root zone is increased when the plant takes up N from sodium nitrate because nitrate N is negatively charged and the primary nutrient in crop production, but sodium is not essential for crop plant growth and development. Therefore, intentional selection of fertilizers, such as potassium chloride or sodium nitrate, can effectively adjust soil pH in the root zone, if needed.

Soil pH vs. Nutrient Losses

Ammonia volatilization: Ammonium-N is one of the two primary forms of commercial N fertilizers. Ammonium and ammonia can form a dynamic chemical equilibrium in soil solution. The shift direction of the chemical equilibrium between ammonium and ammonia is determined by the pH of soil solution. At pH 9.2, both ammonium and ammonia are equal in concentrations. Ammonium is aqueous, but ammonia is both aqueous and gaseous in solution. The solubility of ammonia in water is 31% at 77°F (25°C). This dissolved ammonia can easily be converted into gaseous ammonia that is ultimately released into the atmosphere. This gas emission is called ammonia volatilization. Soil pH mainly determines the extent of the ammonia's volatilization. High soil pH (greater than 7.2) causes ammonia volatilization from fertilized soils with ammoniacal-N sources, such as ammonium sulfate, or ammonium-forming fertilizers, such as urea. In Florida, ammonia volatilization was up to 26% of the applied N fertilizer in Krome Very Gravelly Loam soil in Homestead for potato production (Liu et al. 2007).

Anionic nutrient leaching: At soil pH greater than 7.0, hydroxide ions can replace anionic nutrients from soil particles with positive charges and reduce soil particles' anionic nutrient-holding ability. Nitrate leaching increases proportionately as soil pH increases (Costa and Seidel 2010). Therefore, high soil pH exacerbates anionic nutrient leaching and reduces nutrient use efficiency. To alleviate leaching problems and improve the profitability of vegetable production, soil pH needs to be effectively managed.

Micronutrients: In addition to soil pH, micronutrients are affected by ionic charge (some can have more than one, like Mn and Fe), which is often determined by microsite conditions and oxidation-reduction potential. For example, in appropriately wet soil (between field capacity and wilting point), Fe and Mn are more bioavailable than in dry soil because wet soil has lower oxidation-reduction potential than dry soil. In the same soil, the oxidation-reduction potential increases with pH. This process explains Fe or Mn deficiency in high pH soils, namely as a function of pH greater than 7.0 and during drier soil moisture conditions, which favor deficiency.

Nutrient Use Efficiency

Nutrient use efficiency is defined as vegetable yield per unit of nutrient input. It is much more important than ever because fertilizer prices have risen and profit margins have become thin. Nutrient use efficiency can be measured by calculating the productivity of each unit of a particular nutrient. In 2012, two snap bean trials were done in Lake Harbor and Belle Glade in Palm Beach County. The two trials both showed that 120 lb. phosphorus pentoxide (P_2O_5) per acre was the most efficient P rate. The P use efficiency in snap bean production varied with the trial locations. In Lake Harbor, 1 lb. of P fertilizer yielded 11 lb. of beans. The

P use efficiency for this particular trial in Lake Harbor was 11 (lb./lb.). However, in Belle Glade, 1 lb. of P yielded 22 lb. of beans. The P use efficiency in Belle Glade was 22 (lb./lb.). This difference in P use efficiency can be attributed to the bioavailability of P in soil background. The Mehlich 3 P concentration in the muck soil was 82.3±5.7 ppm (Lake Harbor) and only 37.8±1.9 ppm in the fine sandy soil (Belle Glade).

Modifying Soil pH or Choosing Plants That Will Thrive in Soil

Adjusting soil pH usually involves raising the soil pH by adding agricultural lime if soil pH is too low.

Acidic soils: The bioavailability of Ca, Mg, and Mo is often low and may adversely affect vegetable production. Additionally, toxicity effects discussed previously may also be a factor. An increased soil pH can improve nutrient availability and help avoid toxicity.

Lime and lime requirement: The most common soil additive to increase soil pH is agricultural lime, usually finely ground. The amount of lime required to increase soil pH is determined by the size of the limestone particles being used and, most importantly, the buffering capacity of the soil. The buffering capacity refers to the soil's ability to minimize change in the acidity of a solution when an acid or base is added into the solution. The finer the ground lime, the quicker the neutralization reaction. Buffering capacity is controlled by the soil's clay content and the amount of organic matter present. Soils with more clay content have a greater buffering capacity than soils with less clay content. Similarly, soils with more organic matter have higher buffering capacity than those with lower organic matter. Soils with great buffering capacity need more agricultural lime to adjust soil pH than those with lower buffering capacity for the same incremental change in soil pH. However, sandy soils have lower buffering capacity and need less lime for the same incremental change in pH than clay soils.

The best way to determine the lime requirement for a particular soil is to take a soil sample to the UF/IFAS Extension Soil Testing Laboratory. UF/IFAS Extension faculty members can also help. For more information, see *Soil pH and the Home Landscape or Garden* (http://edis.ifas.ufl.edu/ss480), *Managing pH in the Everglades Agricultural Soils* (http://edis.ifas.ufl.edu/ss500), The Vegetarian Newsletter, Issue 573 (http://hos.ufl.edu/newsletters/vegetarian/issue-no-573), and *The Soil Test Handbook for Georgia* (http://aesl.ces.uga.edu/publications/soil/STHandbook.pdf).

Other amendments, such as dolomite (a white or light-colored mineral, essentially $CaMg(CO_3)_2$), wood ash, industrial burnt lime (calcium oxide), and oyster shells can also increase soil pH. These sources increase soil pH through the reaction of carbonate and protons to produce carbon dioxide and water. However, some wood ash may contain sodium or heavy metals. Before using any of these sources, consult your county Extension agent. Applying calcium silicate can also neutralize active acidity in soil. Local organic sources, such as yard-trash compost and sphagnum moss peat, are all acidic. The pH range can be as low as 3.6–4.2. These sources can be used to neutralize free hydroxide and/or bicarbonate ions.

Use nitrate nitrogen fertilizers: Liming can change the whole soil layer's pH. If nitrate nitrogen fertilizers are used, the root zone's pH can be increased without additional cost because vegetable crops need to balance electrically after absorbing nitrate ions, which are negatively charged. Since N should be added according to recommended fertilizer rates, this process works slowly for the entire soil profile, but it does improve the plant root zone pH in a short time.

Alkaline soils: The bioavailability of P, Fe, Mn, Zn, Cu, and Ni is low and may adversely affect vegetable growth and development. To ensure that vegetable crops will grow well, soil pH may need to be reduced if the high pH was caused by overliming or poor irrigation water quality. If the high pH was caused by a natural condition, usually limestone or beach shells in Florida, the change is too costly. Selection of appropriate cultivars is a must in such a case.

Sulfur and sulfur requirement: The most common soil additives to decrease soil pH are elemental sulfur (S), iron sulfate or aluminum sulfate, peat moss, or any cation nutrients, such as ammonium, potassium, calcium, and magnesium. Therefore, these fertilizers can all decrease soil pH: urea, urea phosphate, ammonium nitrate, ammonium phosphates, ammonium sulfate, and monopotassium phosphate. Organic matter in the form of plant litter, compost, and manure all decrease soil pH through the decomposition process. Certain acidic organic matter, such as pine needles, is also effective at reducing pH.

Applying elemental sulfur can decrease soil pH because the applied sulfur can form sulfuric acid and neutralize free hydroxide or bicarbonate ions in the soil. Similar to the lime requirement for low-pH soils, sulfur requirement for high-pH soil is closely related to the buffering capacity of the target soil. Kissel and Sonon (2008) provide an informative reference to determine the actual amount needed for a particular high-pH soil. It is better to discuss lowering soil pH with a local county Extension agent before taking any action.

Use ammonium nitrogen fertilizers: Ammoniacal-N fertilizers, such as ammonium sulfate and ammonium chloride, and ammonium-forming fertilizers, such as urea, can significantly decrease root zone pH after plants take up ammonium ions from soil. Using suitable fertilizers to adjust soil pH doesn't necessarily incur any additional cost and may improve the profitability of vegetable production. Applying organic matter, such as compost, manure, and pine sawdust, is also effective at reducing soil pH. If soil pH is too low, refer to *Soil Fertility Management for Wildlife Food Plots* (http://edis.ifas.ufl.edu/ss468) and *Diagnostic Nutrient Testing for Commercial Citrus in Florida* (http://edis.ifas.ufl.edu/ss492).

Optimal Soil pH

To enhance vegetable production productivity, optimal soil pH range is essential. Tables 1 through 4 indicate the soil pH ranges in selected counties. The pH ranges for other counties can be found at http://soils.usda.gov/survey/online_surveys/florida/. Figure 1 contains the pH scale and vegetable category based on their tolerance to acidity levels. Figure 2 lists the range in soil pH for optimal growth of selected vegetable crops. Figure 3 indicates the relationship between nutrient bioavailability and soil pH.

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Table 1. Dade County soil pH[z]

Soil name	Depth (inches)	Soil pH
Basinger	0–6	3.6–8.4
Biscayne	0–7	7.4–8.4
Canaveral	0–80	6.6–8.4
Cardsound	0–4	6.1–7.3
Chekika	0–5	7.4–8.4
Dade	0–24	6.1–8.4
Dania	0–15	5.6–7.3
Demory	0–7	6.1–7.3
Hallandale	0–4	5.1–6.5
Kesson	0–33	7.4–9.0
Krome	0–7	7.4–8.4
Lauderhill	0–30	5.6–7.8
Margate	0–9	4.5–6.0
Matecumbe	0–3	5.6–7.3
Opalocka	0–6	6.1–7.3
Pahokee	0–46	5.6–7.3
Pennsuco	0–8	7.9–8.4
Perrine	0–10	7.9–8.4
Plantation	0–14	4.5–7.3
Pomello	0–35	4.5–6.0
St. Augustine	0–80	6.1–8.4
Tamiami	0–12	6.6–7.8
Terra Ceia	0–80	4.5–8.4
Vizcaya	0–15	6.6–7.8

[z]Soil reaction at soil: water=1:1 (*Source:* USDA 1996)

Table 2. Palm Beach County soil pH[z]

Soil name	Depth (inches)	Soil pH
Anclote	0–17	5.6–6.1
Basinger	0–14	5.7–5.9
Beaches	0–60	7.4–9.0
Boca	0–12	5.9–6.2
Chobee	0–26	3.6–7.3
Dania	0–10	6.2–6.3
Hallandale	0–15	5.7
Holopaw	0–14	5.5–6.1
Immokalee	0–11	5.8–6.9
Jupiter	0–11	6.6
Lauderhill	0–18	6.2–6.3
Myakka	0–7	5.0–5.3
Okeelanta	0–8	5.4
Oldsmar	0–8	5.0
Pahokee	0–10	6.1
Palm Beach	0–6	7.9
Paola	0–21	4.9–6.2
Pineda	0–14	5.7–5.9
Placid	0–10	4.6
Pomello	0–16	4.9–5.7
Pompano	0–8	4.4
Riviera	0–28	6.0–6.6
Sanibel	0–20	6.3–6.4
St. Lucie	0–20	4.6–5.9
Tequesta	0–13	6.8
Terra Ceia	0–8	5.7
Torry	0–30	6.4
Wabasso	0–22	3.8–4.2
Winder	0–16	6.3–7.3

[z]Soil reaction at soil: water=1:1 (*Source*: USDA 1976)

Table 3. St. Johns County soil pH[z]

Soil name	Depth (inches)	Soil pH
Adamsville	0–19	5.2–5.3
Astatula	0–14	5.8
Bluff sandy	0–13	6.1–7.6
Cassia	0–18	4.6–5.1
Durbin muck	0–25	4.0–4.6
EauGallie	0–17	4.5–4.9
Ellzey	0–19	6.2–6.3
Fripp	0–9	4.7–5.4
Holopaw	0–13	5.1–5.4
Hontoon muck	0–16	3.3–3.5
Immolalee	0–15	4.0–4.6
Jonathan	0–9	5.2–5.3
Manatee	0–13	5.3–6.3
Moultrie	0–22	6.3–7.6
Myakka	0–14	3.6–4.6
Marcoossee	0–12	4.0–6.3
Orsino	0–18	3.9–4.8
Palm Beach	0–28	7.7–8.2
Paola	0–32	4.4–5.0
Parkwood	0–18	6.8–8.0
Pellicer	0–55	3.4
Placid	0–26	5.4–6.2
Pomello	0–19	4.7–4.9
Pompano	0–28	5.6–6.6
Pottsburg	0–20	4.4–5.0
Riviera	0–23	5.4–6.0
Satellite	0–33	5.6–6.1
Smyrna	0–18	4.7–5.4
Sparr	0–20	4.7–5.4
St. Augustine	0–10	7.4–8.5
St. Johns	0–15	3.6–4.2
Tavares	0–32	4.2–5.4
Tocoi	0–23	5.0–5.1
Tomoka muck	0–21	3.3–3.5
Zolfo	0–19	5.9–6.2

[z]Soil reaction at soil:water=1:1 (*Source*: USDA 1983)

Table 4. Jackson County soil pH[z]

Soil name	Depth (inches)	Soil pH
Albany	0–46	5.2–6.1
Apalachee	0–46	5.1–5.2
Blanton	0–41	5.3–5.4
Chipola	0–35	5.3–5.6
Clarendon	0–52	4.0–5.7
Compass	0–40	4.7–5.1
Dothan	0–34	4.6–5.6
Duplin	0–46	4.9–6.0
Esto	0–43	4.8–5.4
Faseville	0–46	4.9–5.5
Fuquay	0–32	5.3–5.7
Greenville	0–52	4.3–5.4
Hornsville	0–43	5.2–5.6
Lakeland	0–40	5.0–5.8
Leefield	0–43	4.7–5.8
Orangeburg	0–48	4.5–6.1
Pamlico	0–36	3.4–4.4
Red Bay	0–49	5.5–5.9
Troup	0–47	5.4–5.9
Yonges	0–72	5.1–8-4

[z]Soil reaction at soil:water=1:1 (*Source*: USDA 1979)

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SS-AGR-153

Liming of Agronomic Crops[1]

D. L. Wright, C. Mackowiak, and E. B. Whitty[2]

The primary reason for liming acid soil is to improve the yield or quality of the crop being grown. It is difficult to determine the precise factor that is responsible for the improved growth after liming because a number of soil parameters change simultaneously as soil acidity is reduced.

When mineral soil pH is below 5.5, aluminum toxicity can reduce plant growth. Organic soils contain little Al, thus plants can tolerate much lower pH levels on those soils without adverse effects. Many Florida soils are low in magnesium (Mg) and calcium (Ca), and application of dolomitic limestone serves two purposes: (1) it raises the soil pH and (2) it provides Mg and Ca as nutrients and makes other nutrients such as phosphorous (P) more available.

On the other hand, excessive liming can be detrimental. Many Florida soils are quite low in manganese (Mn), and deficiencies of Mn and other micronutrients can occur in soils that are over-limed. The problems begin to appear any time soil pH is raised above 6.3 or so, depending on the level of Mn present and the crop being grown.

Some physiological disorders of plants, such as frenching of tobacco, are associated with high levels of lime. Certain plant diseases, such as black shank of tobacco, are more virulent as the soil pH increases above pH 5.8. Peanuts have a high requirement for Mn and may show yellowing of leaf tissue with high pH, although high levels of Ca are required for peanut seed development. If Ca is low in peanut fields but the pH is at the desired level, materials such as gypsum can be used to supply Ca without raising pH.

It has been noted in many Florida fields that are routinely irrigated from deep wells that the soil pH may not decline over time and may actually increase in some instances. Irrigation water drawn from limestone aquifers contains low levels of dissolved calcium carbonate, and this added lime accumulates over time and affects soil pH variation. Use of soil samples as described below can indicate if irrigation water contributes to the soil pH. Also, the need for lime can be affected by the source and amount of fertilizer applied. Again, a soil test can help reveal the practical effects on soil pH and the need for lime.

In order to obtain the maximum benefits from liming, it is necessary to plan a liming program. Soil and plant factors must be taken into account in determining the type and quantity of lime to apply.

The first step is to take a soil sample that is representative of the field and have it tested by a laboratory that runs a lime requirement test. Since interpretation of soil test results are dependent on the test used and the field correlations of the test, no interpretation will be made here.

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Refer to SL-129 *UF/IFAS Standardized Fertilization Recommendations for Agronomic Crops* (http://edis.ifas.ufl.edu/ss163) for the target pH for agronomic crops.

The decision of whether to use dolomitic or calcitic ("hi cal") lime should be based primarily on the cost of the material to the producer. However, calcitic lime will increase pH faster than dolomitic limestone. When both lime and Mg are needed, dolomite can serve as the liming material of choice. However, if the cost of dolomite is significantly higher than calcite, the producer should consider the alternative of applying calcite as the liming material and Mg in the fertilizer. Application of dolomite as a source of Mg without regard to the liming effect can lead to other nutritional problems in soils with pH above 6.3.

Producers frequently have access to by-product materials that can serve very well for liming agricultural land if the nature of the material is understood and proper precautions are followed. Lime from municipal water treatment plants is an example. Some suggestions follow about the handling and use of lime from water treatment plants:

1. Lime usually has the consistency of a thick paste from water treatment plants. Pile and allow to dry before attempting to spread.

2. Turn with a front-end loader to promote drying. Spread before completely dry and on a calm day to minimize dust drift.

3. Use about 80% as much material as you would agricultural limestone. It will react quickly due to its fineness and thus carry more potential for overliming if not properly used.

4. It is often more difficult to spread since liming soil was not the primary purpose for the material.

Materials sold as aglime are covered by the Florida Commercial Fertilizer Law and must meet specifications of fineness of grind, carbonate equivalance, and Mg content (in the case of dolomite). This affords some consumer protection. Lime by-products are not covered by the law, and the consumer must realize more personal responsibility when dealing with such products. Liming is one of the most important soil fertility practice on strongly acid mineral soils. However, many field crops in Florida produce just as well on moderately acid soils as they do on only slightly acid soils.

Lowering Soil pH

Soil pH is sometimes too high for optimum growth and yield of particular plant species. Most plant species are tolerant to a wide range of soil pH. Do not attempt to lower soil pH unless there is evidence that plant growth is being adversely affected by pH.

If the source of the high pH is naturally occurring carbonates (ex. the rockland soils of Dade County or soil containing limestone outcroppings), it is impractical to lower the soil pH on a field-wide basis. In those situations, application of elemental sulfur (or ammonium sulfate, if N is needed) and micronutrients together in a band is recommended. The micronutrients will remain soluble in the acid band, and adverse effects of high pH may be avoided.

If the soil pH is too high as a result of excessive liming, take note, and pH will gradually become more acid with time. Time is the best cure for over-limed soil in Florida. When high pH has resulted in Mn deficiency on peanuts, ammonium sulfate is effective in lowering the pH enough to make Mn adequate for normal plant growth.

When a more rapid lowering of soil pH is desired, elemental sulfur broadcast and worked into the soil will hasten acidification. **Caution**: Sulfate forms of sulfur <u>will not</u> lower pH. Elemental sulfur (ex. ag grade sulfur, wettable sulfur, flowers of sulfur) is acted upon by soil microorganisms and sulfuric acid is produced. It is the acid, not the sulfate, that neutralizes the excess carbonate in the soil. The effect on soil pH will probably be slow because of microbial action.

Drip Irrigation: The BMP Era—An Integrated Approach to Water and Fertilizer Management for Vegetables Grown with Plasticulture[1]

Eric Simonne, David Studstill, Bob Hochmuth, Teresa Olczyk, Michael Dukes, Rafael Munoz-Carpena, and Yuncong Li[2]

In Florida, plasticulture is currently used on approximately 60,000 acres of vegetable (mainly tomato, bell pepper, eggplant, strawberry and watermelon). The Florida drip irrigation school is a one-day educational program offered by the Institute of Food and Agricultural Sciences at the University of Florida focusing on drip irrigation. Through talks, hands-on demonstrations and discussions, the goal of this program is to teach and help vegetable growers better manage fertilizer, water and fumigant applications through drip systems and to prepare them for the BMP era. This program involves county and state-wide Extension faculty and researchers, and members of the irrigation and fertilization industries.

Additional Florida Drip Irrigation Schools are being scheduled regularly thoughout Florida. These programs are offered at no charge, but require pre-registration. Contact your local Extension office to find out when the next drip irrigation school will be offered in your area or check announcements in the Vegetarian newsletter at http://www.hos.ufl.edu/newsletter/vegetarian.htm

This article presents a summary of the information discussed on fertilizer management, irrigation scheduling, and drip system maintenance and troubleshooting. A list of additional references is also included.

Total Maximum Daily Loads (TMDL) and Best Management Practices (BMP): The Basics

As the development of TMDLs and BMPs for vegetables grown in Florida takes place, growers are eager to find out how this process will affect their operations. TMDLs and BMPs have their origin in Federal and State legislations (Table 1). A TMDL is the maximum amount of a pollutant a water body can receive and still meet its water quality standards. BMPs are specific cultural practices that aim at reducing the load of a specific compound, while maintaining economical yields (Table 2). Growers will benefit three ways from having a documented BMP plan. They will be offered (1) a waiver of liability from reimbursement of costs or damages associated with the evaluation, assessment, or remediation of nitrate contamination of ground water (F.S. 376.307); (2) a presumption of compliance with state water quality standards [F.S. 403.067 (7)(d)]; and, (3) an

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oportunity to receive cost-share reimbursement for implementation of selected BMPs [F.S. 570.085(1)].

