Modeling pecan growth and fertilization under nitrogen and water stress

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Abstract

Rising fertilizer costs and diminishing water resources, have made improved efficiency of water and nitrogen management a top research and extension priority for the deciduous crop industries. Pecan tress use more water (14%) than almonds and consequently the pecan trees are one of the highest water use crops among the deciduous tree crops

Currently, there is no model to simulate pecan tree growth under water and nitrogen stress that has been calibrated and evaluated by experimental data. In this study, a pecan growth model was developed that contains nitrogen and a water stress function. The nitrogen function limits tree growth based on leaf nitrogen concentration. Leaf concentration was calculated by nitrogen concentration at the root zone and nitrogen distribution to the tree components. At the same time, evapotranspiration was reduced by nitrogen stress and interacts with the water stress function. The stress functions and their interactions were derived from a physiological mechanistic model and experimental data. The pecan tree growth model was evaluated by experimental data. The evaluation shows that the water stress function is reasonably accurate, while the model may overestimate the nitrogen uptake. More field experiments needed to calibrate the related nitrogen uptake component of the model.

Introduction

Nut production from pecans, almonds, and pistachios figures heavily in the economies of California, Texas, and New Mexico, and several other states. Production depends upon irrigation, but water supplies for irrigation in the near term appears likely to be cut severely in California (15-50% of normal) and surface irrigation water supplies have been reduced in low runoff years in New Mexico. Only the supplies of the surface water supplemented with ground water has allowed the pecan growers to apply full irrigation amounts to the pecan trees. In the long term, both climate change and population growth and diversion of water to municipal and industrial growth will reduce irrigation water supplies.

Water and nitrogen management in deciduous perennial crops is constrained by a lack of related information and an inability to provide targeted management. Currently, the application of fertilizers and water follows standardized practice with little consideration of spatial, temporal, climatic and crop variability resulting in lost income and negative environmental impact. Rising fertilizer prices, water shortages, market and environmental demands, and the recognition that over 50% of the green house gas production can be attributed to N_2O production by agriculture have resulted in great interest in the development of improved management practice. Irrigation amount at less than the levels that maximize yield and/or profits may have to be done in the future because of water shortages and government regulations. It remains possible to set the timing and amounts of irrigation in such a way as to maximize the yield within the season-total constraints on water use. At the same time, the future yield capacity can be preserved and the death of trees prevented. To develop these optimal schedules for a given fractional availability of water, we must understand how the trees respond to deficit irrigation and its detailed scheduling and get quantitative estimates of how water stress changes tree photosynthesis, its partitioning to nut fill, maintenance respiration, net growth, and reserves, and the dynamics of N in leaves, soil, and reserves. This knowledge that must be incorporated into management practices by the development and use of management tools.

Crop modeling in general is a major research tool in horticulture (Gary et al., 1998), with simulation models being used to understand the integration of physiological processes and mechanisms of tree response to stress. Models are also used to interpret experimental results gained under different environmental conditions and to develop and test new production technologies (Pokovai & Kovacs, 2003). Passioura (1996) argues that models fall into two categories: (1) mechanistic models developed for scientific understanding of processes in nature or (2) functional models developed to solve management problems. Mechanistic models are based on hypotheses, which may or may not be correct, of how plants grow. These models often are difficult to run because of the large number of inputs and state variable changes that occur in the models that cannot be measured in the field. On the other hand, functional models are robust and easy to understand and run but are not necessarily applicable outside the environmental conditions that were used in their development. The functional models can illuminate, to a limited degree, the mechanistic aspect of plant growth within the environment under which they were developed.

Tree growth models usually include four main carbon processes: photosynthesis, respiration, reserve dynamics, and carbon allocation (LeRoux et al., 2001). In forestry, over 27 tree growth models have been developed, each with the main carbon metabolism processes described but each having a different representation of these processes—from empirical relationships to mechanistic models of instantaneous leaf photosynthesis—to account for the major environmental variables. Carbohydrate reserve pools are represented as black boxes in the models with no description of their dynamics except that the pools behave like buffers that absorb the excess carbohydrates on a daily basis. Mobilization from the reserve pool occurs as needed for tree growth processes. In the models, the representation of carbon allocation and of the effects of architecture on tree growth are the main limitations of the models, but reserve dynamics are always poorly accounted for, and the representation of below-ground processes and tree nutrient dynamics is lacking in most of the models (LeRoux et al., 2001). These same processes and deficiencies occur in the smaller number of developed fruit and nut tree models. Fruit and nut tree models have been developed for pecans (Andales et al., 2006), apples (Seem et al., 1986), peaches (two models: Lescourret et al., 1998; Allen et al., 2005), and avocados (Whiley et al., 1988)

