Soil Properties Pertinent to Horticulture in Florida

Willie Harris, Myrlene Chrysostome, Thomas Obreza, and Vimala D. Nair

Introduction

Florida's horticulture is a growing industry that annually brings billions of dollars to the economy in terms of sales (15.24 billion in 2005; Hodges, 2007). It also brings benefits such as jobs, taxes paid to local and state government, and important quality of life items (like food!). Optimizing horticultural production while minimizing environmental impacts requires an understanding of how soil properties affect the fate of water and nutrients (e.g., Stamps, 1996; Muchovej et al., 2005; Simonne and Hochmuth, 2007; Thompson et al., 2007).

Soils strongly influence plant ecology and survival (Raynaud and Leadley, 2004). Native plant communities are associated with specific groups of soils (Florida Soil and Water Conservation Society, 1989) and serve as powerful above-ground indicators in the mapping of Florida soils. Transitions from one plant community to another, such as from sandhills to wet prairie, correspond to parallel transitions in soil properties along landscape and hydrologic gradients. Plants well adapted to one soil condition might fail to survive in another. It follows that soil properties are an important consideration in effective plant management at the field scale. They also affect the nature and degree of environmental risk associated with management practices required for economically viable horticultural production. Hence, soils are a critical consideration in developing sustainable management practices.

Horticulture in Florida is practiced on a wide diversity of soils. The objective of this paper is to provide an overview of Florida soils, with emphasis on soil properties most pertinent to nutrient and water management in horticulture.

Basic Soil Concepts and Conventions

The topics of soil genesis, description, and classification are beyond the scope of this paper. However, it is useful to convey some basic aspects about soils to provide a background for soil interpretations related to nutrient management. More support on soil fundamentals can be found at the following url:http://wgharris.ifas.ufl.edu/hsw.HTM

All soils are a product of climate, parent material, topography, organisms, and time. These classical soil forming factors (Jenny, 1941) are discrete, yet interactive in their effects. For example, a lower landscape position (topography) may have wetter soil (microclimate) and higher annual biomass production (organisms) resulting in a thicker, darker surface horizon (layer) than adjacent uplands. The influences of parent material and topography in Florida soils are manifested most profoundly through their control of hydrology, which is an important determinant of vegetation and soil genesis.

Soils are conventionally described by the color, texture, structure, and consistence of horizons. Textural class (e.g., sandy loam, clay loam, clay) is determined by the relative proportion of sand (2-0.05 mm diameter), silt (0.05- 0.002 mm) and clay (<0.002 mm) particles; structure refers to the nature of soil aggregation (e.g., granular, blocky); and consistence is the way soil responds to stress (e.g., friable, firm, etc.) as well as its stickiness, and plasticity when wet.

Soil horizons are layers formed by soil processes. It is useful to know master horizons, which are summarized here in the sequence that they commonly occur by depth in Florida:

O = High organic matter; generally ≥ 12% organic carbon; dark.

A = Enriched in organic matter, but less than O; can be dark.

E = Depleted of some fine components; generally lighter in color that A & B.

B = Accumulation of fine components transported from above or formed in situ.

C = Little or no evidence of soil weathering

R = Rock

It is also useful to know a few common subordinate distinctions used with master horizons to convey genetic information:

p = plowed or otherwise disturbed; ex: Ap

t = clay accumulation by enrichment from above; ex: Bt.

h = organo-Al accumulation by enrichment from above; ex: Bh.

w = soil color or structure without significant accumulation from above; ex: Bw.

g = dominance of gray color attributable to Fe reduction; ex: Bg or Btg.

i = low degree of organic matter decomposition; ex: Oi.

e = intermediate organic matter decomposition; ex: Oe.

a = high degree of organic matter decomposition; ex: Oa.

The following abridged official description (color notations omitted) of the Myakka soil series (http://www2.ftw.nrcs.usda.gov/osd/dat/M/MYAKKA.html), the State Soil of Florida, provides an example of how it all comes together:

A--0 to 15 cm; black crushed, sand; weak fine granular structure; very friable; matted with many fine and medium roots; strongly acid; clear smooth boundary.

E--15 to 50 cm; white sand; common fine faint vertical dark grayish brown, dark gray, and gray streaks along root channels; single grained; loose; common fine and medium roots; strongly acid; abrupt wavy boundary.

Bh1--50 to 60 cm; black sand; weak coarse subangular blocky structure; many fine and medium roots; sand grained coated with organic matter except for common fine pockets of uncoated sand grains; very strongly acid; clear wavy boundary.

Bh2--60 to 80 cm; dark reddish brown sand; common coarse faint vertical tongues of very dark brown weak coarse subangular blocky structure; many fine and medium roots; sand grains coated with organic matter; very strongly acid; clear smooth boundary.

Bh3--80 to 91 cm; dark reddish brown sand; weak fine granular structure; very friable; few fine roots; sand grains coated with organic matter; strongly acid; clear wavy boundary.

C/B--91 to 142 cm; dark brown sand (C); weak fine granular structure; very friable; few fine roots; common medium distinct dark reddish brown Bh bodies; strongly acid; clear wavy boundary.

C --142 to 216 cm; dark grayish brown sand; single grained; loose; few fine roots; strongly acid.

Thorough and accurate soil descriptions like this are the basis of soil genetic inference, classification, and interpretation for use and management. Soil morphology reveals a lot about soil to the trained eye. It enables inferences about infiltration, hydraulic conductivity, plant-available water, nutrient retention, seasonal high water table, runoff potential, leaching potential, and plant root restrictions. These latter properties are pertinent to horticulture and will be the focus of this paper. Some of them are expensive to measure quantitatively, and qualitative expert judgment is often relied upon.