The BMPs applicable to vegetable production will be included in the Agronomic and Vegetable Crop Water Quality and Water Quantity BMP Manual for Florida for row crops and vegetables, which is under development. BMPs are 1-to-3 page long chapters that include a working definition of the topic, list specific things to do (BMPs) as well as things to avoid (pitfalls), and present existing applicable technical criteria together with additional references. As the new legislative mandate for Florida agriculture, the BMPs largely embrace UF/IFAS fertilization and irrigation recommendations.

Principles of Fertilization Management in the BMP Era

Fertilization principle 1. With plasticulture, think in terms of rows Y and not in terms of field surface for irrigation and fertilization. For bare ground production of vegetables, fertilizer and irrigation rates are typically expressed in lbs/acre and gallons/acre, respectively. However, when vegetables are grown with plasticulture, the number of linear feet of beds in an acre becomes more important than the actual surface of the field. Growers should think in terms of lbs/100 linear bed feet (LBF) for fertilization injections and gallons/100 lbf for irrigation, and take into account the bed spacing. Typical bed spacings are used in the UF/IFAS fertilization recommendations for plasticulture (Table 3).

Fertilization principle 2. Plants need all the essential nutrients. Sixteen essential mineral elements are recognized as the essential elements. Carbon (C), hydrogen (H), and oxygen (O) are supplied by air and water. Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) are the macronutrients. Boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn) are the micronutrients. All these elements are essential because (1) vegetable crops cannot complete their life cycle without all of them, (2) typical deficiency symptoms appear when one is not available, and symptoms disappear upon the application of the deficient element, and (3) each element has a specific metabolic role. The overall success of a fertilizer program is determined by the essential element which is provided in smallest quantity (limiting factor). Adequate fertilization together with soil nutrient reserves should provide all these elements in adequate quantities, thereby ensuring that mineral nutrition is not limiting vegetable growth and yield.

Fertilization principle 3. Soil test and follow the recommendation. The only scientific method to apply fertilizer to vegetables is to use a calibrated soil test. A soil sample has to be recent, representative, and large enough to ensure valid results. The soil test recommendation has to be understood, and properly implemented. Typically, 20% to 50% of N and K_2O, and 100% of P_2O_5 and micronutrients are applied preplant. The remaining 50% to 80% of N and K_2O are injected through the drip system. A fertilizer program may be simply designed from UF/IFAS recommendation using a spreadsheet format (Fig. 1). Correctly implementing soil test results is essential in increasing nutrient management to a level acceptable in the BMP era (Table 4).

	Fertilizer rate (lbs/acre)			
	Nitrogen (N)	Phosphorus (P_2O_5)	Potassium (K_2O)	
Total IFAS recommendation [1] (based on soil test results)	150	0	150	
Preplant fertilizer (15% of total N) (example: 13-4-13 @173lbs/acre)	22	7	22	
Injected fertilizer (85% of total N) (example: liquid 8-0-8 @ 0.8 lb N/gal)	128	0	128	
Week [2]	Weekly recommended rate [1]			8-0-8 injected weekly (gal/acre)
	Nitrogen (N)	Phosphorus (P_2O_5)	Potassium (K_2O)	
1	7 [3]	0	7	0 [4]
2	7 [3]	0	7	0 [4]
3	10.5	0	10.5	13
4	10.5	0	10.5	13
5	17.5	0	17.5	22
6	17.5	0	17.5	22
7	17.5	0	17.5	22
8	17.5	0	17.5	22
9	10.5	0	10.5	13
10	10.5	0	10.5	13
11	10.5	0	10.5	13
12	7	0	7	9
13	7 (1)	0	7 (1)	0 [5]

[1] Recommendations from the Florida Vegetable Production Guide; assumes that beds are on 8-ft centers; weekly rates are calculated as 7 x daily rates
[2] Growing season is 13 weeks for a typical watermelon crop when transplants are used
[3] When no fertilizer is applied preplant
[4] Injections the first two weeks may be omitted with a preplant application
[5] Fertigation may be omitted the week before harvest; irrigation should continue that week

Figure 1. Sample spreadsheet for designing a fertigation program for a 1-acre watermelon field planted on 8-ft centers. Beginning with soil-test results (top section), this worksheet that uses UF/IFAS recommendations provides a weekly schedule for fertigation with liquid 8-0-8 (right column).

Some growers do not believe that economical vegetable yields can be produced with UF/IFAS fertilizer recommendations. Fertilizer recommendations are based on multiple trials and correspond to the fertilizer rates above which no yield response is likely to occur. UF/IFAS fertilizer rate may not be optimal if excessive irrigation is applied. In this case, the solution is to adjust irrigation management, rather than increasing fertilizer rates. Fertilizer applications in excess of the recommended rate should not be made on a routine basis, but only when exceptional circumstances (leaching rain) occur or based on the results of petiole sap test and/or foliar nutrient analyses. UF/IFAS definition of a leaching rain is 3 in. of rain in 3 days or 4 in. of rain in 7 days.

Fertilization principle 4. Monitor crop nutritional status and discover how healthy the vegetable plants are. The nutritional status of vegetables may be monitored with sap test or foliar analysis early in the season (from transplanting to fruit set). A representative sample for petiole and leaf analysis should be made with at least 20 leaves selected randomly throughout the field from most recently, fully mature leaves. For sap analysis, blades should be carefully separated from the petiole and discarded. Fig. 2 shows how to collect sap and perform a reading. For leaf analysis, the sampled part should be the blade and its petiole attached.

Figure 2. Sap testing for vegetables involves separating the petiole from the leaf blade, (2.1) calibrating the nitrate (NO3-N) and potassium (K) ion specific electrodes (Cardi meter shown here) with standard solutions, (2.2) extracting the sap, (2.3) collecting the sap from the press, and (2.4) placing a droplet of sap on the electrode. A hydraulic press may be needed only when few petioles are available or when petioles contain little sap as may occur with strawberry. In most cases, a garlic press will be an adequate tool to extract the sap. Readings should be compared to published sufficiency ranges.

Principles of Irrigation Scheduling in the BMP Era

Irrigation scheduling is knowing when to start irrigation and how much to apply, in a way that satisfies crop water needs, conserves water, and does not leach mobile nutrients. Irrigation scheduling requires (1) a target water volume, (2) guidelines on how and when to split irrigation, (3) a method to account for rainfall, and (4) a practical method to monitor soil moisture.

Irrigation principle 1. Irrigation amount must reflect crop water use, no more, no less. Irrigation amounts may be estimated using historical weather data, climatic measurement in real-time, class A pan evaporation, atmometers, and empirical amounts (Table 5, Fig. 3). Empirical values have the advantage of being simple. However, they often result in excessive irrigation early in the season, and insufficient ones later in the season. This method alone (without monitoring of soil moisture) is unlikely to be part of the BMPs.

Figure 3. Tools and techniques available to estimate evapotranspiration and irrigation needs: (3.1) weather data may be simply downloaded from a small automated weather station to calculate reference evapotranspiration (ETo) and (3.2) water loss in the reservoir of the atmometer mimics ETo.

Irrigation principle 2. Irrigation amount should not exceed soil water holding capacity. Otherwise, water is wasted and mobile nutrients are leached. How far water moves down the soil profile is a rather abstract concept because it is not visible. However, it is possible to visualize soil water movements by using colored dyes (Fig. 4). Wetting patterns are affected by soil type, irrigation amount, and emitter spacing (Table 6). In the sandy soils of Hillsborough and Hendry counties, the wetting front reached maximum rooting depths at irrigation rates nearing 80 gallons/100ft.

Theoretical highest irrigation amounts can be simply calculated based on the soil physical properties. For a soil where the wetting width is 12 inches (6 inches each side of the drip tape), assuming a 0.75 in/foot soil water holding capacity and allowing a 50% soil water depletion, the theoretical largest water amounts that can be stored in the soil are 24 gal/100 ft within the top 12 inches, 36 gal/100 ft within the top 18 inches, and 48 gal/100 ft within the top 24 inches. These numbers can be used as guidelines. Actual amount that can be applied in one irrigation also depends on the rate of crop evapotranspiration, number of drip tapes, and soil type. The difference between observed (Table 6) and theoretical maximum water holding capacity may be due to bed compaction and wetting widths greater than 12 in. Irrigation greater than the maximum water holding capacity is likely to leach mobile nutrients below the root zone. This is why irrigation, fertilization, BMPs and TMDLs are tied together.

Figure 4. Soluble blue dye may be used to visualize wetting patterns and understand how irrigation volume affects water movement in the bed. For short irrigation times (1 hour) a more even water distribution pattern may be expected with a 4-in emitter spacing (4.1) than with an 12-in emitter spacing (4.2). Flow rates were 33 gal/100 ft/hr for the 4-in emitter spacing, and 30 gal/100ft/hr for the 12-in emitter spacing. The presence of an impermeable clay layer at the 10-in depth (in Gadsden county) resulted in lateral movement as shown in (4.3) where the blue dye is in the alley (between the 3rd and 4th bed from the right) after 6 hours of irrigation delivering 180 gal/100ft. The presence of water and soluble nutrients in the row middles will likely promote weed growth. Wetting patterns in the very compacted beds used for strawberry production in Hillsborough county are rectangular which corresponds to an increase in lateral water movement as shown in (4.4) after a 6-hr irrigation that delivered 144 gal/100 ft with a 12-in emitter spacing.

Irrigation principle 3. Rainfall contributes little to replenish soil moisture because of the plastic mulch. Several UF/IFAS fertilizer recommendations for bare ground production allow for additional N and K fertilizer after leaching rains. Leaching rains are defined as three inches of rain in three days, or four inches in seven days**. However, it would take less rain to leach through the soil profile in the coarse soils found in South Florida**. Since the plastic mulch protects the bed from rainfall, there is no need to apply additional fertilizer after a leaching rain. However, when the field gets flooded, mobile nutrients may be leached out of the root zone or carried out of the field through surface run off. The need for additional fertilizer may be assessed after field drainage by monitoring sap tests levels of nitrate and potassium. Another consequence of using the plastic mulch is that an irrigation may be still needed after a small rain. Soil moisture measurements may be used to assess the need for additional irrigation.

Irrigation principle 4. Monitor soil moisture level daily to discover how much water stress the crop is exposed to. Soil moisture may be reported in terms of soil water tension (SWT) or volumetric water content (VWC). SWT represents the suction force that is necessary to free soil water from the soil attraction. The higher the value of SWT, the greater is the force needed. In some publications, SWT values are reported as negative values. The negative (-) sign is there to reflect the fact that the attraction is generated by the soil particles and therefore the plant has to spend energy to absorb water. SWT may be expressed in atmospheres (atm), bar (b), or kilo Pascals (kPa; the international unit). The conversion between units is 1 atm = 1.013 b = 101.3 cb = 100 kPa. The recommended range for vegetable production is to maintain SWT between 6 to 8 cb (field capacity) and 15 cb. Vegetables may tolerate SWT up to 25 cb without yield reduction on loamy soils. However, sandy soils with SWT above 15 cb may be difficult to re-wet. On the other hand, VWC represents the volume of water present in a volume of soil. VWC for sandy soils range between 14% and 18%, whereas it may reach 38% in clay soils. Instruments available for routine monitoring of soil moisture for vegetable crops are tensiometers, time domain reflectometry probes (TDR), and dielectric probes (Fig. 5). Table 7 summarizes a comparison of these instruments in terms of cost, accuracy, response time, preparation, installation, management, and durability.

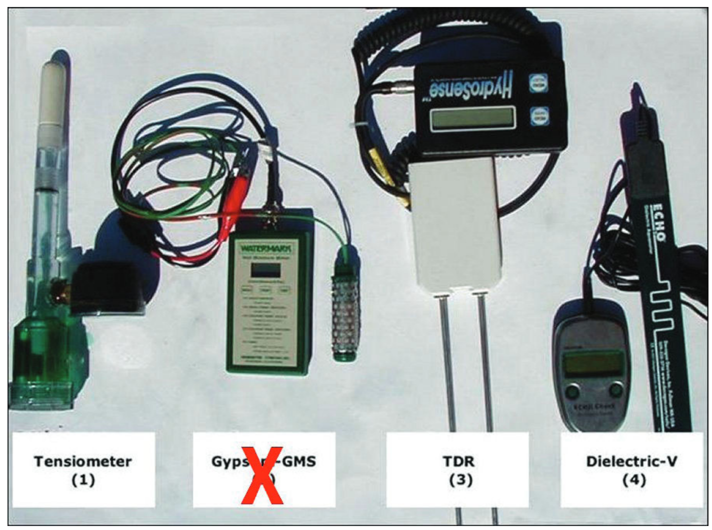

Figure 5. Soil moisture measuring tools currently available for vegetable crops.

Irrigation principle 5. Keep irrigation records daily. Vegetable growers are required to keep pesticide records. Fertilization records are usually kept in relation to soil testing and implementing the recommendations. However, vegetable growers seldom document their irrigation practices. For example, a daily log could contain soil moisture measurements (SWT or VWC) at selected depths, rainfall, an estimate of weather demand for water (evapotranspiration), and irrigation amount (gallons/field or duration of irrigation). Most growers who are already keeping irrigation records find them to be a useful management tool. It is likely that the documentation requested to support a BMP plan will include irrigation records, at the farm level and possibly at the field level.

Drip System Maintenance and Troubleshooting

Application uniformity of 85% to 95% is expected from a new, well-designed drip irrigation system (Fig. 6). As the irrigation system is used for water and fertilizer applications throughout the growing season, the application uniformity may remain the same if the system is well managed, but will most likely decline with time. A comprehensive maintenance plan will reduce the adverse effects of the agents that reduce application uniformity: small solids in suspension, organic matter, micro-organisms, and chemical residues on application uniformity (Fig. 7). Without a maintenance plan, the risk of complete emitter clogging and crop loss becomes real.

Figure 6. Uniform growth and yield may be expected with drip irrigation (7.1) as shown here with strawberry. When the drip tape is not placed in the center, one row may be taller than the other (7.2) as shown here with bell pepper.

Figure 7. Accumulation of precipitates around a drip-tape emitter (8.1) may result in an uneven water distribution pattern (8.2).

Every vegetable grower who uses drip irrigation should recognize that PREVENTION IS THE BEST MEDICINE in drip system maintenance. A maintenance plan should include (1) a filtration system, (2) chlorination and acidification, (3) flushing, and (4) regular observation of irrigation system components (Table 8 and Table 9).

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Table 1. A brief legislative history of the Best Management Practices (BMP).

Year	Origin	Legislation	Public law #
1948	US Congress	Water Pollution Control Act (WPCA)	89-234
1965	US Congress	Amendment to the WPCA created fed. approved water quality standards for interstate waters. Name changed to Water Quality Act	89-234
1972	US Congress	Amendment 303(d) to WQA introduced Total Maximum Daily Loads (TMDL). Name changed to Federal Water Pollution Control Act (FWPCA)	92-500
1977	US Congress	FWPCA amended to introduce BMP development and renamed Clean Water Act	95-217
1987	US Congress	Amendments 304(1) and 319 introduced the development of numerical rather than qualitative water quality criteria. New name: Water Quality Act	100-4
1987	Florida Legislature	The Florida Surface Water Improvement and Management (SWIM) ACT created a program which focuses on preservation of the state's water bodies that were in good condition, and restoration of some of its most significant water bodies.	373.451 - 373.4595

Table 2. Driving forces behind the vegetable BMPs.

BMPs are meant to be	Comments
Educational	Through teaching and demonstration, the BMP process aims at raising the level of nutrient and irrigation management of growers.
Economically sound	BMP implementation is not aimed at reducing production or crop value.
Environmentally robust	BMPs are tools to achieve the TMDLs and therefore reduce nutrient discharge.
Based on science	Only science-based information will separate the facts from the perceptions.

Table 3. Typical bed spacing used in vegetables production and corresponding linear bed feet per acre. This spacing is used for fertilizer recommendations. When a different bed spacing is used, fertigation should be adjusted accordingly.

Bed Spacing	Vegetable Crop	Linear Bed Feet in One Acre
4	Strawberry, lettuce	10,890
5	Muskmelon	8,712
6	Bell pepper, tomato, eggplant, cucumber, summer squash, cabbage, broccoli, cauliflower	7,260
8	Watermelon	5,445
Linear bed feet per acre are calculated by dividing 43,560 sq-ft per acre by the bed spacing.		

Table 4. Levels of fertilizer and water management and corresponding fertilization and irrigation practices for vegetables.

Management Level	Nutrient Management	Irrigation Management
0 - None	Guessing	Guessing
1 - Very low	Soil testing and still guessing	Using the "feel and see" method
2 - Low	Soil testing and implementing 'a' recommendation (not sure about how to correctly implement UF/IFAS recommendations)	Using systematic irrigation for the entire growing season based on irrigation time (for example, three hours per day) and not water volume applied
3 - Intermediate	Soil testing, understanding UF/IFAS recommendations, and correctly implementing them	Using a soil moisture measuring tool to start irrigation
4 - Advanced	Soil testing, understanding UF/IFAS recommendations, correctly implementing them, and monitoring crop nutritional status	Using a soil moisture measuring tool to schedule irrigation and apply amounts based on a budgeting procedure
5 - Recommended	Soil testing, understanding UF/IFAS recommendations, correctly implementing them, monitoring crop nutritional status, and practice year-round nutrient management and/or following BMPs	Adjusting irrigation to plant water use, and using a dynamic water balance based on a budgeting procedure and plant stage of growth, together with a soil moisture measuring tool and/or following BMPs

Table 5. Comparison of methods available for determining crop water use and their adoption level by the vegetable industry in Florida. Although the most promising method uses real-time potential evapotranspiration data, empirical methods are most commonly used by the industry.

Method	Principle	Advantages	Limitation	Level of Adoption by Industry
Historical potential evapotranspiration	Weather data from the past 30+ years are averaged to estimate ETo	IFAS recommended method Crop water use (ETc) simply calculated as ETc=Kc x ETo, where Kc is the crop coefficient	Year to year variability may be +/- 20% of the historical average Most Kc values available are for bare-ground production	None
Real time potential evapotranspiration	ETo is computed daily using site-specific, current weather data	Data more available as the FAWN system expands Increasingly attractive as the cost of small, on-farm weather stations keeps decreasing Crop water use (ETc) simply calculated as ETc = Kc x ETo, where Kc is the crop coefficient. Variable Kc allows daily irrigation adjustment depending on crop age and weather demand. Likely to be part of BMPs	Most Kc values available are for bare-ground production	Currently limited, but with real potential
Class A pan evaporation (Ep)	ETo is related to water loss from a free water surface	Crop water use (ETc) simply calculated as ETc = CF x Ep, where CF is the crop factor. For practical purposes, CF and Kc can be inter-converted Principle can be used with pans other the expensive class A pan Variable Kc allows daily irrigation adjustment depending on crop age and weather demand Possible alternative BMP method	Most CF values available are for bare-ground production Old method that was not adopted widely	Virtually unused; should be replaced by the method above
Atmometers	Water loss from a ceramic plate with a canvas cover mimics ETo	Simple principle: water loss from a small surface closely estimates ETo Units are rather inexpensive	Calibration data usually not available	None
Empirical methods	Rely on experience and individual knowledge to estimate irrigation needs	Simple to implement Most farmers' favorite	Based on experience, rather than science Typically results in over-irrigation early in the season, and sometimes under-irrigation during peak demand periods Likely to be insufficient in the BMP era	Industry standard

Table 6. Effect of irrigation amount on water movement in three vegetable growing areas of Florida. Increasing irrigation volume increases vertical downward movement at a faster rate than the lateral movement. Emitter-to-emitter coverage (length) was reached after 3 hours with 12-in emitter spacings, while it was reached in only one hour with 4-in emitter spacing.

Irrigation volume (gph/100 ft)	Irrigation Time (hr)	Vertical depth (in)	Width (in)	Length (in)	Vertical depth (%)	Width (%)	Length (%)
Hillsborough County - 12-in emitter spacing drip tape (27 gal/100ft/hr)							
27	1	9	11	10	66	25	83
54	2	12	15	11.5	73	38	92
81	3	14	16	11	97	43	100
108	4	13	17	11	97	51	100
162	6	17	20	12	110	54	100
216	8	17	22	12	110	64	100
Hendry County - 18-in emitter spacing drip tape (24 gal/100ft/hr)							
12	0.5	7	6	6	50	17	33
24	1	9	7	7	61	19	39
36	1.5	10	9	8	68	23	43
48	2	10	9	8	68	24	46
72	3	12	10	11	80	26	59
96	4	17	9	14	115	25	80
144	6	15	10	10	102	28	80
192	8	13	10	9	100	28	80
Gadsden County - 4-in emitter spacing drip tape (33 gal/100ft/hr)							
33	1	6	8	4	60	22	100
66	2	8	12	4	80	33	100
132	4	7	20	4	70	56	100
198	6	8	23	4	80	64	100

Vertical depth (V) = vertical length from the top of the bed to the bottom of the blue ring; Vmax = 15 in, except in Gadsen co. where a clay layer was found at the 10-in depth). Width = Hortizontal length perpendicular to the bed axis at the widest point of the wetting bulb; Wmax = bed width = 36 in at all three locations. Length = Horizontal length parallel to the bed axis at the widest point of the wetting bulb; Lmax = emitter spacing.