Models joined with experiments are an excellent way to synthesize what we learn in experiments and then to estimate the best management strategies. Experiments alone are insufficient and inefficient. For example experiments to induce tree responses to water stress are difficult, expensive, and risky - using many replicate trees means using a large area, and it entails a risk of long-lasting damage or death. Furthermore, we need to cover a wide range of climates, interannual variations in weather, soil types, etc. A multifactorial experiment would be wholly impossible. Consequently, limited experiments to parameterize functional model are needed and then verification of the model using limited experimental condition under different climate conditions can be used to verity the model. After model verification, optimal management decision tress can be derived by the model and implemented using rules or simple nomograph for the use by the end user.

Sometimes experiments can be used to parameterize complex submodels such as a mechanistic photosynthesis submodel and then this model used to determine a water use efficiency number to convert evapotranspiration to photosynthesis and biomass in a functional models developed to solve management problems. The submodel can be run independent of the overall plant growth functional model, but the mechanistic submodel generally requires more complex inputs. When developing complex submodels, the models still need to incorporate robust patterns of plant responses to the environment which means response patterns that have been shown to be common among different species and conditions. One very strong example is the relation of leaf photosynthetic rate to CO_2 concentration (partial pressure) inside the leaf and the kinetics of Rubisco enzyme (or, in lower light, a series of photochemical steps all coming down to one parameter, an electron transport capacity). The famed Farquhar - von Caemmerer - Berry model (Farquhar et al. 1980) puts all this into a simple mathematical form. Another robust pattern is in stomatal control through stomatal conductance (gs), the physiological setting of gs by light level, air temperature, CO_2, air pressure, humidity, windspeed, and water stress described by the Ball - Berry equation (Ball *et al*., 1987). The solution of the model requires the simultaneously solution of the Ball –Berry equation, the net assimilation rate equation and the leaf energy balance equation but the model incorporates physiological feedback and feedforward controls.

When developing complex mechanistic submodels, the submodels can be of different complexity. An example is two photosynthesis submodels with different complexity. One submodel can simulate the structure of the canopy, while the other simpler one can only simulate the sunlit and shaded leaf areas as uniform entities. The relation of these sunlit and shaded areas to detailed canopy structure is set, for one particular canopy structure. The simpler model runs much faster and is easier to comprehend. However, it cannot be applied with high accuracy to new canopies of different structure, unless one runs the complex model at least once to parameterize the simpler model again. This parameterization is needed if one is to use them in arbitrary conditions, or, to have the models be transferrable between sites and conditions. The extreme case of non-transferability is the use of a purely statistical model, a fit to data that applies to one site with limited set of conditions.

Although the complex mechanistic submodel may be more transferable than a simpler model, it is "data-hungry," requiring much more information to use it. This may be a realistic expectation - canopies (or systems in general) differ in many details. Some of the details are important for the results that a user is focusing upon, others are not. This leads to another use of complex models - determining which descriptors of the system are important to the results (simulations, predictions) being examined. One can run the complex model with variations in each descriptor, say, foliage density, or root-length density, or average air temperature, and see how much difference each factor makes. For the factors that don't matter much, we can set them as constants in a simple model or otherwise make them unnecessary to specify.

There also remains a hazard in complex models, that of compensating errors. A complex model may describe very many processes, each with descriptions (such as root length density) that may be hard to obtain from experimental data with a level of effort that is affordable. One may make guesses for the poorly-known descriptors, and possibly "tweak" them all to get the right results for a small set of final variables. The results may have come out well only because errors in one description cancelled those in another (or several others). The only way to check for full consistency is to get a wider array of results - say, not just total growth or total nut yield and total water use, but many details of the time courses of transpiration, etc., or more deeply yet, the responses of various leaves. If these data are not obtainable with the effort that one can mount, then one must live with reservations about the full validity of the complex model.

Tree management model should include a pruning submodel that benefits tree growth and optimizes nut production. Figure 1 from Andales et al. (2006) is a flowchart for the pecan tree growth model showing the allocation of growth. Pruning can affect the alternate bearing characteristics of nut trees. Pecan, pistachio, and almond trees show alternate bearing characteristics that need to be described in a nut tree model. In the pecan model, alternate bearing is a function of stored carbohydrate reserves in the beginning of the year. The impact of carbohydrate reserves on nut set, leaf growth, and final nut yield requires further research to determine if the root carbohydrate reserves affect all nut trees as they affect pecan growth, yield, and alternate bearing (Andales et al., 2006).