Overview of Florida Soils

Florida is entirely within the US southeastern coastal plain, thus its soils have formed primarily in marine deposits. Nonetheless, it has an extremely diverse array of soils – sands, mucks, marl, and rock-plowed limestone – ALL of which are used in horticulture and which represent extremely contrasting media for plant propagation. Even among sandy soils there are marked differences in properties and conditions that can affect horticultural crops, as will be elaborated upon in later sections. Soil distribution in Florida (Fig. 1) shows a general correspondence with physiographic features of the panhandle (western highlands) and peninsula (central ridge and Everglades). Flatwoods soils are prevalent throughout the state except at the far western and southern tips.

Florida soils are predominantly sandy from Lake Okeechobee northward (Brown et al., 1990). Soils of the panhandle and the northern to central peninsula formed mainly in sandy to loamy marine and fluvio-marine parent materials, under a variety of drainage conditions. Sandy surface textures along with nearly level topography in much of Florida favor rapid infiltration and result in leaching risks. Surface runoff can occur where soil water storage is limited, as on the poorly-drained landscapes that are prevalent in Florida. Poor drainage in Florida is commonly the result of subjacent aquitards (as in mid-peninsular Florida) or elevations that are near sea level (as in near-coastal regions). Sandy soils that have no subsurface aquitards and that are well above regional base level (ocean or river level) tend to be excessively well drained. Examples of such a setting are "sandhills" ecosystems that are common along the central ridge (generally corresponding to "Entisols B", Fig. 1). In contrast, sandy soils on flatwoods landscapes are generally poorly drained due to subsurface water movement restrictions as well as small hydrologic gradients (nearly level topography).

Soils south of Lake Okeechobee (The Everglades) formed predominately under very poorly drained conditions in sawgrass residue or in calcium carbonate ($CaCO_3$) associated with or derived from shallow or exposed limestone. Consequently, the area is dominated by organic soils (Histosols; Fig. 2) and soils rich in $CaCO_3$. There are fairly extensive areas of secondary $CaCO_3$, called "marl", precipitated in shallow water as promoted by photosynthetic CO_2 uptake by algae. Areas of exposed limestone have been rock plowed and used for horticulture, exploiting the warm winter climate (Li, 2001). The marl soils range from nearly pure $CaCO_3$ to containing a significant quantity of quartz sand. Recent research suggests that their organic fraction behaves anomalously with respect to pesticide sorption (Kasozi, 2007), perhaps because of the prevalence of algal residue versus plant detritus. Organic soils thin southward, and very shallow soils over limestone rock are common southeast of Miami and in the Keys.

The USDA soil taxonomic hierarchy consists of 6 categories: order, suborder, great group, subgroup, family, and series. Seven of the 12 soil orders defined in the USDA system are found in Florida (Fig. 2). The morphology and composition of these soil orders affect their suitability for horticulture, as will be discussed in later sections. In Florida, Spodosols are associated with fluctuating water table, and most Histosols are very poorly drained. The other soil orders can range from well- to very-poorly drained.

There are numerous soils series within each order. The soil series is the narrowest class within the USDA soil taxonomic hierarchy. Series are distinguished by properties related to use and management.

Sources of Florida Soil Information

The most valuable sources of information about Florida soils are county soil survey reports. These can be obtained in hardcopy from the Florida Soil and Water Conservation Districts and from some libraries. Digital (pdf) versions for some counties are also available on line at: http://soils.usda.gov/survey/online_surveys/

Soil survey reports contain maps showing soils delineated on aerial photographs. The map units are usually named by one or more soil series, but the delineations they apply to on the soil map also contain inclusions of other soils as is specified in the map unit write-up. The write-up has information about use and management. Also the report has many tables that rate soils of the county with respect to use and management and that include information pertinent to horticultural crops.

Another excellent source of information about soils and crop production is the Electronic Data Information Source (EDIS) maintained by UF/IFAS Extension: http://edis.ifas.ufl.edu/index.html

Soil Properties Affecting Plant-Available Water and Root Viability

Plant-available water and root viability are critical considerations in horticulture. Water deficits can lead to loss of turgor, partial stomatal closure, reduced nutrient uptake, and ultimately to reduced growth (Haman and Izuno, 2003). Hence, soil-plant-water relations are important to take into account (Bouma et al., 1982a, b, c). Water deficits can ironically be brought about by prolonged water saturation in the root zone (too much water!) which can have a negative effect on root viability and proliferation.

The need to minimize both moisture stress and water use, a particularly difficult balancing act for sandy soils (Madramootoo et al., 1995), has led to sophisticated approaches to soil moisture monitoring in tandem with irrigation control (e.g., Munoz-Carpena et al., 2002; Munoz-Carpena, 2004; Dukes and Scholberg, 2005). Water availability relates to climate, overall soil drainage on the landscape, and soil properties that control water retention. There are seasonal and geographic variations in Florida rainfall distributions (Carson, 1951) that are pertinent to horticulture, but climate is not addressed directly in this paper. Rather, the focus is on soil drainage and the following soil characteristics critical to soil-plant-water relations, as defined below:

- Gravitational water: The fraction of water that drains from gravity following a saturation event.
- Field capacity: The point at which no more water drains from a soil following saturation; not a constant water content or tension; often taken as water held at 33 kPa (1/3 bar) as a rule of thumb, but is at lower tension (e.g., 10 kPa or 1/10 bar) for sandy soils.
- Permanent wilting point: The tension at which plants cannot extract water; generally approximated at 1500 kPa but varies with both soils and plants.
- Plant available water (% volumetric water content): Water held by soil between field capacity and permanent wilting point.
- Soil moisture release curve: The relation between water tension and volumetric water content (Fig. 3).
- Hydraulic conductivity (cm/h): The rate at which water moves through soil.
- Infiltration rate (cm/h): The rate at which water penetrates the soil surface.