Table 7. Comparison of soil moisture measuring devices available to vegetable growers. While cost of the unit is always an issue, adoption of these techniques has been mainly determined by maintenance, reliability and dedication issues.

Point of comparison	Tensiometer	Granular Matrix Sensor (GMS)	Dielectric probe	Time Domain Reflectometry (TDR) probe
Principle of operation	Direct measurement of soil suction: changes in moisture in a porous cup in equilibrium with the soil can be expressed as changes in air pressure inside the cup	Indirect measurement of soil suction: in saturated saline condition, electrical conductivity is a function of soil moisture tension	Indirect measurement of water content: the soil dielectric constant depends on soil moisture and can be measured as an electrical signal (in volts)	Indirect measurement of water content: the soil dielectric constant depends on soil moisture and can be measured as an the speed of travel of wave signal (in seconds)
Unit reported to user	Soil water tension (cb or kPa)	Soil water tension (cb or kPa)	Volumetric water content (%)	Volumetric water content (%)
Cost for a complete operating unit	$70-110	$400-480 ($40 for 2 GMS blocks, $400 for reader)	$525 ($150 for sensor, $375 for reader)	$585 ($260 for sensor, $325 for reader)
Life span	Several years	Few years for sensors, many years for reader	Many years	Many years
Fragility and risk of damage	Very high	Low to very low	Low	Very low
Set-up	Involved	Minor	Minimal	Minimal
Maintenance	High, very important	None	None	None
Time needed for equilibrium with soil (first reading)	Few hours	Few hours	Instantaneous	Instantaneous
Change in moisture reading in response to change in soil moisture	Fast	Fast for fine textured or well compacted soils, but slow for coarse-textured soils	Immediate	Immediate
Need for calibration	No (only adjustment)	Yes	Yes	No (yes)

Table 8. Components of the maintenance-is-best-medicine program for drip irrigation.

Component	Description and Comments	Few Do's and No-no's!
Filtration	Use 200-mesh filter or equivalent when ground water is used Consider media filters when surface water is used. Angular sand particles should be used. Centrifugal sand separators may be used where inorganic particle levels greater than 50 ppm are present	Do not remove or by-pass filters when they are clogged. Clean filter regularly
Chlorination	Hypochlorus acid (HOCl) is the chemical that controls bacterial growth HOCl may react with iron and create a precipitate [Fe(OH)3] More Cl is in the active HOCl form at lower pH: 90% at pH = 6.5 50% at pH = 7.5 20% at pH = 8.0 Inject enough chlorine to detect 1 ppm Cl at the end of the line See references on detailed chlorination procedure	Do not place chlorination point after filter. Instead, place it before, so that precipitates may be filtered out Do not skip chlorination When well done, chlorination will not damage the crop Do handle chlorination products with care
Acidification	Sulfuric (H2SO4), hydrochloric (HCl) and phosphoric (H3PO4) acid are the acids most commonly used. Do run a trial-test in a 55-gal drum to determine the amount of acid needed	Do not ignore the risks of cross precipitation with calcium (Ca) when H2SO4 or H3PO4 are used Do handle acids with care
Flushing	Water velocity and pressure may be increased to 1 foot/sec at the end of laterals and pressure may be increased from 8-10 psi to 12 to 15 psi for flushing Self-flushing valves allow for flushing at every irrigation, although usually these valves do not provide flushing long enough and not at the 1 ft/sec rate Consider flushing every 2 to 3 weeks	After system is installed, allow for thorough flushing as soil materials are likely to be introduced in the system; then tie the ends Do not use self-flushing valves in situations where the system pressure is too low; they may never close
Observation	Regularly look for leaks and system malfunctions Measure water volume delivered, water travel time, and pressure changes regularly Observe crop growth pattern	Do not assume that everything is working properly! Be on the lookout Keep record of benchmark operating values

Table 9. Observation component of the prevention-is-best-medicine maintenance program: possible drip irrigation system checks and frequency during the growing season.

What to check?	How often?	Compared to what?	What to look for?	Possible Causes
Pump flow rate and pressure, for each irrigation zone	Weekly	Design, benchmark flow rate and pressure, or water travel time (using dye)	High flow and/or low pressure Low flow and/or high pressure No flow, no pressure	Leaks in pipelines or laterals Flush valves remain open Open end of laterals Closed zone valves Pipeline obstruction Tape clogging Pump malfunction Well problems Broken well shaft Drop in water level
Pressure difference across filter	At each irrigation	Manufacturer specifications	Exceeds or is close to maximum allowable pressure difference	Filter becoming clogged Obstruction in filter Sudden change in water quality
Operating pressures at ends of laterals	Monthly, unless other checks indicate possible clogging	Benchmark pressures	High end pressure Low end pressure	Possible clogging High system pressure Obstruction in tape Broken lateral Leaks in laterals Low system pressure
Water at lateral ends and flush valves	Bi-weekly	Water source	Particles in water Other debris	Broken pipeline Missing filter screen Hole in filter screen Tear in filter mesh Particles smaller then screen Filter problem Chemical/fertilizer precipitation Algae growth Bacterial growth
Overall pump station	Weekly	Manufacturer's specification and values at startup	Leaks, breaks, engine reservoir levels, tank levels	Mostly mechanical
Injection pump settings	Weekly	Calibrating setting at startup	Reduced injection rate	Injector clogged with debris (check filter) Precipitates in the fertilizer (check fertilizer compatibility) Precipitation between high- calcium water and phosphates or sulfates in fertilizer

What to check?	How often?	Compared to what?	What to look for?	Possible Causes
Overall system	Weekly	System at startup	Discoloration at outlets or ends of laterals Leaks in tape Wilting crop	Indicates possible build up of minerals, fertilizer, algae, and/or bacterial slime Pest or mechanical damage Tape off fittings Tape blow out from high pressure Insufficient irrigation and/or high crop transpiration rate Tape clogged, obstructed or broken Root disease (bacterial and/or fungal soil born diseases, nematodes)

UF IFAS Extension UNIVERSITY of FLORIDA

AE260

Principles and Practices of Irrigation Management for Vegetables[1]

M. D. Dukes, L. Zotarelli, G. D. Liu, and E. H. Simonne[2]

This section contains basic information on vegetable water use and irrigation management, along with some references on irrigation systems. Proper water management planning must consider all uses of water, from the source of irrigation water to plant water use. Therefore, it is very important to differentiate between crop water requirements and irrigation or production system water requirements. Crop water requirements refer to the actual water needs for evapotranspiration (ET) which are related to soil type and plant growth, and primarily depend on crop development and climatic factors which are closely related to climatic demands. Irrigation requirements are primarily determined by crop water requirements, but also depend on the characteristics of the irrigation system, management practices, and the soil characteristics in the irrigated area.

Best Management Practices (BMP) for Irrigation

BMPs have historically been focused on nutrient management and fertilizer rates. However, as rainfall or irrigation water is the vector of off-site nutrient movement of nitrate in solution and phosphate in sediments as well as other soluble chemicals, proper irrigation management directly affects the efficacy of a BMP plan. The irrigation BMPs in the "Water Quality/Quantity Best Management Practices for Florida Vegetable and Agronomic Crops" (accessible at http://www.floridaagwaterpolicy.com) manual cover all major aspects of irrigation such as irrigation system design, system maintenance, erosion control, and irrigation scheduling.

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Irrigation Water Quality Criteria

Understanding irrigation water quality is critical for sustainability of vegetable production. In some areas of Florida, water quality impacts crop productivity more than soil fertility, pest and weed control, variety, and other factors. Irrigation water quality is determined by the following: (1) salinity hazard: total soluble salt content; (2) sodium hazard: ratio of sodium (Na^+) to calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions; (3) water pH; (4) alkalinity: carbonate and bicarbonate; specific ions: chloride (Cl^-), sulfate (SO_4^{2-}), boron (BO_3^-), and nitrate-nitrogen ($NO_{3-}N$); (5) organic contaminates: oil pollutants; and (6) other factors such as heavy metals. Among these factors, salinity is most significant particularly in those areas close to the coast where salt content in ground water is frequently high. Irrigation water quality can be evaluated based on electrical conductivity (Table 1).

There are two main issues related to salinity: short term, i.e., effect of water electrical conductivity on a particular crop and long term, namely, soil salinization. There is abundant biodiversity in crop tolerance to salinity stresses (Tables 2 and 3). Generally speaking, vegetable crops are more susceptible than cereal crops.

Also, different vegetable species differ significantly in tolerance to salinity stress. For example, tomato is relatively tolerant to salinity stress. At 1 dS m^{-1}, tomato yield increased with N rate but there was no yield response to N fertilization at 5 dS m^{-1}. However, carrot is rated as a sensitive crop. Root yield declines 14% for every unit increase in salinity beyond the threshold of 1 dS m^{-1}. Therefore, irrigation management for vegetable production needs to be more careful. To avoid any accidental economic loss, before irrigating vegetable crops, irrigation water quality should be checked based on electrical conductivity with an appropriate salinity meter at least once a year, particularly in the near coastal areas. Vegetable growers may need to consult their extension agent to interpret the results.

Uses of Irrigation Water

Irrigation systems have several uses in addition to water delivery for crop ET. Water is required for a preseason operational test of the irrigation system to check for leaks and to ensure proper performance of the pump and power plant. Irrigation water is also required for field preparation, crop establishment, crop growth and development, within-season system maintenance, delivery of chemicals, frost protection, and other uses such as dust control.

Field Preparation

Field preparation water is used to provide moisture to the field soil for tillage and bed formation. The water used for field preparation depends on specific field cultural practices, initial soil moisture conditions, the depth to the natural water table, and the type of irrigation system. Drip-irrigated fields on sandy soils often require an additional irrigation system for field preparation because drip tubes are not installed until the beds are formed. Many drip irrigated vegetable fields may also require an overhead or subirrigation system for field preparation. However, sprinkler irrigation systems can meet different water requirements. For example, sprinkler irrigation systems installed in many strawberry production fields can work for both irrigation and frost protection. These systems are also used for field preparation and may apply one or more inches of water for this purpose. Subirrigated fields use the same system for field preparation as well as for crop establishment, plant growth needs, and frost protection. Subirrigation water management requirements depend on the soil characteristics within the irrigated field and surrounding areas. Sufficient water must be provided to raise the water table level as high as 18 to 24 inches below the soil surface. Water is required to fill the pores of the soil and also satisfies evaporation and subsurface runoff requirements. As a rough guide, 1.0 to 2.5 inches of water are required for each foot of water table rise. For example, a field with a pre-irrigation water table 60 inches deep may need about 2 inches of water to raise the water table to 18 inches, while a pre-irrigation water table at 48 inches may require 5 inches of water for the same result.

Crop Establishment

Vegetables that are set as transplants, rather than direct seeded require irrigation for crop establishment in excess of crop ET. Establishment irrigations are used to either keep plant foliage wet by overhead sprinkler irrigation (to avoid desiccation of leaves) or to maintain high soil moisture levels until the root systems increase in size and plants start to actively grow and develop. Establishment irrigation practices vary among crops and irrigation systems. Strawberry plants set as bare-root transplants may require 10 to 14 days of frequent intermittent overhead irrigation for establishment prior to irrigation with the drip system. The amount of water required for crop establishment can range widely depending on crop, irrigation system, and climate demand. Adequate soil moisture is also needed for the uniform establishment of direct-seeded vegetable crops.

Crop Growth and Development

Irrigation requirements necessary to meet the ET needs of a crop depend on the type of crop and growth stage, field soil characteristics, irrigation system type and capacity. Different crops vary in growth characteristics that result in different relative water use rates. Soils differ in texture and hydraulic characteristics such as available water-holding capacity (AWHC) and capillary movement. Because sands generally have very low AWHC values (3% to 6% is common), a 1% change in AWHC affects irrigation practices.

Water Application (Irrigation Requirement)

Irrigation systems are generally rated with respect to application efficiency (Ea), which is the fraction of the water that has been applied by the irrigation system and that is available to the plant for use (Table 4). Applied water that is not available to the plant may have been lost from the crop root zone through evaporation or wind drifts of spray droplets, leaks in the pipe system, surface runoff, subsurface runoff, or deep percolation within the irrigated area. Irrigation requirements (IR) are determined by dividing the desired amount of water to provide to the plant (ETc), by the Ea as a decimal fraction (Eq.[1]). For example, if it is desired to apply 0.5 inches to the crop with a 75% efficient system, then 0.5/0.75 = 0.67 inches would need to be pumped. Hence, when seasonal water needs are assessed, the amount of water needed should be based on the irrigation requirement and all the needs for water, and not only on the crop water requirement. For more information, consult IFAS bulletin 247 "Efficiencies of Florida agricultural irrigation systems" (http://edis.ifas.ufl.edu/ae110) and bulletin 265 "Field evaluation of microirrigation water application uniformity" (http://edis.ifas.ufl.edu/ae094). Catch cans can be used in the field to measure the actual amount of water applied.

Eq. [1] Irrigation requirement =

Crop water requirement / Application efficiency

IR = ETc/Ea

Fertigation/Chemigation

Irrigation systems are often used for delivery of chemicals such as fertilizers, soil fumigants, or insecticides. The crop may require nutrients when irrigation is not required, e.g. after heavy rainfall. Fertilizer injection schedules based on soil tests results are provided in each crop production chapter of this production guide. Fertigation should not begin until the system is pressurized. It is recommended to always end a fertigation/chemigation event with a short flushing cycle with clear water to avoid the accumulation of fertilizer or chemical deposits in the irrigation system, and/or rinse crop foliage. The length of the flushing cycle should be 10 minutes longer than the travel time of the fertilizer from the irrigation point to the farthest point of the system.

System Maintenance

Irrigation systems require periodic maintenance throughout the growing season. These activities may require system operation during rainy periods to ensure that the system is ready when needed. In addition, drip irrigation systems may require periodic maintenance to prevent clogging and system failure. Typically, cleaning agents are injected weekly, but in some instances more frequent injections are needed.

Frost Protection

For some crops, irrigation is used for frost protection during winter growing seasons. For strawberry production, sprinkler irrigation is primarily used with application rates of about 0.25 inches per hour during freeze events. Water freezes at 32°F, while most plant tissues freeze at lower temperatures. Overhead freeze protection is efficient for air temperature as low as 26°F–28°F, but seldom below. For vegetable fields with subirrigation systems, the relatively higher temperature of groundwater can be used for cold protection. Growers may also irrigate to raise the water table throughout the field. Frost protection water requirements vary and depend on the severity and duration of freeze events, the depth to the existing water table level, and field hydraulic characteristics. For more information, consult UF/IFAS bulletin HS931 "Microsprinkler Irrigation for Cold Protection of Florida Citrus" (http://edis.ifas.ufl.edu/ch182) and bulletin SL296 "Citrus Cold Weather Protection and Irrigation Scheduling Tools Using Florida Automated Weather Network (FAWN) Data" (http://edis.ifas.ufl.edu/ss509).

Other Uses

Other irrigation uses vary according to the type of crop, system characteristics, and field location. Some examples include: periodic overhead irrigation for dust control; wetting of dry row middles to settle dust and prevent sand from blowing during windy conditions; and wetting of roadways and drive aisles to provide traction of farm vehicles.

Irrigation Scheduling

A wide range of irrigation scheduling methods is used in Florida, with corresponding levels of water management (Table 5). The recommended method (level 5) for scheduling irrigation (drip or overhead) for vegetable crops is to use together: the crop water requirement method that takes into account plant stage of growth associated with measurements of soil water status, and guidelines for splitting irrigation (see below). A typical irrigation schedule contains (1) a target crop water requirement adjusted to crop stage of growth and actual weather demand, (2) adjustment of irrigation application based on soil moisture, (3) a rule for splitting irrigation, (4) a method to account for rainfall, and (5) record keeping (Table 6). For seepage irrigation, the water table should be maintained near the 18-inch depth (measured from the top of the bed) at planting and near the 24-inch depth when plants are fully grown. Water tables should be maintained at the proper level to ensure optimum moisture in the bed without leading to oversaturation of the root zone and potential losses of nutrients. Water tables can be monitored with a section of PVC pipe sunk in the soil with a calibrated float inside the PVC pipe. The calibrated float can be used to determine the exact level of the water table.

Soil Water Status, Soil Water Tension, and Soil Volumetric Water Content

Generally, two types of sensors may be used for measurements of soil water status, those that measure soil water potential (also called tension or suction) and those that measure volumetric water content directly. Soil water tension (SWT) represents the magnitude of the suction (negative pressure) the plant roots have to create to free soil water from the attraction of the soil, and move it into the root cells. The dryer the soil, the higher the suction needed, hence, the higher SWT. SWT is commonly expressed in centibars (cb) or kilopascals (kPa; 1cb = 1 kPa; 7 kPa = 1psi). For most vegetable crops grown on the sandy soils of Florida, SWT in the rooting zone should be maintained between 6 (slightly above field capacity) and 15 cb. Because of the low AWHC of Florida soils, most full-grown vegetable crops will need to be irrigated daily. During early growth, irrigation may be needed only two to three times weekly. SWT can be measured in the field with moisture sensors or tensiometers. For more information on SWT measuring devices, consult UF/IFAS circular 487 "Tensiometers for Soil Moisture Measurement and Irrigation Scheduling" available at http://edis.ifas.ufl.edu/ae146 and bulletin 319 "Tensiometer Service, Testing, and Calibration" available at http://edis.ifas.ufl.edu/ae086

Within the category of volumetric sensors, capacitance based sensors have become common in recent years due to a decrease in cost of electronic components and increased reliability of these types of sensors. However, sensors available on the market have substantially different accuracies, response to salts, and cost. Soil moisture sensors are detailed in the publication, "Field Devices for Monitoring Soil Water Content" (http://edis.ifas.ufl.edu/ae266). All methods under this definition estimate the volume of water in a sample volume of undisturbed soil [ft^3/ft^3 or percentage]. This quantity is useful for determining how saturated the soil is (or, what fraction of total soil volume is filled with the soil aqueous solution). When it is expressed in terms of depth (volume of water in soil down to a given depth over a unit surface area (inches of water), it can be compared with other hydrologic variables like precipitation, evaporation, transpiration and deep drainage.

Practical Determination of Soil Field Capacity Using Volumetric Soil Moisture Sensors

It is very important that the irrigation manager understand the concept of "field capacity" to establish an irrigation control strategy with the goals of providing optimum soil moisture for plant growth, productivity, and reduction of fertilizer nutrient leaching. Figure 2 represents volumetric soil water content (VWC) at depth of 0–6 inches measured by a capacitance sensor during a period of 4 days. For the soil field capacity point determination, it is necessary to apply an irrigation depth that results in saturation of the soil layer, in this particular case 0-6 inches. The depth of irrigation applied is 4,645 gal/ac (equivalent to 0.17 in for overhead or seepage irrigation, or 34 gal/100ft for drip irrigation with 6 ft. bed centers in plasticulture) in a single irrigation event. Right after the irrigation events, there was a noticeable increase in soil moisture content. The degree to which the VWC increases, however, is dependent upon volume of irrigation, which is normally set by the duration of irrigation event. For plastic mulched drip-irrigation in sandy soils, long irrigation events result in a relatively large increase in soil moisture in the area below the drip emitter. The spike in soil moisture appears to only be temporary, as the irrigation water rapidly drains down beyond the 6-inch zone (observed by the decrease in VWC). This rapid spike in soil water content indicates that the VWC has rapidly reached a point above the soil water holding capacity and the water has percolated down to deeper soil layers. Between the end of day 1 and day 3 (Fig. 2), the VWC declined at a constant rate due to some soil water extraction by drainage, but most extraction due to evapotranspiration took place during the day. For sandy soils, the change in the slope of drainage and extraction lines—in other words, changing from "rapid" to "slower" decrease in soil water content—can be assumed as the "field capacity point". At this time, the water has moved out from the large soil pores (macropores), and its place has been taken by air. The remaining pore spaces (micropores) are still filled with water and will supply the plants with needed moisture.

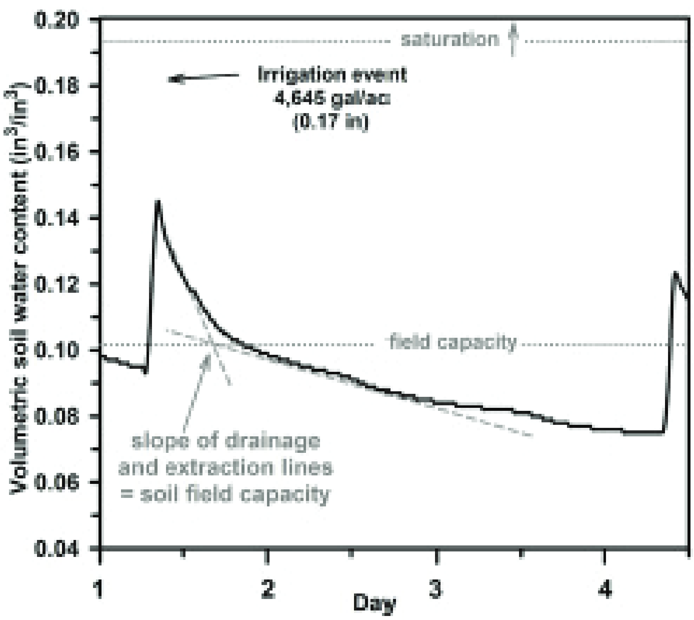

Figure 2. Example of practical determination of soil field capacity at 0-6 inches soil depth after irrigation event using soil moisture sensors.