The pecan nut tree model lacks a fruit abortion subroutine and a nutrient allocation and nutrient stress subroutine. A very simple nutrient balance model that is not mechanistic was developed for almonds (Brown & Zhang, 2008) and represents the state–of-the-art for modeling nut tree nutrient subroutines' effects on nut yield. Most of the fruit and nut tree models have functions that describe the impact of water stress on tree growth, but future nut tree models need to incorporate the interaction of water, nitrogen, and salinity on tree growth and nut yield. However, limited field experiments have been conducted to describe these interactions at the whole tree level. None of the tree models have subroutines to describe the impact of soil-air-oxygen stress caused by prolonged saturation of the soil profile on tree physiology and growth. This will be an important stress function to incorporate into future nut tree models, especially for nuts like pecans that are grown in locations where heavy soils are flood irrigated and water remains on the soil surface for 5 days, which results in a decrease of oxygen levels near a

0 to 50 cm depth that can cause a decrease in photosynthesis (Kallestad et al., 2007). A pistachio tree model is unique in that it will need an object that describes early splitting of nut as a function not of water status but of temperatures lower than 13°C (Gijón et al., 2008).

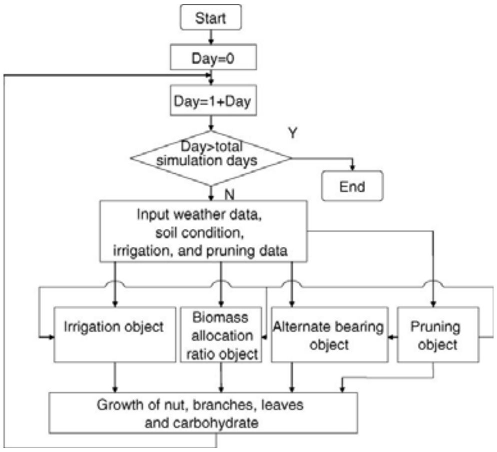

Figure 1. Flowchart of the pecan growth model.

If a tree growth model is built as a user-friendly decision support system, it should include all objects necessary to simulate crop growth using either mechanistic or empirical functional relationships (Reynolds & Acock, 1997). Tree growth models can be built using the traditional method of a main program and a series of subroutines to describe the processes. In this case, the input data is read in through an input subroutine and then information is passed to the other subroutines through common statements. Another programming approach is to develop object-oriented decision support models that contain real-world objects with software counterparts. Each object consists of encapsulated data (attributes) and methods (behavior and interactions). Objects interact with each other and with their environment. Objects also provide interfaces by which users can change attributes or execute methods.

Most computer languages have the ability to program in an object-orientated format, including using an Excel workbook in which each spreadsheet in the workbook can be an object. The advantage of structuring a nut tree model in an object-oriented decision support system is that objects can be added, removed, or changed depending on the model developer's needs. For example, if nutrients are not going to be considered in the model, that object can be removed. As computers and spreadsheet programs have become more powerful, there is no longer a limit to the number of spreadsheet cells that can be used. As a result, spreadsheet nut tree growth models are easy to build and do not require knowledge of FORTRAN or C++ computer languages to change the model. Also, because spreadsheet models do not require compiling, the source code is part of the program and can be either locked to prevent users from changing it or unlocked for future change and development.

With the discussion of the limitation of nut tree model in mind the overall goal of the research was to develop a management model to monitor and predict nutrient demand

and nutrient status in pecan trees along with the interaction of nutrient and water stress on nut yield. Specifically the objective was to develop an optimal schedule (timing and amounts) of irrigation and N fertilization that maximize yield when irrigation water is cut to 50% (or other specified fraction) of normal.

Model description

Because models and submodels can be developed with different complexities a complex mechanistic photosynthesis tree model not including soil water and soil nitrogen balance or growth balance was used to parameterize the water use efficiency, nitrogen stress function, the interaction of water and nitrogen stress in the functional model of pecan tree growth. A description of the function model of pecan tree growth is given by Andales, et al (2006) except for the impact of nitrogen and water stress on water use efficiency and a description of the nitrogen soil transformation and uptake model which will be described latter in the paper.

Description of the complex photosynthesis pecan tree model used to parameterize the pecan tree growth model.

The photosynthesis model resolves the actual structure of the orchard, in which leaves get different light levels. Leaves are in the model are simulated at different angles relative to the direction of the sun, and other leaves intercept part (or all) of the direct sun and part of the diffuse skylight; this includes leaves on neighboring trees, a complexity first addressed by Norman and Welles (1983). The model allows for different three spacing and size with the trees modeled as ellipsoids. The direct solar beam arrives statistically at any spatial location, with a probability calculated by Beers' law and using the real distribution of pecan leaf angles and the total possible obstruction by leaves on all trees between the sun and the location. This is modeled using a probability P_{dir} that the direct beam arrives at full intensity and a probability 1-P_{dir} that is completely blocked at this location. The diffuse beam arrives deterministically, at a fraction P_{diff} that is also computed from Beers' law, but applied to beams from 25 different sky directions.