Soil drainage effects

Most plants cannot reach optimum growth when soil water is in excess, i.e. the soil is not adequately drained. Poor aeration limits oxygen needed for root respiration. In addition, effective drainage stimulates diffusion of carbon dioxide from plant roots. Soil aeration is critical for microorganism activities that increase nutrients availability. Moore (2005) pointed out that in ornamental horticulture, growing substrates can be effective only if they provide good aeration and drainage. As is the case for many crops, poor drainage decreases the resistance of Florida citrus plant roots to many soil-borne diseases (Jackson, 1991). Soil drainage is an overarching factor in controlling crop-available moisture during the growing season. It encompasses the hydrologic dimensions of water flux at the landscape scale (Bouma et al., 1982c) and the properties of soils that affect water retention (Bouma et al., 1982a,b).

Horticultural crops differ in their water needs and tolerance of soil wetness (Stewart, 2007). Hence a good match between the crop and the natural or artificial drainage conditions is of prime importance. *Soil drainage classes* (Table 1) are interpretations about how well suited soil drainage is for crops (NRCS, 2008). Hence, they are not exactly a "one size fits all" designation since optimal drainage conditions vary for different crops. For example, "well-drained" for citrus may amount to deeper drainage than would be optimal for some other crops. The drainage class designation for many Florida soils are based on citrus production.

A high seasonal water table can limit root growth of horticultural crops that are not adapted to poorly-drained conditions. In fact, high water tables result in seasonal root death even for plants adapted to flatwoods hydrology. Prolonged water saturation can ultimately result in too little water foraging volume for some crops. Ditches and tile drains can alleviate the problem if logistics (e.g., proximity to markets, climate, crop value, etc.) warrant the expense. However, artificial drainage can have environmental consequences, as will be addressed later.

Soil morphological and compositional effect

Plant-available water depends on how much water a soil holds within the range of water tension that can be extracted by plant roots. This range varies markedly based on soil properties, including organic matter content, texture, and for sandy soils the abundance of grain coatings (Fig. 4). The high surface area and hydrophilic nature of most soil organic matter result in very high total- and plant-available water content. Plant-available water can be inferred from water release curves, which show declining water content (water release from the soil) as tension increases (Fig. 3). Total water content across the range of tensions is lowest for sandy soils and generally highest for clayey soils, with silty soils being intermediate. However, silty soils tend to have the highest plant available water because they hold more water than either sand or clay between field capacity and the permanent wilting point (Fig. 3). That is because silt-sized particles have a high proportion of voids of the size that retain water against gravity but at tensions that plants can extract. Clay, on the other hand, has a high proportion of very small voids that retain water at tensions above the permanent wilting point.

The effect of sand grain coatings is a "variation on the theme" of soil texture. The presence of coatings markedly increases moisture retention relative to sandy soils with no coatings (Muchovej et al., 2006). That is because the coatings contain clay and silt that impart pores in which water can be held against gravity. Coated sand grains are distinguished by their brownish colors (Fig. 4) as opposed to the light gray to white colors of clean quartz sand (quartz dominates the sand fraction of Florida soils).

Soil Properties Affecting Nutrient Availability and Potential for Loss

Many of the same soil properties and conditions that affect plant-available water also influence nutrient availability and potential for loss. For example, organic matter content and sand grain coatings enhance retention of nutrients as well as water. However, nutrient dynamics are related to their reactivity with soil components, redox-related biogeochemical processes, and to hydrological factors that dictate leaching and runoff potential.

Soils are the "palette" upon which applied nutrients are "painted". Soil drainage is the "brush" to the extent that it determines the part of the palette that is exposed to the "paint" (nutrients) as well as the duration of exposure. The soil palette is not a white canvas, but rather is a compositionally and spatially complex medium. However, that complexity is not random! It is based on the orderly arrangement of horizons that formed from pedological processes. Hence the depth and direction of subsurface water flow in conjunction with soil morphology and composition (horizon distributions) are important and predictable determinants of nutrient retention.

Florida ecological communities are associated with specific landforms, soils, and drainage conditions that relate to horticultural considerations. The prevalent soils associated with three of these are emphasized here – flatwoods, sandhills, and sawgrass marsh – because of their areal prevalence and diverse hydrology. The paper also addresses issues related to karst, which refers to landscapes characterized by subsurface drainage through limestone solution channels.

"Flatwoods" soils

"Flatwoods" is a term applied to nearly-level, poorly-drained uplands with an associated native plant community dominated by pines and relatively dense understory vegetation. "Poorly-drained" and "uplands" might be considered oxymorons in other physiographic regions where wetness is associated with depressions, toeslopes, etc. However, poorly-drained uplands are prevalent in the lower coastal plain of the southeastern US and are characterized by seasonally-fluctuating water tables. Reasons for the poor drainage include minimal gravitational gradient and either the presence of a subsurface aquitard or surface elevation that is minimally above mean sea level. Lateral water movement and evapotranspiration mainly dictate water flux (Martinez et al., 2008); the rate of movement is commonly enhanced by artificial drainage for agricultural and horticultural purposes. Horticultural crops grown on flatwoods soils include citrus, vegetables, and sod (Fig. 1). Citrus on flatwoods requires artificial drainage to avoid root damage (Boman and Tucker, 2002).