Examples of Irrigation Scheduling Using Volumetric Soil Moisture Sensor Devices

In this section, two examples of irrigation management of vegetable crops in sandy soils using soil moisture sensor readings stored in a data logger are provided: one example with excessive ("over") irrigation (Fig. 3) and one with adequate irrigation (Fig.4) using plasticulture. In Figure 3, the irrigation events consisted of the application of a single daily irrigation event of 4,718 gal/ac (equivalent to 0.18 in for overhead or seepage irrigation, or 36 gal/100ft for drip irrigation with 6-ft bed centers in plasticulture. After each irrigation event, there was an increase in the soil water content followed by rapid drainage. Large rainfall events may lead to substantial increases in soil moisture content. On day 2, right after the irrigation, a large rainfall of 0.44 in. occurred, which resulted in a second spike of soil water content in the same day. The following irrigation (day 3) started when the volumetric soil water content was above the soil field capacity. In this case, the irrigation event of the day 3 could have been safely skipped. Between day 3 and 6, no irrigation was applied to the crop. The volumetric water content decreased from 0.14 to 0.08 in^3 water/in^3 soil. Due to the very low water holding capacity of the sandy soils, skipping irrigation for several days could lead to unneeded crop water stress especially during very hot days or very windy days (when high evapotranspiration rates may occur), or during flowering stage. Between day 6 and 10, large daily irrigation events were repeated, exceeding the "safe irrigation zone", and leading to more water drainage and nutrient leaching.

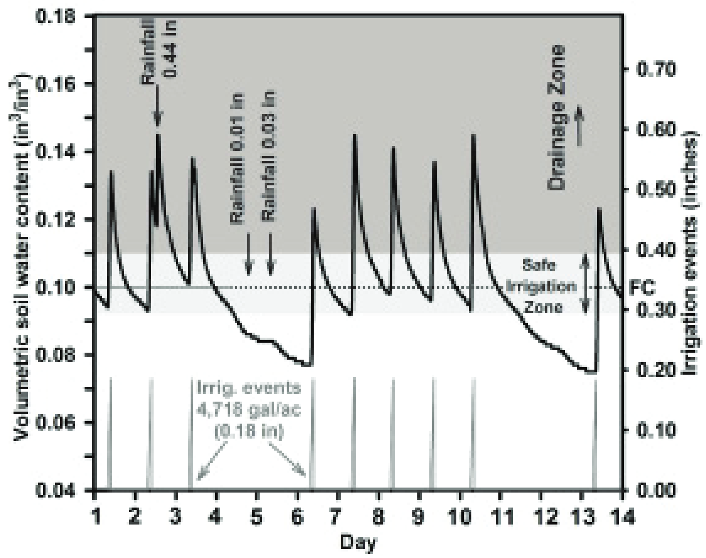

Figure 3. Example of excessive ("over") irrigation of the upper soil layer (0 to 6 inch depth) moisture content for drip-irrigation under plastic mulched condition for sandy soils. Black line indicates volumetric soil water content using soil moisture sensors. Grey line indicates irrigation event, single daily irrigation event with volume application of 65 gal/100 ft (0.18 in). Dotted line indicates soil field capacity line. Arrows indicate rainfall events.

Conversely, Figure 4 shows "adequate" irrigation applications for a 10-day period. In this case, the irrigation event will start exclusively when the volumetric soil water content reaches an arbitrary threshold. For this particular situation, the soil field capacity is known; the irrigation events started when the volumetric soil moisture content reached values below the soil field capacity (or 0.09 in^3/in^3). However, to maintain the soil volumetric water content in the "safe irrigation zone", a previous determination of the length of the irrigation is necessary, to avoid over irrigation (additional information about irrigation depths can be obtained in the UF/IFAS bulletin AE72 "Microirrigation in Mulched Bed Production Systems: Irrigation Depths" at (http://edis.ifas.ufl.edu/ae049).

The example in Figure 4 received irrigation depth of 943 gal/ac (equivalent to 0.03 in for overhead or seepage irrigation, or 6 gal/100 ft for drip irrigation with 6-ft bed centers in plasticulture; this irrigation depth was sufficient to increase the volumetric water content to a given moisture without exceeding the "safe irrigation zone". On average, the volumetric soil water content is maintained close to the field capacity, keeping water and nutrients in the root zone. For this particular example, there was no deep water percolation. In addition, with the information of the soil water status, the irrigation manager might decide to not irrigate if the soil moisture content is at a satisfactory level. For example, in day 8, due to a rainfall event of 0.04 in, there was no need of irrigation because the soil moisture was above the field capacity and the arbitrary threshold, therefore the irrigation event of day 8 was skipped. On the other hand, this "precise" irrigation management requires very close attention by the irrigation manager. For a given reason (such as pump issue), the irrigation was ceased in day 5 and it was resumed late in day 6. As a result, soil water storage decreased to a certain level, and if the water shortage is prolonged, the plants would be water stressed.

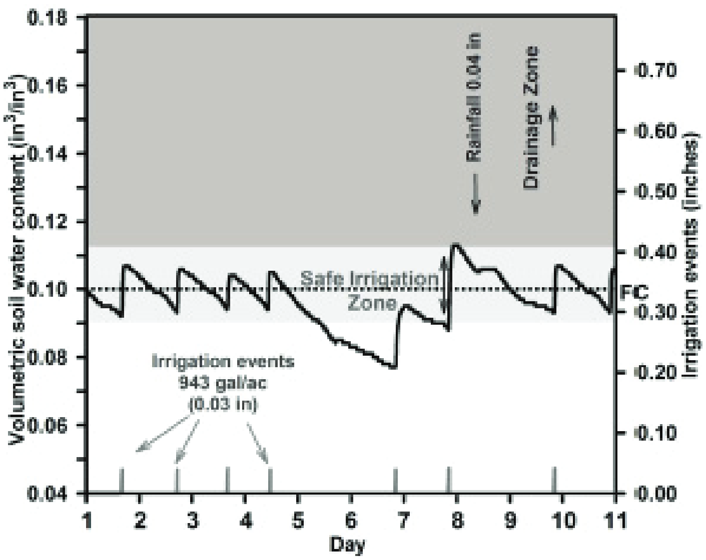

Figure 4. Example of adequate irrigation management using soil moisture sensors for monitoring the volumetric soil moisture content of the upper soil layer (0- to 6-inch depth), on drip irrigation under plastic mulched condition for sandy soils. Black line indicates volumetric soil water content using soil moisture sensors. Grey line indicates irrigation event, single daily irrigation event with volume application of 943 gal/ac (0.03 in.). Dotted line indicates soil field capacity line. Arrows indicate rainfall events.

Tips on Installation and Placing of Soil Moisture Sensor Devices in Vegetable Fields

The use of soil moisture monitoring devices (volumetric or soil water tension) has the potential to save irrigation water application in a given vegetable area by reducing the number of unnecessary irrigation events. However, the effectiveness of the use of these sensors depends on a proper installation in representative locations within vegetable fields. These sensors may be used to monitor water table levels in seepage irrigation.

Sensors should be buried in the root zone of the plants to be irrigated. Most of the vegetable crops have 80% to 90% of the root zone in the upper 12 in., which generally is the soil layer with higher water depletion by evapotranspiration. For vegetable crops cultivated in rows and irrigated by drip tapes, the sensors should be installed 2–3 in. away from the plant row. For single row crops (such as tomato, eggplant, or watermelon), the sensor should be placed on the opposite side of the drip tape; for double row crops (pepper, squash), the sensors should be placed in between the drip tape and plant rows.

Sensors need to be in good contact with the soil after burial; there should be no air gaps surrounding the sensor. Soil should be packed firmly but not excessively around the sensor. In plasticulture, after the installation, the area above the sensor should be recovered back with plastic and sealed with tape.

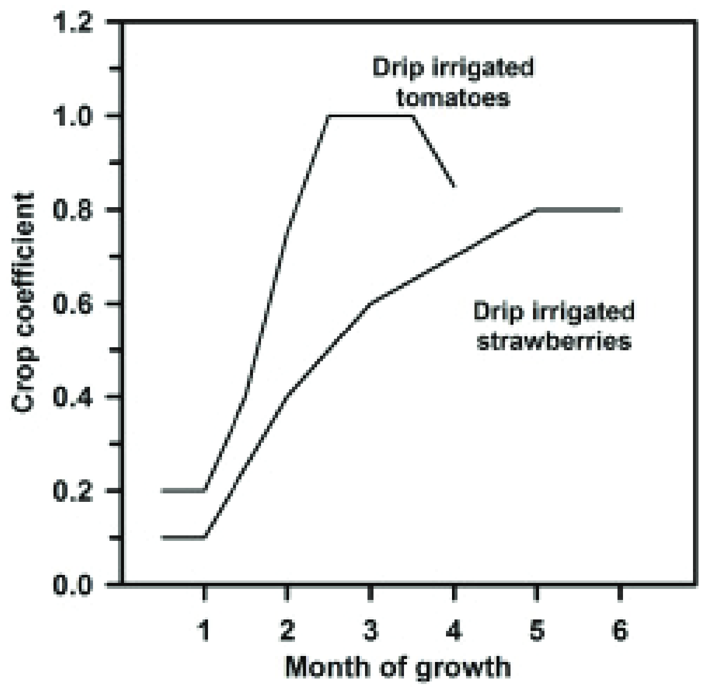

Figure 5. Crop coefficient of drip irrigated tomato and strawberry.

Crop Water Requirement (ET)

Crop water requirements depend on crop type, stage of growth, and evaporative demand. Evaporative demand is termed evapotranspiration (ET) and may be estimated using historical or current weather data. Generally, reference evapotranspiration (ETo) is determined for use as a base level. By definition, ETo represents the water use from a uniform green cover surface, actively growing, and well watered (such as turf or grass covered area).

Historical daily averages of Penman-method ETo values are available for 6 Florida regions expressed in units of acre-inches and gallons per acre (Table 7).

While these values are provided as guidelines for management purposes, actual values may vary above and below these values, requiring individual site adjustments. Actual daily values may be as much as 25% higher on days that are hotter and drier than normal or as much as 25% lower on days that are cooler or more overcast than nor-mal. Real time ETo estimates can be found at the Florida Automated Weather Network (FAWN) internet site (http://fawn.ifas.ufl.edu). For precise management, SWT or soil moisture should be monitored daily in the field.

Crop water use (ETc) is related to ETo by a crop coef-ficient (Kc) which is the ratio of ETc to the reference value ETo (Eq. [2]). Because different methods exist for estimating ETo, it is very important to use Kc coefficients which were derived using the same ETo estimation method as will be used to determine the crop water requirements. Also, Kc values for the appropriate stage of growth (Tables 8 and 9; Fig. 3) and production system (Tables 6 and 7) must be used.

With drip irrigation where the wetted area is limited and plastic mulch is often used, Kc values are lower to reflect changes in row spacing and mulch use. Plastic mulches substantially reduce evaporation of water from the soil surface. Associated with the reduction of evaporation is a general increase in transpiration. Even though the transpiration rates under mulch may increase by an average of 10%-30% over the season as compared to a no-mulched system, overall water use values decrease by an average of 10%-30% due to the reduction in soil evaporation. ETo may be estimated from atmometers (also called modified Bellani plates) by using an adjustment factor. During days without rainfall, ETo may be estimated from evaporation from an ET gauge (Ea) as ETo = Ea/0.89. On rainy days (>0.2 in) ETo = Ea/0.84.

Eq. [2] Crop water requirement =

Crop coefficient x Reference evapotranspiration

ETc = Kc x ETo

Soil Water Holding Capacity and the Need to Split Irrigations

Appropriate irrigation scheduling and matching irrigation amounts with the water holding capacity of the effective root zone may help minimize the incidence of excess leaching associated with over-irrigation. In Florida sandy soils, the amount of water that can be stored in the root zone and be available to the plants is limited. Usually, it is assumed that approximately 0.75 in. of water can be stored in every foot of the root zone. Only half of that should be used before next irrigation to avoid plant stress and yield reduction (this will help maintain SWT below 15 cb). Any additional water will be lost by deep percolation below the root zone.

Table 11 gives approximate amount of water that can be applied at each event in Florida sandy soil under different production systems. When the calculated volume of water to be applied in one day exceeds the values in Table 10, then it is necessary to split applications. The number of split irrigations can be determined by dividing the irrigation requirement (Eq. [1]) by the numbers in Table 11, and rounding up the result to the nearest whole number. Splitting irrigation reduces both risks of water loss through deep percolation and nutrient leaching. Sandy soil with the available water holding capacity of 0.75 in/ft was assumed in these calculations. If a soil contains more clay or organic matter the amount of water applied during one irrigation event and stored in the root zone can be increased. It is recommended to check the depth of wetting after irrigation to assure that the water is not lost from the roots by digging out a perpendicular profile to the drip line and observing the wetted pattern.

Example

As an example, consider drip irrigated tomatoes on 6-ft center beds, grown under a plastic mulch production system in central west Florida (sandy soils). For plants in growth Stage 5 the crop coefficient is 0.85 (Table 10). If this period of growth occurred in May, the corresponding ETo value is 4,914 gal/ac/day (Table 7). Daily crop water use would be estimated as:

ETcrop = (0.85) x (4,914 gal/ac/day) = 4,177 gal/ac/day

If the drip irrigation system can apply water to the root zone of the crop with an application efficiency of 85%, the irrigation requirement would be

Irrigation Requirement = (4,177 gal/ac/day) / (0.80) = 5,221 gal/ac/day

If the maximum water application in one irrigation event for this type of soil is 1,700 gal/ac/irrigation, then the irrigation will have to be split:

Number of events = (5,221 gal/acre/day) / (1,700 gal/acre/day/irrigation event) = 3.1, rounded up to 4 irrigation events each of 5,221 / 4 = 1,305 gal/acre

Therefore, in this example, four irrigations of 1,305 gal/ac each will be needed to replace ETc, and not exceed the soil water holding capacity. This amount of water would be a good estimate for scheduling purposes under average growth and average May climatic conditions. However, field moisture plant status should also be monitored to determine if irrigation levels need to be increased or reduced. While deficit irrigation will reduce fruit size and plant growth, excessive irrigation may leach nutrients from the active root system. This may also reduce plant growth.

Table 1. Suggested criteria for irrigation water quality based on electrical conductivity

		EC[2]	Concentration (TDS)[1] Gravimetric
Classes	**Water quality**	**(dS/m)[4]**	**(PPM)[3]**
Class 1	Excellent	< 0.25	175
Class 2	Good	0.25 - 0.75	175-525
Class 3	Permissible[5]	0.76 - 2.00	525-1400
Class 4	Doubtful[6]	2.01 - 3.00	1400-2100
Class 5	Unsuitable[6]	>3.00	2100

Source: T.A. Bauder, R.M. Waskom and J.G. Davis. 2007. Colorado State University Cooperative Extension Fact Sheet #: 0.506 Also available online at http://dickens.agrilife.org/files/2011/03/irriwtrqalstd.pdf

[1]TDS = total dissolved solids

[2]EC = electrical conductivity

[3]PPM = parts per million

[4]dS/m at 25°C = mmhos/cm

[5]Leaching needed if used.

[6]Good drainage needed and sensitive plants will have difficulty obtaining stands.

Table 2. Threshold and zero yield salinity levels for four salinity groups.

	Threshold Salinity	Zero Yield Salinity
Salinity Rating	**dS/m**	
Sensitive	1.4	8.0
Moderately Sensitive	3.0	16.0
Moderately Tolerant	6.0	24.0
Tolerant	10.0	32.0

Available online at http://edis.ifas.ufl.edu/ae091

Table 3. Salinity level (dS/m) of irrigation water for 100% productivity (zero yield loss) or zero productivity (zero yield) in vegetable production

	Zero yield loss	Zero yield
Species	**Salinity level (dS/m)**	
Beans	1.0	6.5
Beets	4.0	15.0
Broccoli	2.8	13.5
Cabbage	1.8	12.0
Cantaloupe	2.2	16.0
Carrot	1.0	8.0
Cucumber	2.5	10.0
Lettuce	1.3	8.0
Onion	1.2	7.5
Pepper	1.5	8.5
Potato	1.7	10.0
Radish	1.2	9.0
Spinach	2.0	15.0
Sweet corn	1.7	10.0
Sweet potato	1.5	10.5
Tomato	2.5	12.5
Turnip	0.9	12.0
Zucchini squash	4.7	15.0

After Ayers and Wescott, 1985. Available online at http://edis.ifas.ufl.edu/ae091

Table 4. Application efficiency for water delivery systems used in Florida

Irrigation system	Application efficiency (Ea)
Overhead	60-80%
Seepage[1]	20-70%
Drip[2]	80-95%

[1]Ea greater than 50% are not expected unless tailwater recovery is used
[2]With or without plastic mulch

Table 5. Levels of water management and corresponding irrigation scheduling method

Water Mgt. Level	Irrigation scheduling method
0	Guessing (irrigate whenever), not recommended
1	Using the "feel and see" method, see ftp://ftp-fc.sc.egov.usda.gov/MT/www/technical/soilmoist.pdf
2	Using systematic irrigation (Example: ¾ in. every 4th day, or 2 hrs every day)
3	Using a soil water tension measuring tool or soil moisture sensor to start irrigation
4	Schedule irrigation and apply amounts based on a budgeting procedure and checking actual soil water status
5[1]	Adjusting irrigation to plant water use (ETo), and using a dynamic water balance based on a budgeting procedure and plant stage of growth, together with using a soil water tension measuring tool or soil moisture sensor

[1]Recommended method

Table 6. Summary of irrigation scheduling guidelines for vegetable crops grown in Florida

Irrigation scheduling component	Irrigation system[1]	
	Seepage[2]	Drip[3]
1- Target water application rate	Keep water table between 18- and 24-inch depth	Historical weather data or crop evapotranspiration (ETc) calculated from reference ET or Class A pan evaporation
2- Fine tune application with soil moisture measurement	Monitor water table depth with observation wells	Maintain soil moisture level in the root zone between 8 and 15 cb (or 8% and 12% available soil moisture)
3- Determine the contribution of rainfall	Typically, 1 inch rainfall raises the water table by 1 foot	Poor lateral water movement on sandy and rocky soils limits the contribution of rainfall to crop water needs to (1) foliar absorption and cooling of foliage and (2) water funneled by the canopy through the plan hole.
4- Rule for splitting irrigation	Not applicable. However, a water budget can be developed	Irrigations greater than 12 and 50 gal/100 ft (or 30 min and 2 hrs for drip tapes with medium flow-rate) when plants are small and fully grown, respectively are likely to push the water front below the root zone
5-Record keeping	Irrigation amount applied and total rainfall received[4] Days of system operation	Irrigation amount applied and total rainfall received[4] Daily irrigation schedule

[1]Efficient irrigation scheduling also requires a properly designed and maintained irrigation system
[2]Practical only when a spodic layer is present in the field
[3]On deep sandy soils
[4]Required by the BMP

Table 7. Historical Penman method reference evapotranspiration (ETo) for six Florida regions expressed in (A) inches per day and (B) gallons per acre per day[1]

Month	Northwest	Northeast	Central	Central West	Southwest	Southeast
			Inches per day (A)			
JAN	0.06	0.07	0.07	0.07	0.08	0.08
FEB	0.07	0.08	0.10	0.10	0.11	0.11
MAR	0.10	0.10	0.12	0.13	0.13	0.13
APR	0.13	0.14	0.16	0.16	0.17	0.17
MAY	0.16	0.16	0.18	0.18	0.18	0.18
JUN	0.17	0.16	0.18	0.18	0.18	0.17
JUL	0.17	0.16	0.17	0.17	0.18	0.18
AUG	0.15	0.15	0.17	0.16	0.17	0.16
SEP	0.13	0.13	0.14	0.14	0.15	0.14
OCT	0.19	0.10	0.11	0.11	0.12	0.12
NOV	0.07	0.07	0.08	0.08	0.09	0.09
DEC	0.05	0.06	0.06	0.07	0.07	0.07
			Gallons per acre per day[2] (B)			
JAN	1629	1901	1901	1901	2172	2172
FEB	1901	2172	2715	2715	2987	2987
MAR	2715	2715	3258	3530	3530	3530
APR	3530	3801	4344	4344	4616	4616
MAY	4344	4344	4887	4887	4887	4887
JUN	4616	4344	4887	4887	4887	4616
JUL	4616	4344	4616	4616	4887	4887
AUG	4073	4073	4616	4344	4616	4344
SEP	3530	3530	3801	3801	4073	3801
OCT	2444	2715	2987	2987	3258	3258
NOV	1901	1901	2172	2172	2444	2444
DEC	1358	1629	1629	1629	1901	1901

[1]Assuming water application over the entire area, i.e., sprinkler or seepage irrigation with 100% efficiency. See Table 4 for conversion for taking into account irrigation system efficiency.

[2]Calculation: for overhead or seepage irrigation, (B) = (A) x 27,150. To convert values for drip-irrigation (C) use (C) = (B) x bed spacing / 435.6. For example for 6-ft bed spacing and single drip line, C in Southwest Florida in January is C = 2,172 x 6/ 435.6 = 30 gal/100 ft/day.