The total leaf cover is resolved into 125 locations within the canopy. Each location is representative of the same volume of canopy (same number of leaves, and same leaf area) as every other location. At each location the total leave cover for that location is portioned into 10 ranges of angles and thus 10 ranges of direct solar radiation relative to the direct solar beam.

Photosynthesis by the whole canopy

The total photosynthetic rate of the canopy is the sum of the rates for all the leaf areas. It would be computationally very inefficient to compute separately the rate for each location and each leaf angle and each class (directly lit or not). Instead, the model adds up, over all locations, the fraction of leaf area in 10 ranges of total light level (called *irradiance*). Then, the model computes the photosynthetic rate (and transpiration rate) for the 10 different irradiances (the midpoint of each irradiance "bin"). Leaves at different locations also see different temperatures, windspeeds, and humidities which are ignored to simplify the model. The average meteorological conditions for the nearby weather station are used to get the average climate variables adjusted to canopy conditions. The time step for the model is 10 minutes but the time step of the available climate data is 1 hr average values.

The complete environment of the leaf determines photosynthesis. The leaf photosynthetic rate, A_{leaf}, depends not only on the irradiance (in photosynthetically active radiation between 400 and 700 nm in wavelength), but also on temperature, humidity, CO_2 concentration, and windspeed. There are four basic equations that capture the greatest part of the biophysical and biochemical responses and allow a computation of $A_{leaf,}$ the leaf transpiration rate, E_{leaf}, and the stomatal conductance, g_s:

1) The Farquhar - von Caemmerer - Berry model of A_{leaf} in terms of basic photosynthetic capacity ($V_{c,max}$, related to content of Rubisco enzyme, in essence, and closely related to leaf N content), CO_2 partial pressure at the Rubisco sites (C_i), and leaf temperature.

$$\text{Aleaf} = V_{c,\max} \frac{(C_i - \Gamma)}{(C_i + K_{CO})} \tag{1}$$

Where : Γ and K_{CO} are temperature-dependent functions for the Rubisco enzyme.

The temperature of the leaf needed to derive Γ and K_{CO} is determined by the equation of energy balance (the sum of all the methods that a leaf can gain and lose energy, and assume that the leaf is always close to steady state) The model accounts for energy gain from radiation - the PAR portion of the spectrum (close to half of solar radiation), the near-infrared portion (NIR; the other half of sunlight), and thermal radiation. The model has already computed how much PAR reaches various amounts of leaf area and it is assumed that the same amount of NIR reaches these leaves. The model will be in error on this part of the calculation because this is a weak approximation. NIR is absorbed much less strongly; it bounces around in the canopy and reaches leaves deeper in the canopy. This bouncing also means that a significant amount of NIR reaches leaves after first scattering off other leaves.

The thermal infrared radiation (TIR) arrives from two main sources- the sky, radiating from water vapor molecules at a range of altitudes, and the other leaves. The model ignore the radiation from the soil surface. TIR is calculated from:

$$\text{TIR} = rT^4 \tag{2}$$

where :

T is the absolute temperature of the body and
r is the Stef-Boltzmann Constant.

Equation 2 assumes an emissivity of 1 where as leave have an emissivity of 0.98. The effective temperature (T) is assumed to be a fixed number of degrees below air temperature at a weather station which will increase as the pecan leaves become under water or nitrogen stress.

The transpiration rate (E) and evaporative cooling of the leaf depends on the stomatal conductance and a larger boundary-layer conductance, in series, the leaf temperature, and the partial pressure of water vapor in the surrounding air. Because the leaf temperature is part of calculation for the energy balance, the energy-balance equation is solved iteratively. The boundary-layer conductance depends on the leaf linear dimension and on the average windspeed at its location (reference) assumed to be the average wind speed measured at the weather station. The stomatal conductance is calculated from the Ball-Berry equation:

$$g_s = m\frac{A\,h_s}{C_s} + b \qquad (3)$$

Where, A is the leaf photosynthesis rate, A_{leaf},

h_s relative humidity

C_s is the CO_2 mixing ratio at the leaf surface, beneath the leaf boundary layer.

The occurrence of A (A_{leaf})) in equation 3 means that this equation must be solved iteratively with the photosynthesis equation one. This iteration loop represents real physiological feedback and feedforward that occurs in the plant leaves. The values of h_s and C_s depend on A and E of the leaf and on the stomatal and boundary-layer conductance.