The fluctuating water table in a flatwoods soil promotes formation of mainly poorly-drained Spodosols (Harris, 2001). These soils tend to have E horizons of clean (uncoated) quartz sand grains (Fig. 4). The minimal area of reactive surface means that these Spodosol E horizons have essentially no P-retention capacity (Harris et al., 1996). A Bh horizon below the E has a high capacity to adsorb P but retains it less tenaciously than do other subsurface horizons (e.g., Bt) that have less organic C (Zhou et al., 1997). Hence water table depth and flow in relation to E-horizon thickness have a major effect on the potential of P to be transported via lateral subsurface flow to a stream or ditch (Fig. 5). In effect, the deeper the Bh and higher the water table, the less likely that P will encounter a retentive layer in where it could be at least temporarily immobilized. The P enrichment in Lake Okeechobee has been attributed to mobility of manure- and fertilizer P land-applied under this soil-hydrologic scenario. Artificial drainage has potentially offsetting effects on P mobility in that it increases rate of water movement from the site, but it also can lower the water table enough to increase P contact with Bh horizons.

The poorly-drained conditions of flatwoods soils affect the fate of N as well as P. There is a tendency toward denitrification (nitrate reduction and N volatilization) under saturated conditions near the soil surface where there is plenty of organic matter to drive chemical reduction. Hence, nitrate movement to surface water is not generally considered a serious environmental risk (Shukla et al, 2006) relative to P movement despite the minimal affinity of soils for the NO_3^- ion. However, N loss via denitrification is a factor to consider in determining optimal N fertilization rates.

Flatwoods soils constitute a high runoff risk, if "runoff" is expanded to include shallow, subsurface lateral flow. In a sense they are a leaching risk for P in that there is minimal P retention as water flows "sideways" through the E horizon. A "take home" message for flatwoods soils is that there is little margin for error in nutrient management goals to achieve optimal production while minimizing environmental risk. Also, water table manipulations should take into account soil morphological features such as depth to the Bh horizon, since P can be retained there or legacy P (from previous loading) released depending on the P loading history of the site. Application of animal effluent at N-based rates constitutes an environmental risk given that it results in excess P well beyond crop recovery. Soils and hydrologic conditions are conducive to offsite P movement.

"Sandhill" soils

Sandhills are generally gently-sloping landscapes (generally corresponding to "Entisols" in Fig. 1) where there is no subsurface aquitard or sea level influence to restrict vertical water movement. They tend to be recharge areas for deep aquifers. Large areas occur along the central ridge of Florida and are used for citrus production where winter temperatures permit. Soils of sandhills have (not surprisingly) relatively thick sandy horizons. They tend to have upper horizons (e.g., Bw or E) with sand grains that are coated to varying degrees (Fig. 4). Exceptions occur on some positions where deep white E horizons similar to Spodosol E horizons occur. It is common to find Bh horizons below these white horizons at depths below 2 m.

Hydrologic and morphologic differences between sandhill- and flatwoods soils translate into major differences in nutrient dynamics. Sandhill soils typically are excessively well drained. The primarily vertical water movement enables contact of dissolved P with P-retentive soil components. Coated sands of sandhill Bw and E horizons are far more retentive of P than are the clean sands of Spodosol E horizons (Fig 4). That is because the coatings are cemented by metal oxides which, though they comprise a relatively small fraction of coatings by mass, have a high affinity for P. Coatings also contain aluminosilicates (e.g., kaolinite and hydroxy-interlayered) which impart some nutrient retention properties as well. These minerals can specifically adsorb some P and have a finite cation exchange capacity for retaining Ca^{2+}, Mg^{2+}, K^+, and NH_4^+. Hydroxy-interlayered vermiculite reportedly has potential to selectively retain K^+ and NH_4^+ (Rich, 1968). Furthermore, sandhill soils can also have deep loamy Bt horizons that are several-fold more retentive of P and cations than are sandy horizons.

The fate of N in sandhill soils differs from the fate in flatwoods soils. Water saturation does not persist in the near-surface soil environment typical sandhill soils, so good aeration minimizes denitrification (de Ruijter et al., 2007). Furthermore, NO_3^- ions are minimally reactive with soil components. Hence, nitrate movement to groundwater via vertical flow is favored. The minimal organic matter content of deeper horizons, even if saturated, limits the extent of nitrate reduction and hence it can present health and environmental risks.

Sandhill soils have minimal runoff risk due to high infiltration rates and hydraulic conductivity as well as permeable substrata. The latter means that water does not back up into the soil zone during the wet season, as is the case with flatwoods soils.

The horticultural "take home" message for sandhill soils is that they are at less risk of P loss but constitute a greater concern for nitrate than is the case for less well-drained soils. A corollary is that their P retention capacity is still relatively low in comparison with loamy and clayey soils prevalent in other regions. That means they do not have an infinite capacity to safely store P applied in excess of plant requirement for long periods of time.

Sawgrass marsh organic soils of the Everglades

The physical and chemical properties of organic soils are dominated by organic matter, even though organic matter is commonly not the dominant component by mass. Organic matter has mass-disproportionate volume, reactivity, and moisture-retention compared with mineral soil material. Thick, organic soils can only form under very wet conditions in Florida because the warm climate and high decomposition rates otherwise preclude significant organic matter accumulation. Their extensive occurrence in the Everglades is attributable to the long-term build-up from sawgrass roots and detritus. Organic soils require drainage to enable survival of most horticultural crops. An unsettling consequence of drainage is loss of soil due to oxidation that would have been suppressed under the natural submerged condition.