Table 8. Description of stages of growth (plant appearance and estimated number of weeks) for most vegetable crops grown in the spring in Florida[1]

Crop	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Expected growing season (weeks)
Bean	Small plants 2-3	Growing plants 3-4	Pod enlargement 2-3	Pod maturation 2-3		9-10
Cabbage, Cauliflower, Chinese cabbage	Small plants 2-3	Growing plants 5-6	Head development 3-4			10-12
Cantaloupe (muskmelon)	6-in vine 1-2	12-in vine 3-4	First flower 3-4	Main fruit production 2-3	Late fruit production 2-3	11-12
Carrot	Small plants 1-2	Growing plants 3-4	Root development 5-7	Final growth 1-2		10-13
Cucumber	6-in vine 1-2	12-in vine 2-3	Fruit production 6-7	Late season 1-2		10-12
Eggplant	Small plants 2-3	Growing plants 2-3	Fruit production 6-7	Late season 2-3		12-13
Potato	Small plants (after hilling) 2-4	Large plants (vegetative growth) 4-6	First flower (tube initiation and bulking) 3-5	Maturation (top dies) 2-4		12-14
Okra	Small plants 2-3	Growing plants 2-3	Pod production 7-8	Late season 1-2		12-13
Onion		Growing plants 4-5	Bulb development 6-8	Maturation (top falls) 1-2		13-16
Pepper	Small plants 2-3	Growing plants 2-3	Pod production 7-8	Last bloom 1-2	Last harvest 1	13-15
Pumpkin (bush)	Small plants 2-3	First flower 2-3	Fruit enlargement 5-6	Harvest 1-2		9-11
Pumpkin (vining)	6-in vines 2-3	12-in vines 2-3	Small fruit 3-4	Large fruit 2-3	Harvest 1-2	13-15
Radish	Small plants 1-2	Rapid growth 2-4				3-5
Strawberry	Young plants October	Growing plants November	Early harvest December-January	Main harvest period February-March	Late harvest April	23-30
Summer Squash (crookneck, straight- neck, zucchini	Small plants 1-2	Growing plants 2-3	Fruit production 3-4	Late fruit production 1		7-9
Sweet corn	Small plants 3-4	Large plants 5-8	Ear development 2-3			10-15
Sweet Potato	Early vine growth 2-3	Expanding vines 5-6	Storage root enlargement 6-10		Late season	13-17
Tomato	Small plants 2-3	1st bloom 2-3	2nd-3rd bloom 6-7	Harvest 1-2	Late harvest 1-2	12-14
Watermelon	6-in vines 2-3	12-in vines 2-3	Small fruit 3-4	Large fruit 2-3	Harvest 1-2	13-15

[1]Same growth stages used for irrigation and fertilizer schedules; for South Florida, each stage may be 30% longer because of winter planting during short days.

Table 9. Crop coefficient estimates for use with the ETo values in Table 6 and growth stages in Table 7 for unmulched crops. (Actual values will vary with time of planting, soil conditions, cultural conditions, length of growing season and other site-specific factors)

Crop	Growth Stage	Crop Coefficient[1]
All field-grown vegetables	1 2	0.202 to 0.403 Stage 14 value to Stage 3 value (See Figure 3-3)
Legumes: sandbean, lima bean, and southernpea	3 4	0.955 0.855
Beet	3 4	1.00 0.90
Cole crops: Broccoli, brussels sprouts cabbage, cauliflower, Collards, kale, mustard, turnip	3 4 3 4	0.95 0.805 0.905 1.005
Carrot	3 4	1.00 0.70
Celery	3 4	1.00 0.90
Cucurbits: cucumber, cantaloupe, pumpkin, squash, watermelon	3 4	0.90 0.70
Lettuce: endive, escarole	3 4	0.95 0.90
Okra	3 4	1.005 0.905
Onion (dry)	3 4	0.95 0.75
Onion (green)	3 and 4	0.95
Parsley	3	1.005
Potato	3 4	1.10 0.70
Radish	3 4	0.80 0.75
Spinach	3 4	0.95 0.90
Sweet corn	3 4	1.10 1.00
Sweet Potato	3 4	1.105 0.705

[1]Adapted from Doorenbos, J., and Pruitt, W. O. 1977. Crop water requirements. Irrigation and Drainage Paper No. 24, (rev.) FAO, Rome and Allen, R.G., L.S.Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements Food and Agriculture Organization of the United Nations, Rome.
[2]Low plant population; wide row spacing
[3]High plant population; close row spacing
[4]0.30 or Kc value from Stage 1
[5]Values estimated from similar crops

Table 10. Crop coefficient estimates (Kc) for use with ETo values in Table 6 and growth stages in Table 7 for selected crops grown in a plasticulture system[1]

Crop	Growth Stage	Crop Coefficient (Kc)
Cantaloupe[1]	1	0.35
	2	0.6
	3	0.85
	4	0.85
	5	0.85
Cucumber[1]	1	0.25
	2	0.5
	3	0.9
	4	0.75
Summer squash[1]	1	0.3
	2	0.55
	3	0.9
	4	0.8
Strawberry (4-ft bed centers)[2]	1	0.4
	2	0.5
	3	0.6
	4	0.8
	5	0.8
Tomato (6-ft bed centers)[3]	1	0.4
	2	0.75
	3	1.0
	4	1.0
	5	0.85
Watermelon (8-ft bed center)[1]	1	0.3
	2	0.5
	3	0.7
	4	0.9
	5	0.8

[1]Adapted from Tables 12 and 25 in Allen, R.G., L.S.Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: guidelines for computing crop water requirements Food and Agriculture Organization of the United Nations, Rome.

[2]Adapted from Clark et al. 1993. Water Requirements and Crop Coefficients for Tomato Production in Southwest Florida. Southwest Florida Water Management District, Brandon, FL.

[3]Adapted from Clark et al. 1996. Water requirements and crop coefficients of drip-irrigated strawberry plants. Transactions of the ASAE 39:905-913.

Table 11. Maximum water application (in gallons per acre and in gallons/100 lbf) in one irrigation event for various production systems on sandy soil (available water holding capacity 0.75 in/ft and 50% soil water depletion). Split irrigations may be required during peak water requirement

Wetting width (ft)	Gal/100ft to wet depth of 1 ft	Gal/100ft to wet depth of 1.5 ft	Gal/100ft to wet depth of 2 ft	Bed spacing (ft)	Vegetable crop	Bed length (100 lbf/a)	Gal/acre to wet depth of 1 ft	Gal/acre to wet depth of 1.5 ft	Gal/acre to wet depth of 2 ft
1.0	24	36	48	4	Lettuce, strawberry	109	2,600	3,800	5,100
				5	Cantaloupe	87	2,100	3,100	4,100
				6	Broccoli, okra, cabbage, pepper, cauliflower, summer squash, pumpkin (bush), eggplant, tomato	73	1,700	2,600	3,500
				8	Watermelon, pumpkin (vining)	55	1,300	1,900	2,600
1.5	36	54	72	4	Lettuce, strawberry	109	3,800	5,800	7,600
				5	Muskmelon	87	3,100	4,700	6,200
				6	Broccoli, okra, cabbage, pepper, cauliflower, summer squash, pumpkin (bush), eggplant, tomato	73	2,600	3,900	5,200
				8	Watermelon, pumpkin (vining)	55	1,900	3,000	3,900

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SS-AGR-155

Water Use and Irrigation Management of Agronomic Crops[1]

D. L. Wright, D. Rowland, and E. B. Whitty[2]

To obtain maximum yields from agronomic crops, plants should remain relatively free of water stress. Although different crops may vary in their responses to water deficits at different growth stages, the amount of water used by a crop is closely associated with final vegetative and grain yield.

Maximum yields of agronomic crops can be achieved by avoiding stress, with water deficits often causing the greatest impacts on yield. Although different crops may vary in their responses to water deficits at different growth stages, most crops have their highest water requirements and water-stress sensitivity during late vegetative and early reproductive phases of growth.

Evapotranspiration (ET)

Evapotranspiration (ET) is a term used to describe the water loss from land on which vegetation is growing. The evaporation component (evapo-) of ET is the process by which water in the soil is changed to the vapor state and moved into the atmosphere. This is the same evaporation process that results in water being lost from the surface of a lake or an ocean.

The second component of ET (-transpiration) refers to the vaporization and loss of water from the leaves of a crop through the small pores or stomata in the leaf. Although this is also an "evaporation process," it is termed transpiration because the evaporated water has been taken up by the plant roots from the soil, moved up through the plant stem, and evaporated from the plant leaves.

If the amount of water which is evaporated from the soil surface (the *evapo-* part) is added to the amount of water which is transpired from the leaves above the soil surface (the *-transpiration* part), the resulting amount is the total amount of water loss, or ET. Thus, ET is composed of evaporation from the soil plus transpiration from plant leaves. Values of ET for a crop are usually expressed as the amount of water lost (inches, cm, mm) per unit of time (hour, day, week, month, season, or year).

At planting time, ET rates consist only of evaporation of water from the soil surface. As the crop emerges and begins to develop leaf area, an increasingly larger portion of ET results from transpiration from the crop's leaves. When leaves completely shade the soil surface (canopy coverage), ET consists largely of transpiration. Actually, during most of the growing season of typical agronomic crops, transpiration is responsible for the largest portion of the water loss from the field. Even during early crop development when the soil surface is exposed to direct sunlight, evaporation is small if the soil surface is dry. Clearly, the largest seasonal

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requirement for water in most field crop situations is to supply transpirational needs and not for evaporation from the soil surface.

Seasonal ET

Calculated seasonal ET values for several agronomic crops range from about 15” (38 cm) for tobacco to approximately 49” (124 cm) for sugarcane (Tables 1 and 2). For most agronomic crops that produce leaf canopies that fully cover the soil surface, variations in the amounts of water required for ET are primarily dependent on the time of season during which the crop is grown, the water stress imposed on the crop, and the length of the growing season. Net irrigation requirements (NIR) (see equation below) necessary to satisfy the ET needs in 80% of the crop years are also given in Tables 1 and 2. For example, in 8 of 10 years for corn, 12” (25 cm) of irrigation water supplementing rainfall would provide adequate water to meet the ET demand of 25” (64 cm). Since ET is quite responsive to many weather variables including radiation, temperature, humidity, and wind speed and also to numerous crop characteristics, values of both ET and NIR will vary from season to season. Data reported in Table 1 must only be considered as values representing average environmental and crop conditions. Also, the NIR values given in Tables 1 and 2 do not consider irrigation efficiency. See the section on “Efficient Irrigation Management” for further information.

Sensitive Crop Growth Stages for Water Deficits

Severe water stress at any crop developmental stage will usually result in some growth and yield reduction. However, certain stages of growth are sensitive to even mild water stress. Knowledge of these particularly sensitive growth stages and ET rates during these growth periods can be helpful when deciding whether to irrigate or delay for a few days in anticipation of rainfall.

Table 3 gives a summary of crop growth stages that are most sensitive to water stress, the approximate days after planting at which the critical stages occur, and the expected maximum daily water use rates during the indicated periods. Days after planting and daily water use rates are only to be used as general guidelines since dates of planting, variety, plant population, and numerous environmental factors will cause the actual values to vary. The ET estimates given, however, are representative of a typical crop planted at a recommended date and population on a relatively clear day during the indicated crop growth stage. Generally, the ET requirements during the most sensitive growth stages are similar for the various crops and range between 0.20” and 0.28” (0.51 to 0.71 cm) per day. While replacing ET losses is the goal of most irrigation scheduling tools, obtaining correct ET values for individual fields can be challenging. To aid in irrigation scheduling, there are instruments available that measure soil moisture levels as well as plant stress so that irrigation for individual fields can be timed to meet the needs of the plant before stress occurs.

For grain crops, yield is determined by both the total number of seeds produced and by the weight of each seed. Thus, any stress which causes a reduction in either the number of seeds produced or the weight of the seed will result in yield reductions. Growth stages that are most sensitive to water stress are usually the growth stages during which either seed numbers or seed weights are being established (Table 1). Crop yield is generally reduced less by water stress occurring during the vegetative stage than during the reproductive stage of growth for most crops.

Some crops, including corn, sorghum, and small grains, have relatively short periods of growth during which seed numbers are determined, and severe water stress at this growth stage may be quite detrimental to grain yield. Conversely, crops such as soybeans, cotton, and peanuts bloom over an extended period of time in which the crop can set seed or bolls and are not as severely affected by short term stresses. For a crop such as tobacco, where leaf production is most important, water stresses during most growth stages can be detrimental to yield.

Water deficits may also affect crop management and production other than the direct effect on plant growth. The efficacy of many herbicides and other pesticides depends on soil moisture. Plants under moisture stress may not respond to foliar applied chemicals or fertilizer, or, in some cases, may be damaged by chemical burns. Nutrient utilization and fertilization practices are influenced by the moisture status of the crop plants. Application of pesticides must be scheduled according to irrigation applications or to moisture stress in the crop.

Efficient Irrigation Management

The most sensitive growth stages for most crops coincide with time intervals during which the crop is also utilizing the most water (Table 3). The most important irrigation management decisions must be made when the crop is using large amounts of water and when the crop may progress from being well-watered to severely stressed in a period of a few days. This emphasizes the importance of designing an irrigation system so that it will be able to apply water in amounts and rates sufficient to supply maximum ET demands. Furthermore, all of the water applied does not become available for ET. Some water is unavoidably lost during the delivery to the crop. In Florida, most agronomic crops are irrigated by sprinkler irrigation systems. Sprinkler systems deliver water with approximate efficiencies of 70 to 75%, depending on the system and environmental conditions. Therefore, for an irrigation system with 75% efficiency, if 1” (2.5 cm) of water is pumped, only 0.75” (1.9 cm) reaches the soil surface and is available for ET. To ensure 1” (2.5 cm) of water is actually available to the crop, 1.33” (1.0 ÷ 0.75) must be applied. Therefore, amounts of water actually applied must be increased above the ET requirements (presented above) to allow for the delivery losses. Irrigation efficiency can be improved by use of low pressure systems and by irrigating at night. However, most pivots cover enough acreage that they must be run continuously during critical, dry periods.

Although the preceding paragraphs have referred to critical crop growth stages, this does not suggest that stress at other periods will not reduce yields. The critical growth periods only imply that added attention should be given to irrigation management decisions during those stages.

Some general guidelines for irrigation management of several agronomic crops are given in the following paragraphs. On coarse-textured soils dominating much of Florida, more frequent irrigations with smaller amounts of water (1” or less) allow for more efficient storage of rainfall that may occur shortly after irrigation. The goal of efficient irrigation management should be to minimize the loss of water to runoff, deep percolation, and evaporation, and to maximize water used for crop transpiration. Efficient irrigation requires careful management and is attainable if an understanding of water use and stress responses of the crop is applied.

Corn, Tobacco, and Peanuts

Research has indicated that corn and tobacco, two of the more sensitive crops to water stress, can be effectively irrigated on sandy soils with the aid of tensiometers or other types of moisture monitoring equipment placed at various depths including 6” (15 cm) deep in the crop root zone. For tensiometers, when the soil moisture tension at that depth approaches 20 to 25 centibars, irrigation water should be applied. It is well documented that corn is extremely sensitive to water stresses during silking and tasseling, but research also indicates that 2 weeks of midday wilting during early vegetative growth can reduce yields by as much as 10% to 15%. Additional tensiometers placed at 12” (30 cm) and 18” (45 cm) depths will help determine the amount of water to apply without leaching nutrients through the soil profile. Irrigation of peanuts with tensiometers installed at the 12” (30 cm) depth and using an irrigation trigger of 30 centibars has also proven effective. Tensiometers allow the manager to apply irrigation water before crop stress symptoms become visible. If tensiometers are not utilized, an accounting method can also be quite effective.

Accounting methods are more practical for determining when to irrigate with overhead sprinklers than are tensiometers and other moisture-sensing devices placed in the soil. Accounting methods are much like keeping a bank account ledger, in that records of rainfall and irrigation are maintained and water use by the crop is estimated. Water use estimates can be based on the experience of the irrigation manager, but may become difficult when several systems at various locations must be monitored. Use of weather instruments can improve the reliability of water use estimates and can be coupled with computer programs that are available to quickly provide reliable irrigation recommendations. In general, when using the accounting method, irrigation should begin when 50 percent of the available water in the root zone is depleted. Estimates of the water-holding capacity of the soil and changes in the rooting depth as the crop grows must be estimated, if not actually measured.

Estimates are based on soil type and are available from soil surveys and other references. In general, sandy soils contain less than an inch of available water per foot of depth, while soils that contain significant levels of clay or organic matter can hold well over an inch of available water per foot of depth. The rooting depth of the crop varies with species, age of plant, and soil properties. More detailed information on irrigation scheduling can be found in UF/IFAS Extension Bulletin 249, *Basic Irrigation Scheduling in Florida* (http://edis.ifas.ufl.edu/ae111).

Soybeans

The appearance of midday wilt appears to be a reasonable indicator for applying water for soybeans during reproductive growth. However, research results have indicated that 2 weeks of midday wilting during vegetative growth resulted in only small (2% to 5%) yield reductions. Thus, it appears that some water stress can be tolerated by soybeans during vegetative growth without significantly reducing yields, but more liberal applications of irrigation water are necessary from early pod-set to maturity. As new varieties of higher-yielding soybeans come on the market, moisture stress can result in higher yield losses.

Sugarcane

There are two factors to consider in reviewing the water requirements of sugarcane; one is the actual amount of water required to produce the sugarcane, the other is the management of the water table in the cane field.

Approximately 80% of all sugarcane grown for commercial sugar production in Florida is grown on organic soils in which the water table should be maintained at a certain level to reduce soil subsidence. A water table depth of 24” (61 cm) or greater is usually maintained on well-decomposed organic soils. According to a seven-year study conducted at the UF/IFAS Everglades Research and Education Center, a water table of 30” (76 cm) resulted in the best sugar tonnage per acre, but a water table of 15” (38 cm) reduced production only 5%. The rate of subsidence with a 20” (51 cm) water table for example, is less than half of the rate for soil with a 36” (91 cm) water table.

A higher water table maintained to reduce subsidence will require more water for irrigation during the dry season and more pumping for drainage during the wet season.

The actual amount of water required to produce 2.2 lb (1 kg) of cane ranged from 196 lb (89 kg) for plant cane (freshly planted sugarcane) to 260 lb (118 kg) for ratoon cane (sugarcane that was harvested and allowed to grow back). The water use efficiency for the ratoon cane is less than that for the plant cane. The water required to produce 2.2 lb (1 kg) of sugar ranged from 1,948 lb (884 kg) in plant cane to 2,485 lb (1115 kg) in the ratoon cane.

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Table 1. Seasonal evapotranspiration and net irrigation requirements for several agronomic crops.[1]

Crop	Seasonal ET (in.)	NIR-80
Corn	25	12
Grain Sorghum	20	6
Peanuts	22	7
Soybeans	23	7
Small Grains	20	9
Tobacco	15	7

[1] From Rogers and Harrison, Water Resources Council Report No. 5 as calculated from U.S. Soil Conservation Service, Technical Release No. 21.

Table 2. Consumptive use, or ET (Evapotranspiration), of sugarcane for Everglades area of Florida.

Month	ET	NIR-80
January	1.4	0.5
February	1.1	0.5
March	2.5	0.9
April	3.4	1.8
May	4.8	1.7
June	6.0	1.2
July	6.5	1.6
August	6.7	1.7
September	5.1	0.7
October	5.2	2.2
November	3.2	1.7
December	2.6	1.5
Total	49.5	17.9

NIR-80 = Net irrigation at 80% rainfall probability. Divide by irrigation efficiency for gross irrigation requirements. For sugarcane, seepage irrigation is used and the efficiency is 30 to 50%.

Table 3. Sensitive growth stages, dates of occurrence, and maximum daily water use required of several agronomic crops.

Crop	Sensitive Growth Stage[1]	Approx. Days After Planting	Expected Maximum Water Use Requirements During Critical Growth Stage[2] (in/day)
Tobacco	2 to 3 week period near flowering[3]	50 - 65	0.22 - 0.25
Corn	Tasseling and silking	65 - 75	0.22 - 0.28
Sorghum	Early boot through bloom	45 - 70	0.20 - 0.25
Peanuts	Mid-flowering through completion of pod set	45 - 90	0.22
Soybeans	Early to late bean fill	50 - 100	0.20 - 0.25
Cotton	Bloom period	45 - 90	0.20 - 0.25

[1] Growth stage at which yield is most sensitive to water stress.
[2] Value should only be used as estimates for maximum rates since many environmental factors affect water use. The range in values given for a particular crop represents values obtained from different experiments or changes associated with crop development during the critical period.
[3] Represents maximum water use period. Data are limited for growth stage sensitivities.