Equation 1 also needs C_i calculated from the external CO_2 partial pressure, C_a:

$$C_i = C_a - A\,P_{air} / g_{tot,CO2} \qquad (4)$$

Where: P_{air} is the total air pressure because

$g_{tot,CO2}$ is the total conductance for CO_2 through the stomata and the boundary layer.

Equations 1-4 are solved using a binary search over magnitudes of g_s until all the equations are solved simultaneously. First a guess is made for the value of g_s. The energy-balance equation has all the other quantities specified, the model calculates the leaf temperature using the iteration of procedure. We combine the enzyme-kinetic equation (1), with its parameters corrected for the leaf temperature, and the transport equation (4) to get a single equation for C_i. When we use the form of the enzyme-kinetic equation generalized to handle light-limited photosynthesis, this becomes a quartic equation. We solve it rapidly by iteration. Now we have both C_i and A. Finally, we rewrite the Ball-Berry equation to highlight the error in the solution, as

$$F = g_s - (m\frac{A\,h_s}{C_s} + b) \qquad (5)$$

When we have the right guess for g_s, F becomes zero. We home in on the proper value of g_s by a binary search. We guess the min and max values that g_s could lie between. We compute F at each end, and then for g_s in the middle. The solution has to lie between the values of g_s where F changes sign. We take these two values as the new min and max, thereby halving the interval. We keep doing this until the interval is less than some preset accuracy, say, 0.00001 mol m-2 s^{-1}.

Photosynthesis gross rate is debited for instantaneous respiration in the leaf. This has been found repeatedly, including by us, to be 8 to 10% of gross PS at the current twoweek-average air temperature, T_{mean}. We input the latter and calculate the respiration rate for any leaf, applying an exponential factor in actual leaf temperature, $exp(0.07*(T-T_{mean}))$.

The rate of photosynthesis is not to be compared with net CO_2 exchange of an orchard, because respiratory losses of CO_2 (partial undoing of photosynthesis) occur at night everywhere, and at all times in the trunk and in the soil…at a rate that makes net CO_2 uptake as small as 20%, or even 0% or less, of this "canopy gross" photosynthetic rate. The soil respiration is typically largest. It comes from living root tissue, when sugars are metabolized for energy to drive synthesis of new tissue and to maintain all tissue. It also comes from microbes in the soil, using up direct exudation of sugars and acids by the roots (done by the tree for a variety of ecological reasons) and also breaking down dead roots, which arise on a short turnover time from live roots. These corrections need to be made to the output of the model to determine WUE under different water and nitrogen stress conditions.

Limitation of the model. The transpiration by all leaves in the canopy adds humidity to the canopy, changing the environment of the leaves. Also, photosynthesis lowers the CO_2 level in the canopy, and convective energy transfer alters the air temperature in the canopy. Consequently, within the canopy the rate of photosynthesis and transpiration change meteorological conditions as the model iterates the solution for, particularly, the air temperature, T_{air}, and water-vapor partial pressure, e_{air}. At each iteration, the model get a new e_{air} and a new T_{air}…and then new canopy totals of A and E…which gives us new e_{air} and T_{air}. The iterations are prone to oscillate and divergence, and the model consequently limits the changes in e_{air} and T_{air}, from their values in "free" air above the canopy for any iteration, depending on the boundary-layer (or aerodynamic) conductance of the canopy as a whole. This depends inversely on windspeed, with a constant of proportionality that depends on canopy leaf-area index, *LAI*. Windspeed comes from the weather data, and *LAI is* based tree size and spacing and total leaf area. All these processes change in rate over the day, as the solar angles, air temperature, humidity, and windspeed changes.

With this complexity, the model still has left out a number of processes:

* Energy balance of the soil and soil evaporation (this is in the pecan plant model)

* The model assumes a canopy photosynthetic capacity linearly related to nitrogen content in the leaves which has to be change as an input variable over time.

* Rainfall interception is ignored

* Stomatal control parameters, m and b, are constant. Under water stress, m certainly declines and this is being put into the model. The root water potential can be used to estimate the drop in Ball-Berry slope, m.

Description of Nitrogen submodel in the Pecan tree growth model.

The nitrogen submodel presented simulates the interaction of nitrogen transformation, soil temperature, water, and nitrogen uptake to describe nitrate distribution in the root zone of a growing crop for the entire growing season. The model requires both a soil water balance submodel and a soil temperature submodel. It is not meant to critically evaluate the individual processes; rather, the model is intended to serve as a management tool for guiding nitrogen fertilizer and water application and for scheduling irrigation. Volatilization and microbial immobilization of nitrogen were not treated in this model: They were assumed to be negligible.