Drained organic soils provide an exquisite plant growth medium with respect to physical and water retention characteristics, though alkalinity can limit availability of some nutrients Hochmuth et al, 1996). A variety of vegetable crops are grown in the drained organic soils of the Everglades agricultural area (EAA). These soils retain cationic nutrients and maintain their plant availability. However, they are less retentive of P because they lack significant concentrations of metal oxides and other P-retaining minerals. Phosphorus movement from the EAA has been invoked as a factor in cattail encroachment on native sawgrass along P enrichment gradients to the south of that area (Newman et al, 1998; Debusk et al., 2001). Sulfate from fertilizer application in the EAA has been implicated in redox-related enhancement of Hg methylation (Bates et al, 2002), the first step to biomagnifications of Hg in the region.

Carbonatic soils of the Everglades

Two types of carbonatic soils occur in the Everglades area: (i) very poorly drained marl soils that form in secondary carbonates in association with organic soils and (ii) soils made by rock-plowing limestone for vegetable production on better drained positions originally occupied by pineland vegetation (Li, 2001). They differ markedly in texture; marl soils are silty while rock plowed soils are very gravelly. The dominance of $CaCO_3$ imposes chemical conditions that must be dealt with in horticultural management (Li, 2001). The carbonates tend to fix P to the extent that plant availability can be a problem. Magnesium uptake can be suppressed by Ca. Micronutrients deficiencies (Fe, Zn, Mn) can be a problem for some crops. Application of chelated Fe and foliar Zn and Mn are used to overcome these deficiencies where they occur (Li, 2001).

Karst considerations

There are large areas of karst landscapes in Florida, including the lower Suwannee River Basin. The combination of well- to excessively-well drained sandy soils and porous limestone bedrock amounts to high vulnerability to contamination for the underlying Floridan aquifer and associated springs, particularly for pesticides and nutrients (such as nitrate-N) that are minimally reactive with soils. Water on karst landscapes moves mainly vertically (Fig. 6) until it reaches the aquifer; graded streams are rare or absent. Hence, like sandhills landscapes and soils, surface runoff is minimal but leaching risks can be high. Risk of P loss is less than for nitrate in horticultural operations since karst soils commonly have coated sands and Bt horizons that can retain P moving vertically in the soil. However, soils could become a P source if loaded with excess P for a sufficient duration, as could happen with sprayfield applications of flushed dairy manure to meet N-based crop requirements.

Assessing Risks and Mitigating Nutrient Loss from Soils

Loss of applied nutrients and other amendments from soils amounts to profit loss in horticulture as well as a potential ecological liability. The risk of loss relates to site characteristics such as sorption capacity of soils for a given amendment, loading history ("legacy"), and potential for transport from a field. Transport can occur via runoff (Sharpley, 1995), leaching (Breeuwsma and Schoumans,1987; Breeuwsma and Silva, 1992), or some combination of these two modes. Approaches are needed to practically and effectively identify site-specific liabilities so they can be addressed by management. The nutrients of greatest concern in balancing crop production and environmental interests are N and P.

The important N solution species in soils are NO_3^- and NH_4^+, both of which can undergo redox transformations leading to N loss via volatilization (Strous et al., 1999). Loss of NH_4^+ decreases with increasing cation exchange capacity because its retention on the exchange complex reduces leaching and volatilization. Nitrate is minimally sorbed in soils due to its low electronegativity and other properties that reduce its coordination with metals. Managing soils to minimize N loss requires taking losses of volatilization and leaching into account and recognizing the critical importance of the timing of application given the unstable nature of N species.

Phosphorus in soils occurs mainly as PO_4^{3-}, which in contrast to NO_3^-, is highly electronegative and strongly inclined to coordinate with Fe and Al (Rhue and Harris, 2001; Harris, 2002). Also, phosphate is not subject to volatilization as is nitrate. Therefore, retention of phosphate is greater than that of nitrate in most arable soils, including most sandy soils of Florida where grain coatings are present (Harris et al., 1996). However, some Florida soils (e.g., Spodosols, Histosols) do not retain P sufficiently to prevent environmental impacts, as has been documented for the Okeechobee Basin (Federico et al., 1981; Allen, 1987; Mansell et al., 1995; Nair et al., 1998) and the Everglades (Newman et al, 1998; Reddy et al., 1998).

The environmental concern about P movement from soils stems from its potential to induce eutrophication in receiving surface waters (Correll, 1998; Daniel et al., 1998). This concern has stimulated much interest in risk assessment and mitigation approaches involving land-applied P. A number of states, including Florida, have drafted a "P index" tailored to the perceived risk factors for soils of the region. The Florida P index as currently drafted gauges factors such as runoff, leaching, previous loading, erosion, potential to reach water body, and source of P.

Considering the P source is important because sources vary in solubility (Shober et al., 2007; Elliot and O'Connor, 2007), and it is the solubility of the P form rather than its concentration per se that dictates risk of off-site movement (Harris, 2002). For example, Fe- and Al-stabilized biosolids contain relatively high concentrations of P, but it is bound in a form that is less soluble than for manures (Harris et al., 1994; Graetz and Nair, 1995; Nair et al., 1995; Wang et al, 1995; Nair et al, 2003) or some other biosolids (Shober and Sims, 2003; Elliot and O'Connor, 2007).