Automatic Irrigation Based on Soil Moisture for Vegetable Crops[1]

Rafael Muñoz-Carpena and Michael D. Dukes[2]

Water Conservation and New Irrigation Technology

Improving irrigation efficiency can contribute greatly to reducing production costs of vegetables, making the industry more competitive and sustainable. Through proper irrigation, average vegetable yields can be maintained (or increased) while minimizing environmental impacts caused by excess applied water and subsequent agrichemical leaching. Recent technological advances have made soil water sensors available for efficient and automatic operation of irrigation systems. Automatic soil water sensor-based irrigation seeks to maintain a desired soil water range in the root zone that is optimal for plant growth. The target soil water status is usually set in terms of soil tension or matric potential (expressed in kPa or cbar, 1 kPa=1 cbar), or volumetric moisture (expressed in percent of water volume in a volume of undisturbed soil). Another benefit of automatic irrigation techniques is convenience. In a previous experience working with a soil-moisture-based automatic irrigation system, Dukes et al. (2003) found that once such a system is set up and verified, only weekly observation was required. This type of system adapts the amount of water applied according to plant needs and actual weather conditions throughout the season. This translates not only into convenience for the manager but into substantial water savings compared to irrigation management based on average historical weather conditions.

Soil Moisture Sensors for Manual Irrigation Control

Although soil water status can be determined by *direct* (soil sampling) and *indirect* (soil moisture sensing) methods, direct methods of monitoring soil moisture are not commonly used for irrigation scheduling because they are intrusive and labor intensive and cannot provide immediate feedback. Soil moisture probes can be permanently installed at representative points in an agricultural field to provide repeated moisture readings over time that can be used for irrigation management. Special care is needed when using soil moisture devices in coarse soils since most devices require close contact with the soil matrix that is sometimes difficult to achieve in these soils. In addition, the fast soil water changes typical of these soils are sometimes not properly captured by some types of sensors (Irmak and Haman, 2001; Muñoz-Carpena et al. 2002; Muñoz-Carpena et al. 2005).

Many indirect methods are available for monitoring soil water content. An in-depth review of available techniques is given in EDIS Extension Bulletin 343 (5*)* focusing on working principles, advantages and drawbacks (Tables 1

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and 2 in Bul. 343). These methods estimate soil moisture by a calibrated relationship with some other measurable variable. The suitability of each method depends on several issues such as cost, accuracy, response time, installation, management and durability. Depending on the quantity measured (i.e., volumetric water content or soil tension), indirect techniques are first classified into *volumetric* and *tensiometric*. Both quantities are related through the soil water characteristic curve that is specific to a given soil. Therefore, it is important to remember that they cannot be related to each other the same way for all soil types. In addition, this relationship might not be unique and may differ along drying and wetting cycles, especially in finer soils. To calculate irrigation requirements (the amount of water that needs to be applied with each irrigation based on crop needs), suction values from tensiometric methods need to be converted to soil moisture through the soil characteristic curve. Among the available tensiometric techniques, tensiometers and granular matrix sensors (GMS) are the most used for automatic irrigation.

Most of the currently available volumetric sensors suitable for irrigation are dielectric. This group of sensors estimate soil water content by measuring the soil bulk permittivity (or dielectric constant) that determines the velocity of an electromagnetic wave or pulse through the soil. In a composite material like the soil (i.e., made up of different components like minerals, air and water), the value of the permittivity is made up by the relative contribution of each of the components. Since the dielectric constant of liquid water is much larger than that of the other soil constituents, the total permittivity of the soil or bulk permittivity is mainly governed by the presence of liquid water. The dielectric methods use empirical (calibrated) relationships between volumetric water content and the sensor output signal (time, frequency, impedance, wave phase). These techniques are becoming widely adopted because they have good response time (almost instantaneous measurements), do not require maintenance, and can provide continuous readings through automation. Although these sensors are based on the dielectric principle the various types available (frequency domain reflectometry-FDR, capacitance, time domain transmission-TDT, amplitude domain reflectometry-ADR, time domain reflectometry-TDR, and phase transmission) present important differences in terms of calibration requirements, accuracy, installation and maintenance requirements and cost. An evaluation of available commercial low cost sensors for manual monitoring of soil water status in South Florida vegetables is presented in EDIS Fact Sheet ABE 333 (Muñoz-Carpena et al., 2002).

Automatic Soil-Water-Based Irrigation Control: Water Use, Yields and Implications

A soil water-based irrigation control system uses feedback on the soil water status to bypass a time-based pre-programmed schedule or to maintain soil water content with a specified range. These two approaches are *bypass* and *on-demand*, respectively. Bypass configurations skip an entire timed irrigation event based on the soil water status at the beginning of that event or by checking the soil water status at intervals within a time-based event.

Tensiometers and GMS were the first types of sensors adapted to automatic irrigation control. Phene and Howell (1984) first used a custom made soil matric potential sensor to control subsurface drip-irrigated processing tomatoes. Their results indicated that yields of the automated system were similar to those from tomatoes irrigated based on pan evaporation with the potential to use less irrigation water.

Switching tensiometers are devices that operate in bypass mode typically with a timer such that irrigation will be allowed within a timed irrigation window if the soil matric potential exceeds a threshold setting. Smajstrla and Locascio (1996) reported that using switching tensiometers placed at 15 cm depths and set at 10 and 15 kPa tensions in a fine sandy soil in Florida reduced irrigation requirements of tomatoes by 40-50% without reducing yields.

Meron et al. (2001) discussed the use of tensiometers to automatically irrigate apple trees. They noted that spatial variability was problematic when the tensiometers were installed 30 cm from the drip irrigation emitters. Smajstrla and Koo (1986) discussed the problems associated with using tensiometers to initiate irrigation events in Florida. Problems included entrapped air in the tensiometers, organic growth on the ceramic cups, and the need for re-calibration.

Muñoz-Carpena et al. (2005) found that both tensiometer- and GMS- controlled drip irrigation systems on tomato saved water when compared to typical farmer practices.

The irrigation savings of switching tensiometers set at 15 kPa on a coarse soil compared to farmer practices was 70%. The GMS-controlled system failed to bypass most irrigation events due to slow response time. Tomato yields were similar across all soil-water-based control systems and the farmer field. Shock et al. (2002) described a system to irrigate onion with frequent bypass control using GMS. The overall water used was slightly lower than calculated crop evapotranspiration with acceptable yields.

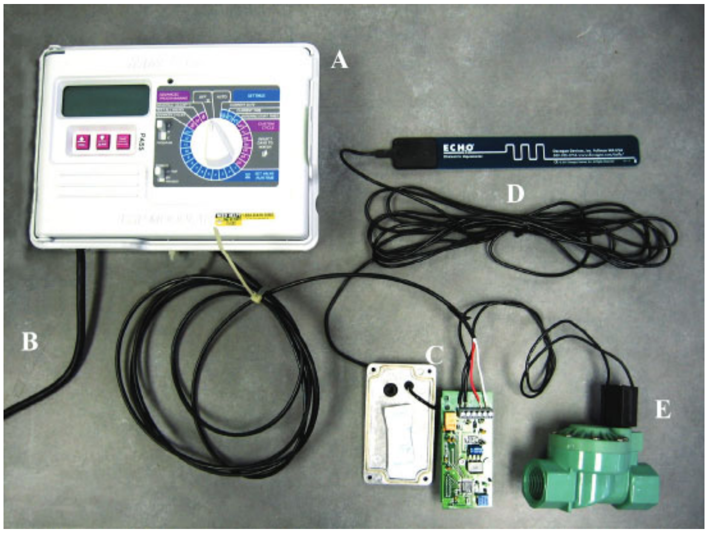

Figure 1. Details of the irrigation soil moisture interface (QIC) prototype developed at UF Agricultural & Biological Engineering Department. Here is shown retrofitted with a standard irrigation timer and solenoid valve where: A) time-based controller, B) power supply, C) Quantified Irrigation Controller circuitry, D) capacitance soil water probe (ECH_20, Decagon Devices, Inc., Pullman, WA), and E) solenoid valve.
Credits: UF-IFAS ABE Rafael Munoz-Carpena

Although dielectric sensors have only found limited use in vegetable production, research to date shows promising results in terms of water savings. Nogueira et al. (2003) described an automatic subsurface drip irrigation control system used in a sweet corn/peanut crop rotation. This system used TDR sensors to control a subsurface drip irrigation system on-demand. During subsequent testing of this system, 11% irrigation savings with the on-demand subsurface drip irrigation system (23 cm deep) compared to sprinkler irrigation was reported with similar yields between the systems (Dukes and Scholberg, 2005). Dukes et al. (2003) used a commercially available dielectric sensor for lawns and gardens to control irrigation on green bell pepper (*Capsicum annuum L.*). They found 50% reduction in water use with soil-water-based automatically irrigated bell pepper when compared to once daily manually irrigated treatments that had similar yields; however, maximum yields and water use were on the farmer treatment that was irrigated 1-2 times each day.

Recently, an irrigation controller has been developed that uses a voltage signal from a dielectric probe that is related to soil water (Muñoz-Carpena et al., 2004) (Fig. 1). This system performed similarly to switching tensiometers (both in bypass mode) by reducing irrigation water by 70% on drip irrigated tomato in South Florida (Fig. 2).

Figure 2. Application of the QIC prototype to automatic soil moisture based irrigation of tomatoes at UF Tropical Research and Education in Homestead, FL.
Credits: UF-IFAS ABE Rafael Munoz-Carpena

Conclusions and Future Direction

As water supplies become scarce and polluted, there is a need to irrigate more efficiently in order to minimize water use and chemical leaching. Recent advances in soil water sensoring make the commercial use of this technology possible to automate irrigation management for vegetable production. However, research indicates that different sensors types may not perform alike under all conditions. Reductions in water use range as high as 70% compared to farmer practices with no negative impact on crop yields. Due to the soil's natural variability, location and number of soil water sensors may be crucial and future work should include optimization of sensor placement. Additional research should also include techniques to overcome the limitation of requiring a soil specific calibration.

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Phosphorus Management for Vegetable Production in Florida[1]

George Hochmuth, Ron Rice, and Eric Simonne[2]

Introduction

Phosphorus (P) is an important nutrient for plant growth and economical vegetable production in Florida. A deficiency of P leads to reduced plant growth and reduced yields, and in extreme cases the plant fails to grow much beyond the seedling stage. Although P shortage can severely limit vegetable growth, severe P deficiency is rarely observed in commercial vegetable fields in Florida because P has built up in many agricultural soils, and vegetable growers typically apply P to most vegetable crops each season, irrespective of the soil test results.

P has generally been thought of as immobile in most agricultural soils, including those in Florida. P mobility is a function of the type of soil and the chemistry of the soil, being somewhat mobile in very coarse, acidic soils with low concentrations of iron, aluminum, and calcium. There are situations where these types of soils exist in Florida; one such soil was researched by Rhue et al. (1987). P is relatively immobile in most commercial vegetable soils in Florida because of the presence of large quantities of calcium, and iron which precipitate P, reducing the P leaching potential. In many of these soils, P has been built up to great concentrations, and crop response to added P fertilizers on these soils is unlikely (Hochmuth et al., 1993). There are, however, reports of crop responses to small amounts of P added as starter fertilizer on soils with high P and calcium concentrations, such as some shallow Histosols in southern Florida (Hochmuth et al., 1994; 1996).

Soil Testing for P

Since P is typically immobile in most Florida soils, it is amenable to soil testing programs. The University of Florida employs the Mehlich-1 extractant for determining soil-test P concentrations for mineral soils. The calibration of the Mehlich-1 soil test is presented in Table 1 and the P fertilizer recommendations for vegetables grown on mineral soils in Florida are presented in Table 2. The University of Florida employs water as the extractant to determine soil-test P levels for organic (Histosol) soils. The P recommendations for vegetables grown on organic soils are presented in Table 3. These Florida fertilizer recommendations are based on many years of field research with most vegetable crops. The research with P has been reviewed, for several vegetable crops, by Hochmuth and Cordasco (2000a-k). More detail on the P fertilization recommendations are presented in Circular 1152 "IFAS Standardized Fertilization Recommendations for Vegetable Crops" by Hochmuth and Hanlon (2000b), available on the web at http://edis.ifas.ufl.edu/CV002.

P Application

When required for crop production, P fertilizers can be supplied from several sources, including triple- or

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single-superphosphates, various ammonium phosphates, potassium phosphates, or phosphoric acid. Most research dealing with comparisons of sources for effects on crop production on most soils documents negligible differences among the sources for their ability to supply P to the crop. Liquid or dry forms of P fertilizers have performed similarly for crop production.

On soils where P is not likely to be mobile, the P fertilizers should be placed in the root zone. Typically, P should be banded near the root of the transplant or near the germinating seed. Work with vegetables grown on the Histosols of the Everglades Agricultural Area (EAA) showed that banding reduced the P fertilizer needs by up to 50% with some crops (Sanchez et al., 1990; 1991). The research with fertilization of vegetables produced on Histosols in the EAA was reviewed by Hochmuth et al. (1994; 1996). In most production situations with mineral soils, P can be banded near the seed or plant or incorporated in the bed area prior to planting. This latter method would be the choice for polyethylene mulch culture systems. Where crops are established in cool soils, small amounts of P (so-called starter P) can be applied with the seed, seedpiece, or transplant (Hochmuth, 2000) to hasten early plant development. Supplemental or sidedress applications of P are usually not needed during the season when careful attention is given to the P fertilizer needs of the crop before or at planting. Rarely will P be needed in a nutrient solution being injected into a drip irrigation system.

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Table 1. Mehlich-1 soil test indices and interpretations for vegetable crops grown on mineral soils in Florida.

Element	Very Low	Low	Medium	High	Very High
	Mehlich-1 index (ppm)				
P	<10	10-15	16-30	31-60	>60
K	<20	20-35	36-60	61-125	>125
Mg		<15	15-30	>30	
Ca	<50	50-100	101-300	301-500	>500
Adapted from Hochmuth and Hanlon, 2000b.					

Table 2. Phosphorus fertilizer recommendations for vegetable crops grown on mineral soils in Florida.

Crop	Mehlich-1 soil-test index values and interpretations				
	<10 Very Low	10-15 Low	16-30 Medium	31-60 High	>60 Very High
	P recommendation (lbs. P_2O_5/acre)				
Beans	120	100	80	0	0
Broccoli	150	120	100	0	0
Cabbage	150	120	100	0	0
Carrot	150	120	100	0	0
Celery	200	150	100	0	0
Cucumber	120	100	80	0	0
Eggplant	150	120	100	0	0
Endive, escarole	150	120	100	0	0
Lettuce (head, leaf)	150	120	100	0	0
Muskmelon	150	120	100	0	0
Mustard, kale	150	120	100	0	0
Okra	150	120	100	0	0
Onion (bulb)	150	120	100	0	0
Onion (bunch)	120	100	80	0	0
Parsley	150	120	100	0	0
Pepper	150	120	100	0	0
Potato	120	120	60	0	0
Radish	120	100	80	0	0
Spinach	120	100	80	0	0
Squashes	120	100	80	0	0
Strawberry	150	120	100	0	0
Sweet Corn	150	120	100	0	0
Sweet Potato	120	100	80	0	0
Tomato	150	120	100	0	0
Watermelon	150	120	100	0	0
Adapted from Hochmuth and Hanlon, 2000b.					

Table 3. Phosphorus fertilizer recommendations for vegetable crops grown on organic (histosol) soils in Florida.

Crop	**Soil-test index values with the water soil extraction (P_w)**								
	3	**6**	**9**	**12**	**15**	**18**	**21**	**24**	**≥ 27**
	P recommendation (lbs. P_2O_5/acre)								
Celery	260	200	140	80	20	0	0	0	0
Endive	200	175	150	125	100	75	50	25	0
Escarole	200	175	150	125	100	75	50	25	0
Lettuce (Head)	200	175	150	125	100	75	50	25	0
Radish	100	40	0	0	0	0	0	0	0
Romaine	200	175	150	125	100	75	50	25	0
Sweet Corn	160	120	80	40	0	0	0	0	0
Adapted from Hochmuth et al. (1994; 1996).									

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HS1247

Description of Enhanced-Efficiency Fertilizers for Use in Vegetable Production[1]

Luther Carson and Monica Ozores-Hampton[2]

Nutrient losses from the soil in cultivated fields may reduce yields and cause environmental impacts, which are of concern for growers, environmentalists, and legislators. For example, soluble fertilizer (SF) nitrogen (N) recovery of seepage- and drip-irrigated tomatoes ranged from 61% to 96% and from 36% to 74%, respectively (Scholberg 1996). Thus, in response to the Federal Clean Water Act of 1972 and the Florida Restoration Act of 1999, a series of best management practices (BMPs) was implemented to improve surface and ground water quality (Bartnick et al. 2005). BMPs are cultural practices that, when implemented as a plan, help reduce the environmental impact of production while maintaining yield and quality. One of these BMPs includes the use of controlled-release fertilizer (CRF), which is an enhanced-efficiency fertilizer (EEF). This publication describes the common EEFs and the factors affecting their use in Florida vegetable production.

Enhanced-efficiency fertilizers

EEFs increase nutrient use efficiency by maintaining nutrients in the root zone, increasing the availability of nutrients to plants, and decreasing nutrient losses to the environment (Slater 2010). Although changes in cultural practices may increase fertilizer use efficiency, these practices cannot completely suppress the loss of N to the environment. In circumstances with a high risk of N losses, EEF such as slow-release fertilizers (SRFs), CRFs, and stabilized fertilizers may reduce this risk (Chen and Hutchinson 2008). EEF types and the factors affecting their performance are described below.

1. Slow-release fertilizers

SRFs contain N in a low-soluble, plant-unavailable form that usually requires microbial degradation to release plant-available N. Thus N release is slower than conventional soluble fertilizers, but the release rate, pattern, and duration are not well-controlled compared to CRFs. The two most common slow-release mechanisms include materials of low solubility, such as isobutylidene diurea (IBDU), and biologically decomposable, low-solubility materials, such as urea-formaldehyde (UF) (Ni et al. 2010; Trenkel 2010). Several research studies have been conducted in vegetable crops using SRF with mixed results (Csizinszky 1989; Csizinszky et al. 1992; Ozores-Hampton 2009). Since the N release duration is less controlled compared to CRFs, N release of longer than the season length may result, which is a major drawback to SRFs. In fertility programs that include SRF, these fertilizers often constitute less than 30% of the total N, though this amount may vary widely.

1A. COMMON TYPES OF SLOW-RELEASE FERTILIZERS

Urea-Formaldehyde (UF) and Methylene-Urea (MU): These SRFs are condensation products of urea and formaldehyde in a reaction that includes water, sulfuric acid, sodium hydroxide, and surfactants. This reaction results

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in chains of alternating urea and methylene molecules in varying lengths. The chain length may be selected for during the manufacturing process by controlling the reaction time, pH, temperature, and amount of each component in the reaction (McVey n.d.). UF and MU differ in molecule chain length, the amount of unreacted urea, and the activity index. Table 1 provides a description of activity index and terms found on a UF/MU label.

Urea-Formaldehyde (UF): Among the manufactured SRF and CRF, UF was the first. Patented during 1924 in Germany, it still remains an important SRF (Trenkel 2010). UF contains at minimum 35% cold-water insoluble N and 38% total N. During the manufacturing process of UF, the formaldehyde is transformed into methylene (McVey n.d.). Soil microorganisms break down UF into plant-available N; thus, the mineralization of UF will be affected by microbial activity (Alexander and Helm 2006; Dave and Mehta 1999).

Figure 1. Urea-formaldehyde slow-release fertilizer.
Credits: Monica Ozores-Hampton, UF/IFAS

Methylene-urea (MU): MU contains 40% N in which 60% of the total N is water soluble (Morgan et al. 2009). Varying MU chain lengths are selected for during production (Koivunen et al. 2003). Lower soluble MUs have longer chain lengths and higher slow-release characteristics. Soil temperature and microbial activity are important components of MU degradation (Morgan et al. 2009).

1. **Isobutylidene diurea (IBDU)—31% N:** IBDU is the condensation product of isobutyraldehyde (a liquid) with urea, which results in a single oligomer (a polymer whose molecules consist of relatively few repeating units) of low solubility. In contrast to UF or MU that depends on biological degradation for N release, the release pattern of IBDU is dependent on chemical dissolution (IBDU is hydrolyzed to urea in the presence of water). Thus IBDU release rate is influenced by particle size and less influenced by environmental variations compared to MU and UF (Miner et al. 1978; Trenkel 1997).

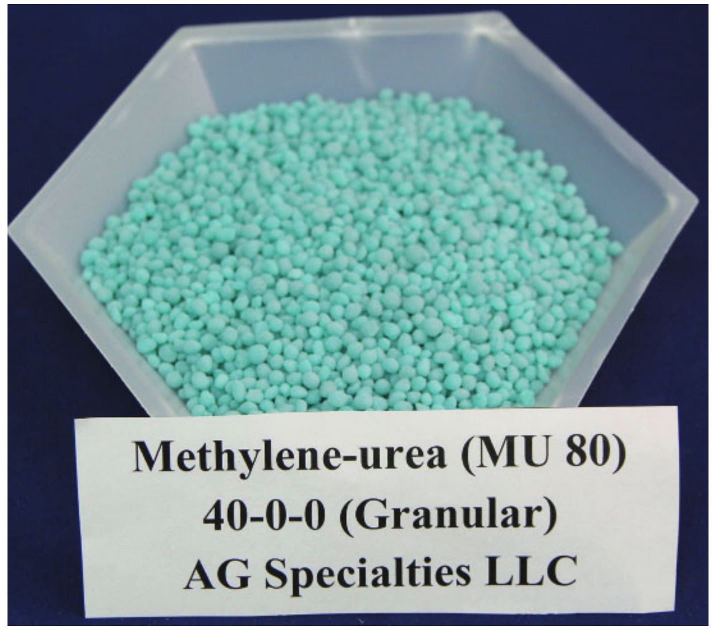

Figure 2. Methylene-urea slow release fertilizer.
Credits: Monica Ozores-Hampton, UF/IFAS

Crotonylidene diurea (CDU)—32.5% N: Crotonylidene diurea (CDU) is produced by the reaction of urea and acetic aldehyde catalyzed by acid. When CDU is placed in the soil, it is degraded into urea and crotonaldehyde through hydrolysis and biological activity. Similar to IBDU, the N release rate of CDU is influenced by particle size; the larger the particles, the slower the release rate (Trenkel 1997).