Nitrogen Transformation

Nitrogen transformation is microbial mediated. The process is assumed to occur actively in the top 30 cm of the soil because of a higher concentration of carbon in that layer. Nitrogen transformation is assumed to follow irreversible first-order rate kinetics proposed by Mchran and Tanji (1974) as

$$\frac{dN}{dt} = -KN \qquad (6)$$

where N is the concentration of nitrogen specie (substrate) in question, dt is the time interval, and K is a rate constant.

Hydrolysis

Hydrolysis is one of the nitrogen transformations. The process involves the conversion of urea into ammonium. Hydrolysis is assumed to occur within days so that applied urea is quickly converted to ammonium.

Mineralization

Mineralization of organic matter to ammonium is modeled based on the modification and the rearrangement of the first order kinetics equation developed by Stanford and Smith (1972) and Stanford et al. (1973) and presented by Stockle and Campbell (1989) and Watts and Hanks (1978) as

$$M = (M_0(1 - exp(-K_m t)))F(fps) \qquad (7)$$

Where M is nitrogen mineralized (K_g N m^{-2}) in time t (day) at the corresponding soil water content; M_0 (K_g N m^{-2}) is the potentially mineralizable nitrogen at the start of the time interval t ; K_m is the mineralization rate constant (day $^{-1}$); and F(fps) is a function of soil moisture. Using the work by Stanford and Epstein (1974) and Pilot and Patrick (1972), the function (*fps*) was described by Watts and Hanks (1978) as

$$F(fps) = 1.111 fps; 0.0 \le fps < 0.9 \qquad (8)$$

$$K_n = K_{n35}(0.0105T_s + 0.00095T_s^2); 0°C \le T_s < 10°C \qquad (9)$$

$$K_n = (0.032T_s - 0.12)K_{n35}; 10°C \le T_s < 35°C \qquad (10)$$

$$K_n = (-0.1T_s + 4.5)K_{n35}; 35°C < T_s < 45°C \qquad (11)$$

Where K_n is the nitrification rate constant) (day^{-1}); T_s is the soil temperature in °C; and K_{n35} is the rate constant at 35 °C.

Denitrification

Denitrification of nitrate is modeled along the same pattern as nitrification proposed by Stockle and Campbell (1989):

$$D = D_0(1 - exp(-K_d)) \quad (12)$$

Where D is the amount of nitrate denitrified (kg NO_3 m^{-2}) in time t;D_0 (kg NO_3 m^{-2}) is the amount of nitrate available at the beginning of the time interval t; and K_d (day^{-1}) is the denitrified rate constant. The Denitrification rate constant is corrected for soil water content and temperature as proposed by Greene (1983):

$$K_d = exp(0.08(T_s - 15))K_{d15}F(\theta_i) \quad \text{for} \quad T_s \leq 10°C \quad (13)$$

$$K_d = 0.67\,exp(0.43(T_s - 10))K_{d15}F(\theta_i) \quad \text{for} \quad T_s > 10°C \quad (14)$$

Where K_{d15} is the rate constant at 15 °C; T_s is the soil temperature in °C; and $F(\theta)$ is water content correction function for denitrification, defined as

$$W = 47(\theta_s - \theta)^2 \quad (15)$$

$$F(\theta) = exp(0.304 + 2.94(\theta_s - \theta) - W) \quad (16)$$

Where θ_s and θ are saturated current volumetric soil moisture content, and W is a variable.

Average soil temperature on any day needed by the rate functions is modeled based on the method developed by Jones and Kiniry (1986) and then modified by Sharma et al. (2009). The method requires daily maximum and minimum air temperature, solar radiation, soil bulk density, and moisture content and percent cover estimated from a crop coefficient used to calculate evapotranspiration in the soil water balance subroutine.

Nitrogen uptake

The mechanistic N transport and uptake model is based on model by Yanai (1994) that actively take N from the soil water, transport it into the xylem and into the leaves where N transformation will occur into organic N or stored as nitrate. The organic N level will control the photosynthesis rate and stomatal resistance, which in turn will control the transpiration rate and biomass growth including nut yield (Gutschick 2007).

Nitrogen uptake (U) in the model is defined by equation 17.

$$U = 2\pi r_\circ L \alpha C_\circ \Delta t \quad (17)$$

Where: $2\pi r_{\circ}L$ = the surface area of the roots.

Δt = time step.

α = a rate uptake constant which is calculated from a Michaelis-Menton equation that decrease uptake as the concentration at the root surface increases.

$C_{\circ}$ = concentration of solute at the root surface calculated from the average concentration in the bulk solution C_{av} is described by equation 18.

$$C_{\circ} = P_c C_{av} \tag{18}$$

P_c is a function of the inward velocity of water at the root surface, the radius of the root, the average radial distance from the center of the root to the next root's zone of influence, the effective diffusion coefficient of the solute through the soil.