Soil-test P (STP) measures initially calibrated for crop nutrient recommendations have been adapted for P-related environment risk assessment (Sims et al., 2000). Another existing risk indicator, called the P saturation ratio (PSR), is the ratio of molar extractable P to the sum of molar extractable (Fe + Al). This ratio generally has a threshold value ("change point") above which the P released to solution abruptly increases (Nair et al., 2004). Neither STP nor PSR provides a means of predicting the "safe lifespan" of a P application site. However, the PSR can be used to calculate a "safe P storage capacity" (SPSC) in conjunction with the PSR threshold using the formula:

SPSC = (threshold PSR-soil PSR)*(molar extractable Al + Fe) (Nair and Harris, 2004)

This calculation amounts to a determination of remaining capacity (mg kg^{-1}, kg ha^{-1} "furrow slice", etc.) if the metal extractant exhaustively extracts the metal phases primarily responsible for P sorption (Chrysostome et al., 2007).

The SPSC would capture the risk of non-impacted soils that have low P sorption capacity, while STP and PSR would not. For example, Florida Spodosols with negligible P retention would typically produce an STP measurement of < 5 mg kg^{-1}. Thus it would get a "green light" from the STP assessment despite the considerable risk this soil would represent if excess P beyond crop requirements was applied. However, an SPSC- (capacity-based) assessment would reveal the "true colors" of the soil and provide a basis for predicting how long the site could be safely used for further P application. Hence the SPSC has the potential to enable prediction of the lifespan of a P application site with knowledge of the P loading schedule.

One approach to mitigating risk of P loss from soils is to land-apply drinking water treatment residuals (WTR). These residuals are benign waste products that have a high P retention capacity (Elliot et al., 2002; Makris et al., 2004; Makris et al., 2005). Their application can reduce risk of P loss from soils that have minimal P retention capacity or that are a P source due to a history of heavy P loading. A WTR loading rate can be set on a site-specific basis using capacity (SPSC) calculations to reduce risks of P loss while assuring adequate availability P for crops (Oladeji et al., 2007).

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Table 1. Summary of criteria for soil drainage classes. Specific water table depths for drainage class would vary with the nature of the crop. Drainage classes in Florida are calibrated for citrus production.

Drainage Class	**Water Table Levels and Water Holding Capacity**
Very poorly drained	At or above surface for much of the growing season
Poorly drained	At shallow depths for much of the growing season
Somewhat poorly drained	At shallow depths for some of the growing season
Moderately well drained	In rooting zone for short periods during the growing season
Well drained	Too deep to hinder normal plant growth but shallow enough for optimal growth
Somewhat excessively drained	Rarely in rooting zone
Excessively drained	Very deep; water holding capacity lower than for somewhat excessively drained

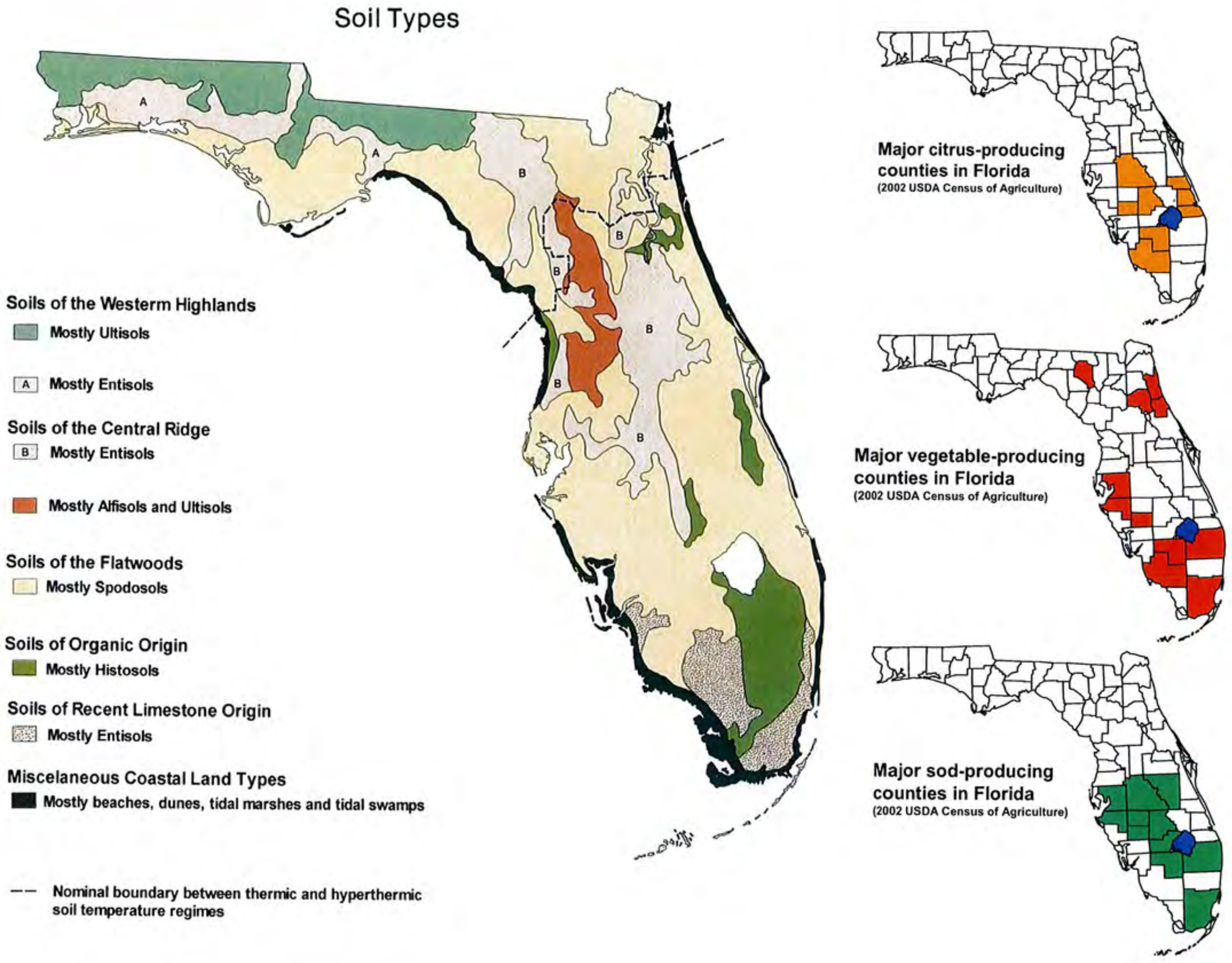
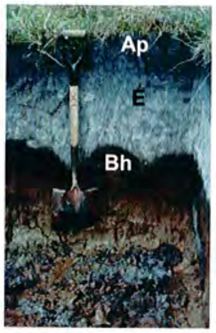