Urea-triazone (UT)—28% N: UT is the reaction product of urea, formaldehyde, and ammonia, which produces uniform, N-containing rings that must be degraded to release plant-available N (Clapp and Parham 1991). The resulting liquid SRF contains 7.8% free urea and 20.2% slow release N that may be foliar- or soil-applied, including through fertigation. UT should not be applied with ammonium-based N fertilizers, due to the risk of ammonia volatilization, or with ferrous iron fertilizers, due to the risk of iron oxidation to a plant-unavailable form (Liu and Williamson 2013).

1B. FACTORS AFFECTING NUTRIENT RELEASE FROM SLOW-RELEASE FERTILIZERS

Soil microbes degrade UF, MU, and UT into urea and then into ammonium (NH_4^+), providing plant-available N, whereas soil moisture causes dissolution of IBDU and CDU (Clapp and Parham 1991; Fuller and Clark 1947; Morgan et al. 2009; Trenkle 2010). Therefore, factors affecting soil microbes and hydrolysis, which are often the same, affect SRF degradation. Increasing and decreasing moisture and temperature will increase and decrease SRF nitrification, though an optimum soil-temperature range for microbe activity is between 67˚F to 74˚F (Swift 2012). Soil microbes slow their activity at low and high soil-moisture contents (permanent wilting or flooded conditions) and extreme soil temperatures (<40 °F and >95°F). UF and MU are nitrified at a greater rate at pH 6 compared to 5 or 7. Thus a soil pH that affects soil microbe activity will also affect N release. In the presence of phosphorous (P) and potassium (K), MU and UF were nitrified at a greater rate compared to UF alone (Kralovec and Morgan 1954). High soluble salts and soil incorporation will also affect SRF N release by affecting microorganisms. In all SRFs, fertilizer granule size affects SRF nitrification due to surface area. For instance, one pound of large-particle fertilizer will contain less surface area and release N more slowly compared to one pound of small-particle fertilizers.

2. Controlled-release fertilizer

No official differences between CRF and SRF are recognized by the American Association of Plant Food Control Officials (AAPFCO), though the term CRF is used to represent SRFs occluded in a coating. This coating may be composed of polymer, resin, sulfur, or both sulfur and polymer coatings. CRF nutrient release duration is controlled by temperature, coating thickness, and coating composition, though many other factors influence release (Carson and Ozores-Hampton 2013). Thus the term CRF is suitable terminology, because factors affecting nutrient release rate, pattern, and duration are recognized and controlled during the manufacturing process to design CRFs of specific release durations (Shaviv 2001). Ideally, the release pattern and duration will match crop N uptake, though this is difficult to accomplish due to the effect of temperature on nutrient release (Lammel 2005). The sigmoidal nutrient release pattern of CRF begins with a lag period while water is imbibed into the CRF, then shows a constant rate of release at a given temperature that slows after a given amount of time. The slow phase after the constant or linear nutrient-release period is known as the decay phase (Figure 3).

2A. COMMON TYPES OF CONTROLLED-RELEASE FERTILIZERS (TABLE 2)

Sulfur-coated urea—30% to 40% N: Sulfur coated urea (SCU) fertilizer was developed by the Tennessee Valley Authority (TVA) during the 1960s. Granular urea is coated with several layers of molten sulfur and a soft wax coating to seal cracks and blemishes that may occur as the sulfur cools. The wax coating also protects the brittle sulfur coating during handling (Booze and Schmidt 1997). The SCU fertilizer normally consists of 30% to 40% N, 14% S, 2.1% sealant, and 2.5% conditioner. The S and wax coatings slowly degrade through microbial, chemical, and physical processes, which open cracks or holes through which nutrients may diffuse (Figure 3) (Trenkel 1997). Once diffusive release is complete, coatings may be found in the soil as open or broken spheres. SCU is subject to two release problems: catastrophic-type release and lock-off or non-release. The prill may be cracked or broken, thereby releasing all of its content at once, which is called catastrophic release. In the case of lock-off, whole SCU prills may be found with none of their contents released (Trenkel 1997).

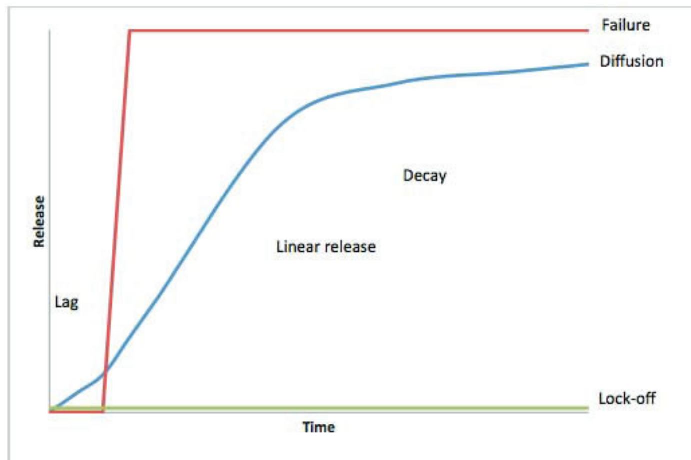

Figure 3. Release from an individual controlled-release fertilizer prill: diffusive release (blue), catastrophic failure (red), and lock-off (green).

Polymer/resin-coated fertilizers—18% to 44% N: Polymer coatings may be manufactured as semipermeable or impermeable membranes with small pores through which nutrients diffuse. Crop nutrients such as N, P, K, micronutrients, and combinations thereof may be coated, though it should be noted that smooth spherical granules coat with greater uniformity and release with greater predictability compared to angular fertilizers. Many coatings can be used in polymer CRFs including polyolefine, polyethylene, ethylene-vinyl-acetate, polyesters, urea formaldehyde resin, alkyd-type resins, and polyurethane-like resins (Carson and Ozores-Hampton 2013; Trenkle 2010). For example, Osmocote (Everris Inc., Dublin, OH) is a CRF with an alkyd-resin coating. When the prills come in contact with moisture, the pores in the resin coating allow water to diffuse into the core, dissolving the water-soluble compounds inside. This increases the osmotic pressure and causes the coating to stretch and the pore size to increase, which allows the nutrients to diffuse back out through the pore (Booze and Schmidt 1997; Trenkel 2010). Since nutrient release from

CRFs is not greatly affected by soil properties—such as microbial activity, redox potential, pH-value, and soil texture—nutrient release may be predicted based on time and temperature (Carson and Ozores-Hampton 2013; Trenkel 1997). This is the leak-type release as fertilizer moves out of the prill slowly. Once release is complete, prills may be found in the soil as intact spheres, full of water.

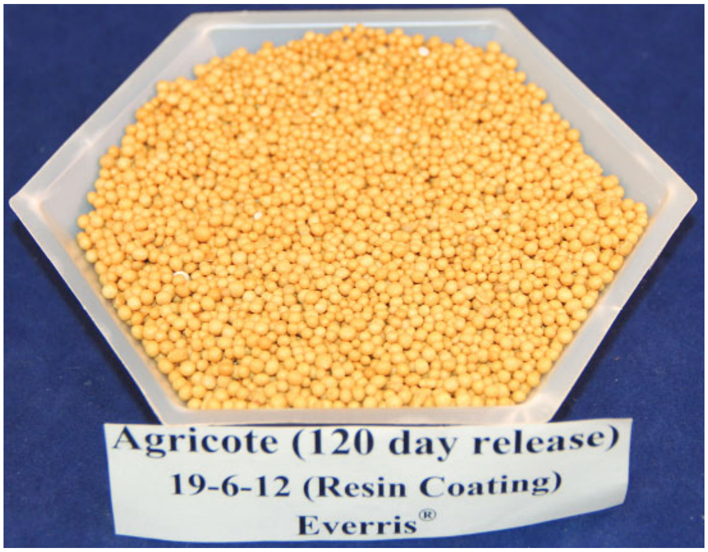

Figure 4. Resin-coated, controlled-release fertilizer.
Credits: Monica Ozores-Hampton, UF/IFAS

Figure 5. Polymer-coated, controlled-release fertilizer.
Credits: Monica Ozores-Hampton, UF/IFAS

Polymer sulfur hybrid coated urea (PSCU)—37% to 43% N: Due to comparatively poor performance of SCU, several CRF manufacturers added a thin polymer coating to improve function (Shaviv 2001). Polymer-sulfur-coated fertilizer containing N, P, or K may be found, but the vast majority contains urea. PSCU is SF coated with sulfur, then coated with a polymeric membrane, which improves the abrasion resistance of the coated granules. The basis for this hybrid coating is to merge the control-release benefits of polymer coatings and the lower cost of the SCU. The modified PSCU releases nutrients in the same manner as polymer-coated fertilizers and shows an improved release behavior compared to the SCU (Trenkel 1997).

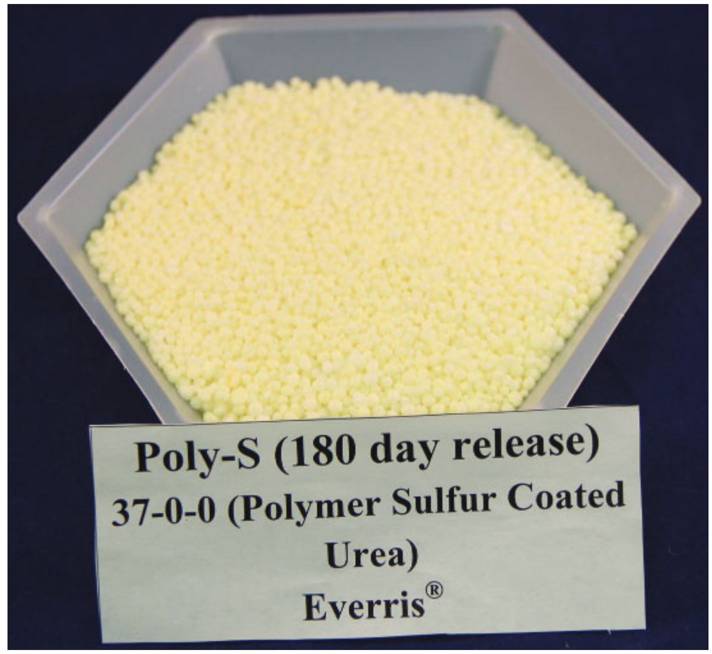

Figure 6. Polymer-sulfur–coated, controlled-release fertilizer.
Credits: Monica Ozores-Hampton, UF/IFAS

2B. FACTORS AFFECTING NUTRIENT RELEASE FROM CONTROL RELEASE FERTILIZERS

Prior to field application, CRF nutrient release may be influenced by management, such as storage, improper handling, and transportation (Shaviv 2001, 2005). Controlled-release fertilizers may imbibe water and release nutrients when stored in high-humidity environments or may become damaged by rough handling. Some manufactures of PSCU require distributors to pass a handling test to ensure that the CRF is handled in a manner that will not cause physical damage.

Soil conditions such as temperature (including thawing and freezing), moisture content, and osmotic potential may influence N release (Carson et al. 2013; Carson and Ozores-Hampton 2013). A reliable understanding of the environmental factors influencing CRF nutrient release allows for use with highest efficiency. In general, nutrient release from CRF is positively correlated with soil temperature and moisture (increases or decreases in soil temperature or moisture result in increases or decreases in nutrient release) (Carson and Ozores-Hampton 2013). Manufacturers of CRFs test nutrient-release duration at a particular temperature (e.g., Agrium Advanced Technologies, Everris, and

J. R. Simplot [patent previously owned by Florikan ESA] and Chisso-Asahi Fertilizer determine nutrient-release duration at constant temperatures of 68°F, 70°F, and 77°F, respectively) (Agrium Advanced Technologies 2010; Everris 2013; Florikan 2012a, 2012b). Temperatures higher or lower than the temperature stated on the label will shorten or lengthen the release duration, respectively. Thus in a raised bed covered with polyethylene mulch during the fall, when temperatures may reach 104°F, a CRF release duration greater than the season length may be necessary. Sartain (2012) describes Florida law regarding fertilizer labels. CRFs should be incorporated in the bed or soil when possible to limit NH_3 volatilization that may occur with urea-based fertilizers. Furthermore, the moisture content inside the bed or soil will be more uniform than the moisture content on the soil surface; thus CRFs will not be subjected to wetting and drying patterns that slow release and that have been reported in non-incorporated CRFs (Medina et al. 2008). Proper CRF placement in the bottom mix is important in polyethylene-mulched vegetable production (Carson and Ozores-Hampton 2013; Csizinszky 1994). CRFs should not be placed in the hot mix due to elevated osmotic potential and temperature, which decreases and increases CRF nutrient release, respectively, making it less predictable in seepage-irrigated crops. Furthermore, use of CRFs in the top mix resulted in similar or reduced marketable tomato yields compared to SF tomato fertility programs (Csizinszky 1989; Ozores-Hampton et al. 2009)

3. Stabilized fertilizers

Nitrification inhibitors (NI) and urease inhibitors (UI) are products added to fertilizers, which are then referred to as *stabilized fertilizers*. The inhibitors are not actually fertilizers in themselves, but they retard bacteria and enzymatic activity in the soil to maintain fertilizers in a form with reduced probability to move out of the root zone by leaching or gaseous losses. The reduced leaching loss is contingent on a soil cation-exchange capacity sufficient to hold the NH_4^+ ions from leaching. Stabilized fertilizers are not frequently used in vegetable production in Florida. In studies on potato and sweet corn, a lack of response to stabilized fertilizers was found, in part due to the low cation-exchange capacity (Hochmuth and Hanlon 2010, 2011). Furthermore, some crops, such as tomato, are sensitive to the high levels of NH_4^+ that results from use of these fertilizers.

3A. COMMON TYPES OF STABILIZED FERTILIZERS

Nitrification inhibitors: NIs retard bacterial oxidation of NH_4^+ to nitrate (NO_3^-) by *Nitrosomonas* and *Nitrobacter* soil bacteria (Trenkel 2010). The aim of using NIs is to maintain NH_4^+ in the ammoniacal form. Once NH_4^+ becomes NO_3^-, it will be subject to greater leaching and losses due to denitrification in high soil-moisture conditions, which are prevalent in seepage-irrigated vegetable production. A common N stabilizer is dicyandiamid or N-Serve by Dow AgroSciences.

Urease inhibitors: UIs slow the conversion of urea to NH_4^+ by slowing the urease enzyme. Urease hydrolyzes urea in/on the soil, which may volatilize in high soil pH and moisture conditions (Trenkel 1997). Thus UIs are used only in conjunction with urea fertilizer. Slowing the rate of urea hydrolysis by the use of UIs can decrease volatilization losses from surface applications of urea fertilizers. The most common UI in the market is Agrotain by Koch Agronomic Services.

3B. FACTORS AFFECTING STABILIZED FERTILIZER EFFECTIVENESS

The factors affecting NIs include those that affect the stability and mobility of the inhibitor in the soil, such as volatilization, decomposition, and degradation. Soil temperature negatively correlates with inhibitor effectiveness. Higher temperatures will increase the rate of inhibitor and NH_4^+ volatilization, microbial degradation of the inhibitor, and the actions of nitrifying bacteria and urease enzymes (Slangen and Kerkhoff 1984). Placement of stabilized fertilizers in bands will slow the rate of NI loss by slowing inhibitor volatilization, which is controlled by vapor pressure, and by increasing soluble salt concentration that may slow microbial degradation. NIs have greater effectiveness in light soils than in heavy soils. Increasing levels of soil pH and organic matter content will require a greater amount of NI to obtain the similar effects.

4. Enhanced-efficiency fertilizer prices

EEFs provide additional value or benefits to the fertilizer and thus cost more than SFs (Table 3). The price of EEfs varies greatly, depending on the type and technology. Stablized fertilizers are the least expensive EEF, and SRFs have prices similar to or higher than CRFs.

Several EEFs are available for vegetable growers to choose from when developing a fertility program. In Florida, EEFs will be most effective in seasons where N loss from the soil may be high due to factors such as high rainfall, light soil textures, and low soil organic matter content. Understanding and applying the factors affecting EEF performance will help growers obtain the greatest benefit from their use.

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Table 1. Explanation of the fertilizer characteristics for urea formaldehyde (UF) and methylene urea (MU).

Characteristics	Explanation
Total nitrogen	The fertilizer grade typically 38% to 40% for UF and MU.
Cold-water soluble nitrogen (CWSN)	This nitrogen fertilizer fraction is soluble in 71.6°F water and is available to plants immediately or within a few weeks. The CWSN fraction contains unreacted urea, methylene diurea, and dimethylene triurea.
Cold-water insoluble nitrogen (CWIN)	This is the slowly available and unavailable nitrogen fertilizer fraction that is not soluble in 71.6°F water.
Hot-water insoluble nitrogen (HWIN)	This nitrogen fertilizer fraction is not soluble in 212°F water, and may be reported indirectly through back calculation using the activity index. The HWIN may not be available to the plants during the season applied.
Activity index	This represents the slow release portion of the fertilizer that is available over the course of several months and is calculated as: AI = ((%CWIN – %HWIN)/%CWIN) * 100.

Table 2. Manufacturer, trade name, control release fertilizer (CRF) type, coating description, and formulation of different CRFs.

Manufacturer[1]	Trade name	Type of CRF	Coating description	Formulation examples
Agrium, Inc.	ESN	Polymer-coated urea	Flexible micro-thin polymer coating	ESN (44-0-0)
Agrium, Inc.	Polyon	Polymer-coated	Ultra-thin ployurethane coating that uses patented "Reactive Layers Coating"	Polyon NPK (20-6-13), Polyon (41-0-0)
Agrium, Inc.	Duration	Polymer-coated	Micro-thin polymer membrane	Duration (44-0-0), Duration (19-6-13)
Agrium, Inc.	XCU	Polymer/sulfur-coated urea	Urea coated first with polymer and then sulfur and wax	XCU (43-0-0)
Chisso-Asahi Fertilizer Co.	Nutricote	Resin-coated	Resin coating with a special chemical release agent	Nutricote (28-0-0)
Chisso-Asahi Fertilizer Co.	Meister	Resin-coated	Granular urea coated with a polymer composition of natural products, resin, and additives	Meister (21-7-4), Meister (19-5-14)
Everris, Inc.	Osmocote	Resin-coated	Alkyd-resin coating made in a batch process from vegetable oil and resin	Osmocote Classic (8-16-12), Osmocote Plus (16-9-12), Osmocote Pro (17-11-10+2MgO+TE)
Everris, Inc.	Poly-S	Sulfur/polymer- coated urea	Urea coated first with sulfur and then polymer	Poly-S (37-0-0)
Everris, Inc.	Agrocote	Sulfur/polymer- and resin-coated	Either 100% N or K potassium fully coated with polymer/sulfur and resin coatings	Agrocote (39-0-0+11%S), Agrocote (0-0-42+14%S),
Haifa Group	Multicote	Resin-coated	Water-soluble nutrients encapsulated in a polymeric shell	Multicote Agri 4 (34-0-7), Multicote Agri 6 (22-8-13) and (34-0-7), Multicote Agri 8 (34-0-7)
J. R. Simplot	Florikote	Polymer-coated	Dual-layer technology coats the fertilizer with a smooth exterior coating with no breaks	Florikote (12-0-40), Florikote (19-6-13), Florikote (40-0-0)

[1]Mention of trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the University of Florida and does not imply its approval to the exclusion of other products or vendors that also may be suitable.

Table 3. Prices of enhanced-efficiency fertilizers for use in vegetable production[1].

Fertilizer	Price ($/ton)
Soluble urea	380 to 560
Soluble potassium nitrate	1,150 to 1,500
Methylene urea	750 to 1,000
Urea-formaldehyde	1,100 to 1,300
IBDU	1,400 to 1,600
Controlled-release urea (sulfur coated)	775 to 875
Controlled-release urea (polymer/sulfur coated)	500 to 1,000
Controlled-release urea (polymer)	700 to 1,500
Controlled-release NPK (polymer)[2]	810 to 2,000
Urease inhibitor	20 to 30[3]
Nitrification inhibitor	4 to 8[3]

[1] Fertilizer prices were obtained from one to three sources between April and May 2014.
[2]Nitrogen = N, phosphorus = P, and potassium = K.
[3]These products are marketed in 2.5 gallon containers. The listed price is in addition to the price of the soluble fertilizer and does not reflect additional application costs that may be associated.

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Using Composted Poultry Manure (Litter) in Mulched Vegetable Production[1]

George Hochmuth, Robert Hochmuth, and Rao Mylavarapu[2]

What Is Poultry Manure and Litter?