In order to solve equations 17 and 18 knowledge must be known about the root length density of both the old and new roots along with the nitrogen concentration in the bulk soil water nitrogen transformation submodel and the water balance submodel. Nitrogen is then partitioned into the roots, trunk, branches, and leaves based on the carbohydrate allocation to each part. When the leaf nitrogen content falls below 2.72%, nitrogen stress occurs and photosynthesis and evapotranspiration will decrease according to a function reported by Sparks and Baker (1975) and by the complex photosynthesis tree model described by equations 1-5.

Material and methods

If trees or other plants are given reduced and water supplies, many physiological acclimations occur with the first response of the tree to be a reduction in stomatal conductance, g_s. This cuts leaf transpiration almost in proportion - not quite as much, because leaf cooling is reduced, and the rise in temperature raises the leaf-to-air gradient in water-vapor pressure. The reduction in g_s also cuts leaf photosynthesis, but considerably less than proportionally - the stomatal resistance (inverse of conductance) is a much smaller part of the total pathway resistance for incoming CO_2. Consequently, water-use efficiency (WUE), as the ratio of photosynthetic rate to transpiration rate, rises. Measurements of water use efficiency under non-water stress conditions have been previously be made (Wang et al. 2007) to verify both the complex photosynthesis model and the simple pecan plant grow model. The complex photosynthesis model was calibrated again in two dry down irrigation cycles imposed on a pecan orchard near Las Cruces, NM to verify the model under moisture stress conditions and against selected pecan trees in the same orchard showing nitrogen and water stress conditions. The complex photosynthesis model was then run under moistures and nitrogen stress conditions to develop the WUE function vs. plant water potential and leaf nitrogen level used in the whole pecan plant model. The nitrogen stress function was incorporated into the pecan tree functional model that was then tested against a separate water nitrogen stress experiment in another climate environment in Oklahoma (Smith et al 1985). The pecan trees at the Oklahoma study site only received rainfall, and nitrogen amounts from 0 to 265 kg/ha. The climate data was acquired from NCDC for Stillwater Oklahoma 16 km north of Perkins Oklahoma where the study was conducted. There was no statistical difference in the pecan yield each year for the different fertilizer treatments so the mean yield each year for all the treatments was used in the comparison to the model prediction of yield.

Results

The photosynthesis pecan model's relative change in transpiration occurs linearly as leaf N decreases expressed as a relative value of the 2.8% nitrogen starting point (Nr) under water stress condition when E was 50% of E non-stressed (Figure 2). Modeled WUE also decrease linearly with a decrease in relative N because the leaf temperature rises when Photosynthesis capacity is lowered due to nitrogen stress conditions in the leaves. When water is not limiting decrease in transpiration caused only by nitrogen stress also resulted in leaf temperature to rise by 3 °C. A decrease in N level causes a decrease in WUE and relative E(Er). The measured relative decrease in growth related linearly to relative E from the experiment by Sparks and Baker (1975) agrees with the model simulation of pecans under both nitrogen and water stress until the nitrogen level becomes less than 1.66% nitrogen at which time the relative transpiration decreases as a non-linear function (Figure 2). The functions of WUE vs. nitrogen and E vs. nitrogen can be:

$Er = 0.7134\ Nr + 0.326$ (19)
Coefficient of determination = 0.9865

$WUE = 0.4059Nr + 0.6015$ (20)

The coefficient of determination = 0.9971
Consequently, the interaction between nitrogen stress and water stress on evapotranspiration (Et) in the pecan growth model is multiplicative:

Et= Etns* soil water stress function* nitrogen stress function. (21)

where Etns is the non-stressed Et.
The nitrogen stress function is from Figure 2 (equation 19) and the water stress function is:
$Et/Etns= 0.5RAW$ (23)
Where: RAW is relative available water.

All the N values are "photosynthetically active N. Consequently, it was assumed that 0.3% is the structural part of leaf N added to the non-structural N used by the model.