Figure 1. General soils map of Florida (reprinted with permission) by Dr. Victor Carlisle in Water Resources Atlas of Florida (1998) and maps indicating counties of major production for specified horticultural crops. Legend of the general soils map was abridged for the purposes of this paper.



1. Spodosols:

2. Entisols:

Only A, E, Bw, or C

3. Ultisols:

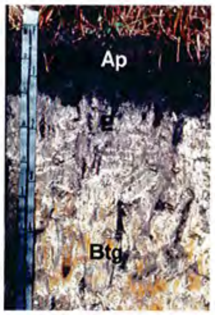
Bt or Btg with low base

4. Histosols:

≥12% organic C

5. Alfisols:

Bt or Btg with high base



6. Mollisol:

Thick dark A horizon

Figure 2. Soil profile images and brief criteria for 6 of the seven soil orders in Florida, in order of areal extent. These profiles are only examples of soils in the designated orders; there is a considerable range in morphological properties for each order. Orders are distinguished on the basis of soil properties, including diagnostic horizons. No image is shown of Inceptisols, the least extensive soil order in Florida. Inceptisols do not have Bt or Bh horizons but can have Bw horizons and thick dark A horizons. Soil photographs were from a pool of soil profile images shared with the senior author by Dr. Vic Carlisle, Mr. Frank Sodek, and various other scientists who contributed to the Florida Cooperative Soil Survey Program.

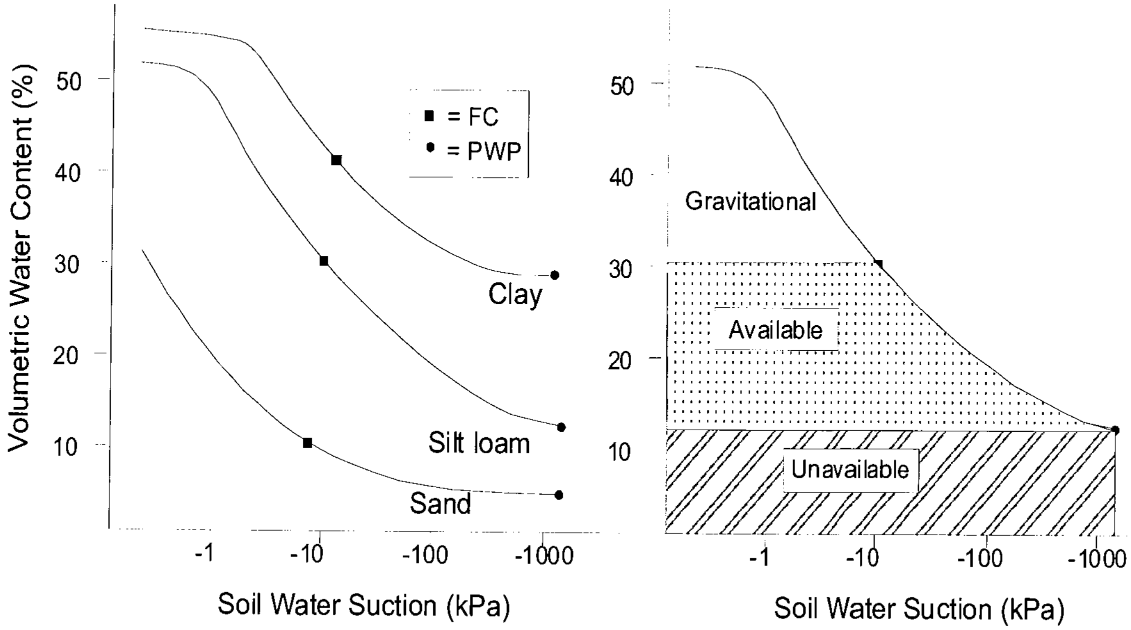


Figure 3. Idealized water release curves showing (left) typical relative distinctions as influenced by texture and (right) schematic distinctions between gravitational-, plant-available- , and plant-unavailable water for the case of the hypothetical silt loam. Note that the silt loam shows the highest available water content, based on having the maximum difference between field capacity (FC) and permanent wilting point (PWP).

Figure 4. Images of soil profiles with coated and uncoated sand grains. The presence of significantly enhances moisture- and P retention in sandy soils. Coatings impart a brownish color to sands, and can be seen with a hand lens. Soil photographs were from a pool of soil profile images shared with the senior author by Dr. Vic Carlisle, Mr. Frank Sodek, and various other scientists who contributed to the Florida Cooperative Soil Survey Program.