Poultry manure is the organic waste material from poultry consisting of animal feces and urine. Poultry litter refers to the manure mixed with some of the bedding material or litter (wood shavings or sawdust) and feathers (Figure 1). This publication deals with litter. Poultry houses are regularly cleaned out by removing a thin layer of the bedding along with the manure (Figure 2). The most common source of poultry litter in Florida is from broiler houses (Figure 3). Most of the litter from poultry houses in northern Florida is composted under a covered structure for several weeks to start the decomposition process. Currently, there are no restrictions on the use of poultry manure for vegetable crop production. However, fresh animal manures are known to harbor human pathogens, such as *E. Coli* or *Salmonella spp*. Factors that mitigate the possibility of vegetable contamination include the use of composted manure instead of fresh manure, incorporating the manure in the soil, and using polyethylene mulch to cover the soil.

Poultry manure is an excellent fertilizer material because of its high nutrient content, especially for nitrogen (N), phosphorus (P), and potassium (K). These nutrients plus others come largely from the bird feces. Manures decompose (mineralize) in the soil releasing nutrients for crop uptake. If poultry litter is readily available locally, it can help reduce fertilizer costs in vegetable production. The vegetable producer should conduct a cost analysis between litter and chemical fertilizers to determine the economic benefit. A listing of nutrient concentrations in typical poultry manure or litter is presented in Table 1.

Figure 1. Typical broiler poultry house ready for clean-out.
Credits: G. Hochmuth

In addition to supplying nutrients, poultry manure or litter serves as a soil amendment increasing the soil organic matter content. The added organic matter increases the moisture holding capacity of the soil, lowers soil bulk density, and improves overall soil structure, thus increasing the efficiency of the crop production and irrigation. Organic matter accumulation in the soil will depend largely on the type of manure or litter, rainfall, and on soil type and temperature. There is little information about how rapidly

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poultry litter will mineralize in sandy soils under mulched-vegetable production systems in Florida. Some research is underway to determine the mineralization rate and nutrient-supplying capacity of poultry manure and litter.

Figure 2. Machine used to scrape a layer of litter (manure and bedding) in the poultry house.
Credits: J. Jones

Figure 3. Poultry manure (litter) ready to apply to a vegetable field.
Credits: G: Hochmuth

What Plant Nutrients Are Typically Found in Poultry Litter?

The key to proper use of manures as plant nutrient sources comes in the knowledge of the nutrient content and the nutrient requirement of the crop to be fertilized with nutrients from manure or litter. Many laboratories offer manure nutrient analyses to determine specific nutrient contents and make recommendations for use as a fertilizer for vegetables. These analyses can be done at the University of Florida Livestock Waste Testing Laboratory on the campus of the University of Florida, in Gainesville: http://soilslab.ifas.ufl.edu. Litters are organic materials and are similar to mixed chemical fertilizers in that the manure supplies an array of nutrients, some of which may not be required by a crop on a particular soil. Phosphorus (P) will build up in most soils where manures are used frequently, because all manures contain P and most soils in Florida retain much of the P applied. Poultry litter might not be the most suitable fertilizer chosen for a soil in a watershed where there are concerns about existing high levels of soil-P.

The actual nutrient content of manures may vary from one livestock operation to another or even over time at a single operation. Factors that contribute to this variation include: the number of animals per operation, composition of the animal feed ration, design of the waste management system including the presence of intermixed bedding materials (litter), and season. Therefore, livestock manures should be sampled and analyzed to determine their nutrient concentrations before a sound nutrient management plan can be designed and implemented.

What Are Some Considerations of Using Poultry Litter in Vegetable Production?

Environmental considerations. Utilizing poultry manure as a fertilizer is recommended as a best management practice (BMP) when applied to meet crop nutrient needs in conjunction with appropriate soil tests. As a BMP, using poultry litter in crop production removes the manure from concentrated areas where there is potential for nutrient runoff. The most common procedure for determining the amount of manure to add per acre is to consider the manure's N content and the N needs of the crop. In areas where off-site P movement (leaching or run-off) can lead to eutrophication of surface waters, P rather than N should be the factor determining application rate of manure.

How much of the fertilizer requirement should be applied from manure? Typically soil testing labs recommend supplying up to 50% of the nutrient requirements from manure. This is a good rule of thumb, but can be modified where multiple crops will be grown in succession on the same mulched bed. There are several challenges with attempting to supply 100% of the fertilizer from manure. Since the manure releases about 50% of its nutrients upon mineralization within the first year, one would need to apply high rates of manure to get all the nutrient requirements for that year. Then there would be significant nutrient left to mineralize over the intervening non-crop period. These nutrients could be lost to runoff or leaching unless there was a cover crop planted after mulch removal, or another crop planted immediately on the mulched beds. Also, if the C:N ratio of the applied litter is high, the nutrient release can be delayed or limited and piling up of high amounts of manure on plant beds can interfere with plant emergence. The user should inquire about the degree of composting and how mature the compost is; generally, composting speeds the decomposition and availability of nutrients. Variations in composting periods and among sources make laboratory analyses important.

Economic considerations. Poultry manure is considered a "low-analysis" nutrient source. That is, it contains low concentrations of plant nutrients. Therefore, costs for moving and applying manure are typically not favorable compared with high-analysis chemical fertilizers. Economic considerations for using manure will include: its overall nutrient value, the proximity to the fields where it will be applied, and other values to the manure that are not available from chemical fertilizers (organic matter for example). Another consideration might be the longevity of the manure's nutrient supplying capacity. In this regard, the manure might be similar in function to a controlled-release fertilizer, therefore obviating the need for (and costs associated with) nutrient side-dressing or injection into a drip irrigation system.

Mineralization rates in sandy soils. Since manures and litters are organic materials, they will decompose or mineralize in aerated soils such as we have in Florida. Mineralization rates of manure materials in warm, moist, sandy soils are rapid, and this factor must be taken into account when calculating the application rate for crop production. Laboratories typically take into account the mineralization rate in soils when making recommendations for manure application. Most labs assume that 50% of the manure will be mineralized and release nutrients in the first year, the remaining nutrients will be held in the organic matter for later release at about 50% of the remaining amounts each year. These release rates were developed in northern states and no such rates have been developed for Florida. Based on preliminary research conducted at the UF/IFAS North Florida Research and Education Center (NFREC), near Live Oak, the rates of mineralization for Florida appear to be greater than for northern states, probably nearly complete over a three-year span. The mineralization and release of N from manures is of particular concern where nitrate contamination of water bodies is an issue. If manure were applied at rates that would release more N than a crop could remove, then nitrate could be lost to leaching to the groundwater. This environmental aspect is becoming an important consideration for regular testing of manures and their application at appropriate rates for crop utilization. Development of the nutrient management plan is a sound investment to avoid environmental issues.

Several seasons of research, funded by the Florida Department of Agriculture and Consumer Services, Office of Agricultural Water Policy, has recently been completed by the UF/IFAS NFREC-Suwannee Valley near Live Oak, to evaluate the mineralization rate for typical poultry manure with litter (Figure 3). The treatments are presented in Table 2 and the application of manure shown in Figure 4. Crop responses are shown in Figure 5. The results from all three seasons were similar. The results from the final season, 2006, showed that poultry manure can be used successfully for mulched vegetable production. Applying 25% to 100% of the total N needs of the crop from manure resulted in similar crop yields (Figure 6). As the proportion of poultry manure or litter used to supply the total N exceeded 25 to 50%, greater amounts of N remained in the soil to be mineralized late in the season (Figure 7). Greater rates will risk leaching losses of N from unmineralized manure late in the season or after the crop season is completed.

Figure 4. Poultry manure (litter) being applied in research plots to determine manure mineralization rates and crop response to rates of manure. The manure will be incorporated in the soil with drip irrigation and polyethylene mulch applied to the beds to grow vegetables.
Credits: G: Hochmuth

Other Examples of Research with Poultry Manure in Vegetable Production in Florida

Poultry manure applied at rates recommended from a manure analysis can be used successfully to grow vegetables. The following graph presents the results of a study conducted at the UF/IFAS NFREC-SV near Live Oak, FL in 2000 (Figure 8). The project compared watermelon production with three fertilizer treatments: (1) the IFAS recommended rate (150 lb/acre N), (2)1.5 x the IFAS recommended rate, and (3) the UF/IFAS recommended rate with 50% of the N from manure. The third treatment resulted in the highest fruit yield.

Other studies conducted in the 1990s with eggplant, cabbage, and squash (Hochmuth et al., 1993; 1997) showed poultry manure can be successfully used as a source of nutrients for mulched vegetables. Mineralization rate is rapid so that little nutrient value remains for a second crop, if the recommended rate of manure was used for the first crop.

Figure 5. Responses of muskmelon to rates of manure; foreground is recommended rate of fertilizer from manure; behind are plants with no fertilizer.
Credits: G: Hochmuth

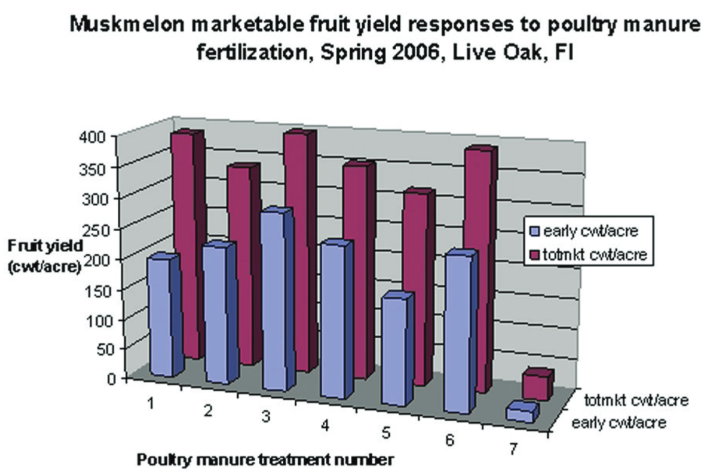

Figure 6. Marketable yield responses to poultry manure fertilization, Spring 2006, Live Oak, FL.

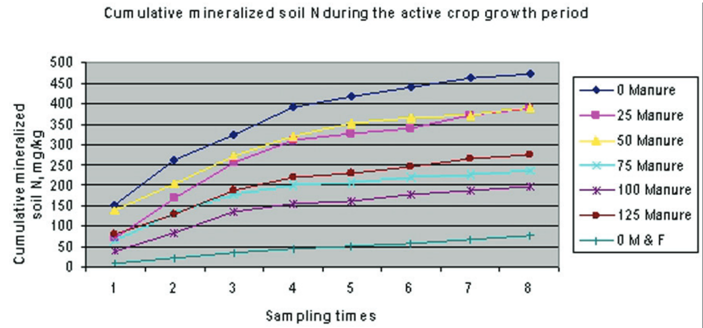

Figure 7. Mineralized soil nitrogen during the 8 weeks of active crop growth period. The "0 Manure" treatment consisted of 100% N from ammonium nitrate (F). Treatments are expressed as the % of crop N supplied from manure-remainder was supplied from ammonium nitrate.

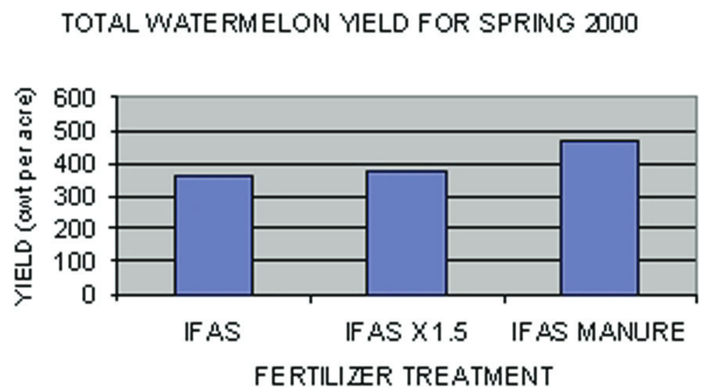

Figure 8. Watermelon yield with soluble N at IFAS rate and 1.5 X IFAS recommended rate (150 lb/acre), and recommended poultry manure rate assuming 50% mineralization, spring 2000, Live Oak, FL.

Steps for Using Manure in a Mulched-Bed System for Vegetable Production

Step 1. Determine a **source for manure** and confirm the economic benefit. Ideally, the grower will want a dependable source that can supply the needed amounts in timely order.

Step 2. Determine the fertilizer recommendations for the crop by submitting a **representative soil sample** to the UF/IFAS Extension Soil Testing Lab at http://soilslab.ifas.ufl.edu which provides a standard soil test for lime and nutrient requirements and standard UF/IFAS nutrient recommendations. Guidelines for sampling poultry manure can be found at http://edis.ifas.ufl.edu/SS495.

As part of step 2, determine the **nutrient content of the manure** and the rates of application for specific crops. The UF/IFAS Livestock Waste Testing Lab (LWTL) follows the Standardized Nutrient Recommendations and provides the recommended rates calculated on a broadcast-acre basis, i.e., uniformly spread over the surface of the acre. For mulched crops, we recommend applying this amount of manure to the bedded area only, so that all the nutrients in the manure are in the soil under the mulch and available to the crop.

Step 3. **Calibrate the manure spreader to apply the recommended rates of manure**. A carefully calibrated manure spreader should be used for the manure application that can drop the manure in a wide band in the area where the planting bed will be made. This application technique will place all of the manure in the planting area, resulting in all of the manure ending up in the root zone under the mulch. Information on calibrating manure spreaders can be found at http://www.caes.uga.edu/publications/pubDetail.cfm?pk_id=6428 and at http://www.ces.purdue.edu/extmedia/AY/AY-277.html

Step 4. **Apply the manure in timely manner**. Manure for mulched vegetable production should be applied as close to planting as possible. It is possible to lose a significant portion of the nitrogen in the manure from volatilization if it is left on the soil surface for several days prior to incorporation (Figure 9).

Figure 9. Manure spreader that can be used to apply manure for mulched vegetable crop production.
Credits: J. Jones

Step 5. **Following spreading of the manure, the manure should be thoroughly incorporated by rototilling**. The drip-irrigation tubing and the plastic mulch can be applied after bedding (Figure 10).

Collecting Poultry Manure Samples

Vegetable growers should have a plan with the supplier of the manure to be used for crop production so that adequate sampling and analyses can be completed before the fertilizer program is determined. A sample about 1 month ahead of application provides enough time to have the sample analyzed and time to calculate the amount of manure needed. Sampling methods are described in detail in the publication HS 938 "Collecting a poultry litter sample for analysis" available at http://edis.ifas.ufl.edu/SS495. Manure should be stored under cover, such as in a concrete-floor stack barn (Figure 11) in the time before field application. A second sample at the time of field application will allow accurate calculation of the nutrients applied from the manure. All samples should be as representative as possible of the bulk manure and carefully packaged for delivery to the laboratory (Figure 12). To see a copy of the manure sample submission form, please go to http://arl.ifas.ufl.edu/ARL_files/formsubmit/webfiles/login.asp

Figure 10. Incorporating manure in the beds for vegetable production.
Credits: G: Hochmuth

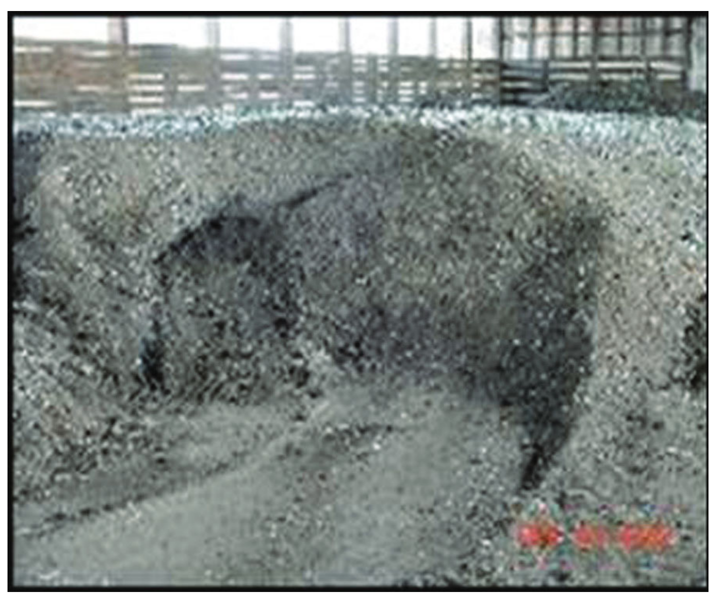

Figure 11. Poultry manure stored in a covered stack composting barn.
Credits: J. Jones

Figure 12. Manure sample ready for delivery to the laboratory.
Credits: J. Jones

Choose a Laboratory

Growers should consult with the lab that will do the analyses to be sure the recommendations are supported by research. Research documentation should reflect manure use under warm, humid, sandy soil growing conditions.

Who Should Use the Manure-Testing Service?

- Livestock producers who would like to use livestock waste as a nutrient source, soil amendment or animal feed.
- Crop producers who plan to use livestock waste for application to cropland.
- Homeowners who plan to use livestock waste as a fertilizer or soil amendment.

How Do I Use Their Service?

Simply contact your local county extension office personnel. They will make an appointment to discuss your manure management system and provide advice in the collection of waste samples to be analyzed. The laboratory results and specific manure management recommendations will be provided within two weeks via your extension agent.

What Will the Laboratory Provide?

The UF/IFAS LWTL, located at the UF/IFAS Analytical Services Laboratories in Gainesville, will provide N, P, and K contents, solids, and pH analyses of livestock waste samples. The following specific analyses will be provided:

1. **Total Solids** is the dried weight of the submitted sample divided by its original weight or volume. Useful in determining the residues from land application.

2. **Ash** is the weight of the dried solids after ignition at 555°C divided by its original weight. The difference between the total solids and ash content is the organic matter in the sample which is useful in determining soil amendment properties and mineralization rates after application.

3. **Total Kjeldahl Nitrogen** is determined by the Kjeldahl procedure which measures the organic and ammonia nitrogen in the submitted sample. This value includes all nitrogen except nitrate and nitrite which are in low concentrations in manure samples.

4. **Ammonium Nitrogen** is the common inorganic form in which nitrogen exists in waste and waste water samples. Ammonium can be rapidly converted to ammonia gas under basic (high pH) soil conditions. Ammonia is highly volatile and is useful in estimating potential losses of nitrogen before it becomes available for plant use.

5. **Total Phosphorus (P)** is the total phosphorus in the submitted sample as determined by the persulfate digestion, stannous chloride method at the LWTL. NOTE: Results are given as elemental P and therefore must be multiplied by 2.3 to be converted to P_2O_5.

6. **Total Potassium (K)** is the total potassium in the submitted sample as determined by the ion specific electrode method. NOTE: Results are given as elemental K and therefore must be multiplied by 1.2 to be converted to K_2O.

7. **pH** is a measure of the acidity / alkalinity of the submitted sample. A pH of 7 is neutral, a pH less than 7 is acidic, and a pH greater than 7 is alkaline. High pH can increase the volatilization of ammonia from the sample.

For more information about BMPs and implementation on your farm, please see the *Agronomic and Vegetable Crops BMP Manual for Florida* http://www.floridaagwaterpolicy.com/PDF/Bmps/Bmp_VeggieAgroCrops2005.pdf.

Also contact your local UF/IFAS Extension Office: http://solutionsforyourlife.ufl.edu/map/index.html, or visit the EDIS website: http://edis.ifas.ufl.edu.

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Table 1. Average nutrient composition of poultry manures[1].

Manure Type	Total N	Ammonium (NH_4-N)	Phosphorus (as P_2O_5)	Potassium (as K_2O)
Broiler	**lb/ton**			
Fresh (no litter)	26	10	17	11
Broiler house litter[2]	72	11	78	46
Breeder house litter[2]	31	7	54	31
Stockpiled litter[2]	36	8	80	34
Layer				
Fresh (no litter)	26	6	22	11
Undercage scraped[3]	28	14	31	20
Highrise stored[4]	38	18	56	30
	lb/1,000 gallons			
Liquid slurry[5]	62	42	59	37
Anaerobic lagoon sludge	26	8	92	13
	lb/acre-inch			
Anaerobic lagoon liquid	180	155	45	265

[1]Source: Biological and Agricultural Engineering Dept., North Carolina State University, as reported in "Poultry Manure as a Fertilizer Source," 1997, Soil Facts fact sheet AG 439-5 authored by J.P. Zublena, J.C. Barker, and T.A. Carter, http://www.soil.ncsu.edu/publications/Soilfacts/AG-439-05/ North Carolina Coop. Ext. Serv., Raleigh.
[2]Annual manure and litter accumulation; typical litter base is sawdust, wood shavings, or peanut hulls.
[3]Manure collected within two days.
[4]Annual manure accumulation on unpaved surfaces.
[5]Six to 12 months' accumulation of manure, excess water usage, and storage-surface rainfall surplus; does not include fresh water for flushing.

Table 2. Fertilizer treatments (rate based on N) used in poultry manure mineralization study with muskmelon at NFREC-SV, Spring, 2006.

Treatment	Percentage of recommended N from:		Manure ton/acre	From manure (lbs/A)		
	Manure	Ammonium nitrate		N	P_2O_5	K_2O
1	0	100	0	0	0	0
2	25	75	0.73	38	50	34
3	50	50	1.44	75	98	66
4	75	25	1.92	100	130	88
5	100	0	2.88	150	196	132
6	125	0	3.61	188	245	166
7	0	0	0	0	0	0

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