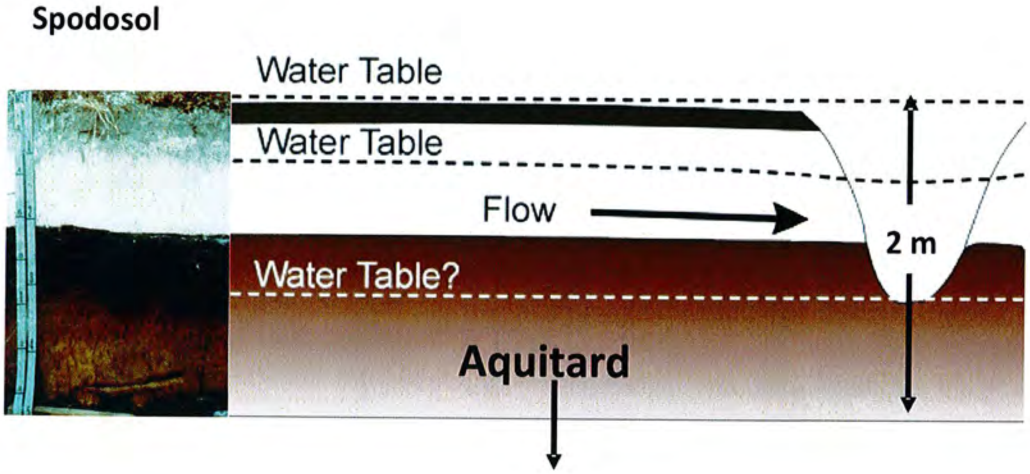


Figure 5. Generalized representation of flatwoods hydrology, depicting low gradient, restricted vertical water flow by aquitard, and fluctuating water table that commonly resides in the E horizon dominated by clean and minimally-reactive quartz sand grains. Soil photograph was from a pool of soil profile images shared with the senior author by Dr. Vic Carlisle, Mr. Frank Sodek, and various other scientists who contributed to the Florida Cooperative Soil Survey Program.

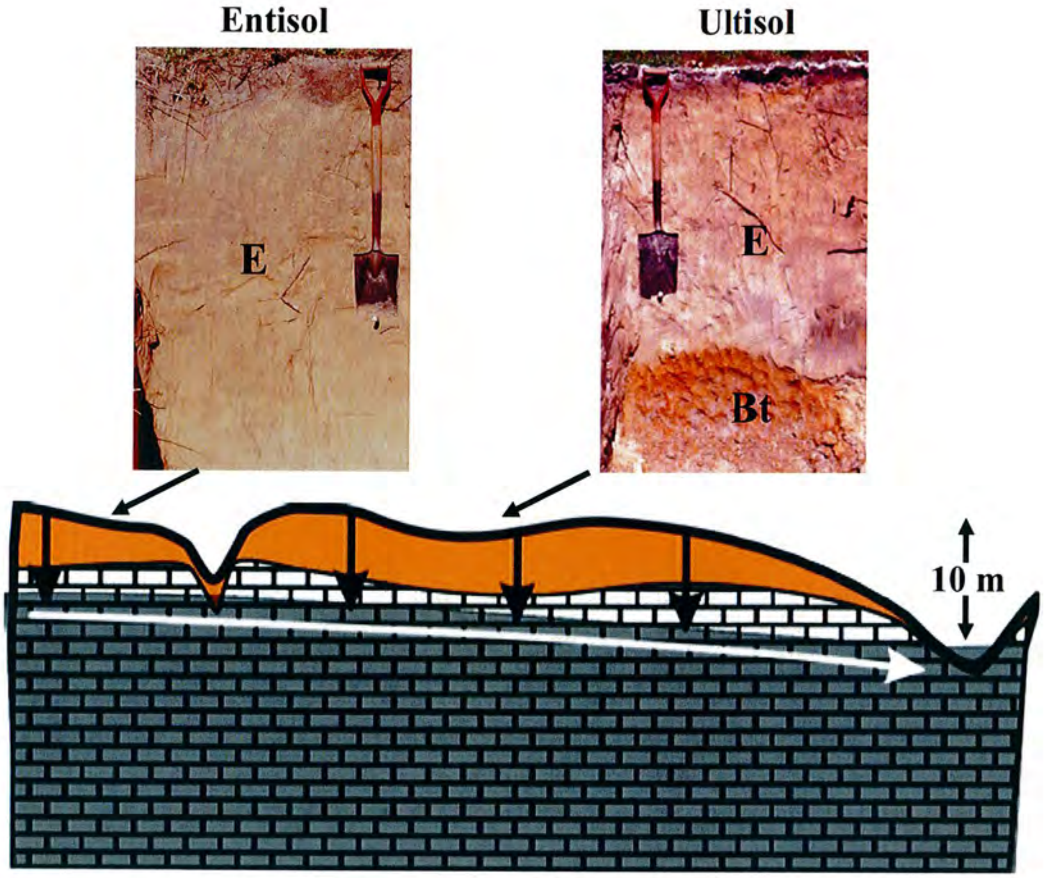


Figure 6. Schematic cross section of a karst landscape and hydrology. Hydrology is generally applicable to sandhills as well; sandhill soils can occur on karst. Black arrows depict vertical water flow from the soil (orange color) to the limestone aquifer (block pattern) and the white arrow indicates gradient and flow direction in the aquifer. Dark region in the limestone represents the water level in the aquifer, which is several meters below the soil surface. Morphology of karst soils suggest components such as metal oxides (Fe oxides impart the color) and clay (Bt horizon) which can retain P. However, the oxidized Fe indicates that the soils are not wet enough in the near surface to promote denitrification. Hence nitrate and other nonreactive soil and crop amendments have potential to move vertically to groundwater without careful management. Soil photographs were from a pool of soil profile images shared with the senior author by Dr. Vic Carlisle, Mr. Frank Sodek, and various other scientists who contributed to the Florida Cooperative Soil Survey Program.