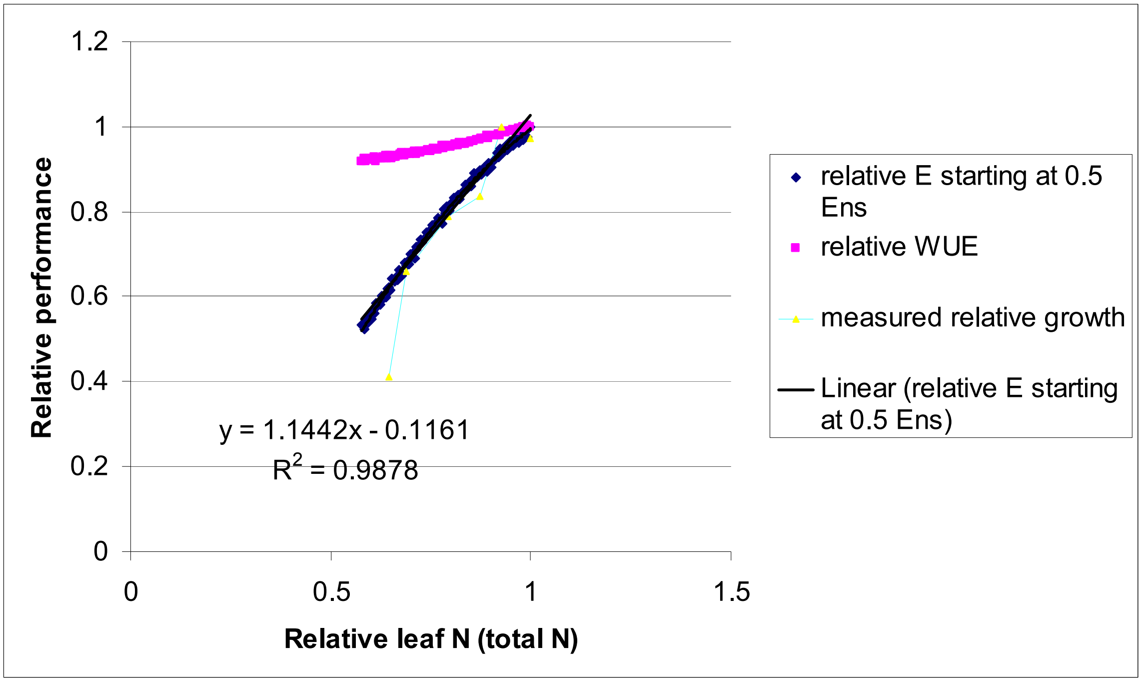

Figure 2. Modeled relative N of total N (0.3% is the structural part of leaf N) vs. relative transpiration, relative WUE and measured relative growth under water stress conditions (Sparks and Baker, 1975) .

The pecan tree growth model was run using the climate data from Stillwater, Oklahoma and both 0 and 260 kg/ha of nitrogen was applied respectively throughout the growing season. The model, same as the measured data, did not show any response to the application of nitrogen because the water stress decreased evapotranspiration and growth sufficiently that the mineralization rate was sufficient to supply the nitrogen need by the pecan trees under the water stress conditions. The nitrogen stress function was the same for 0 and 260 kg/nitrogen (Figures 3 and 4).

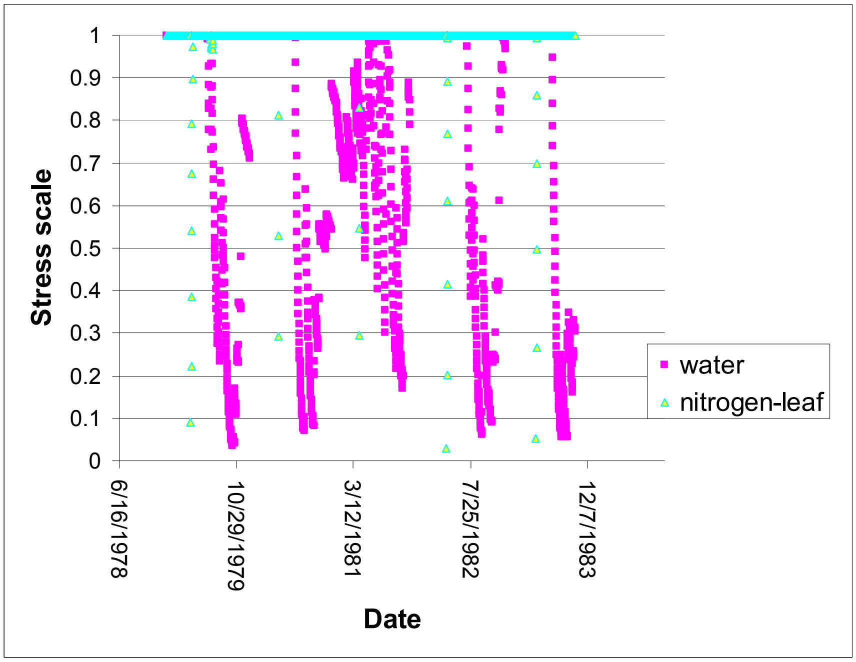

Figure3. Stress response output from Pecan Growth Model when 260 kg/ha of nitrogen was applied through the growing season at Stillwater, Oklahoma.

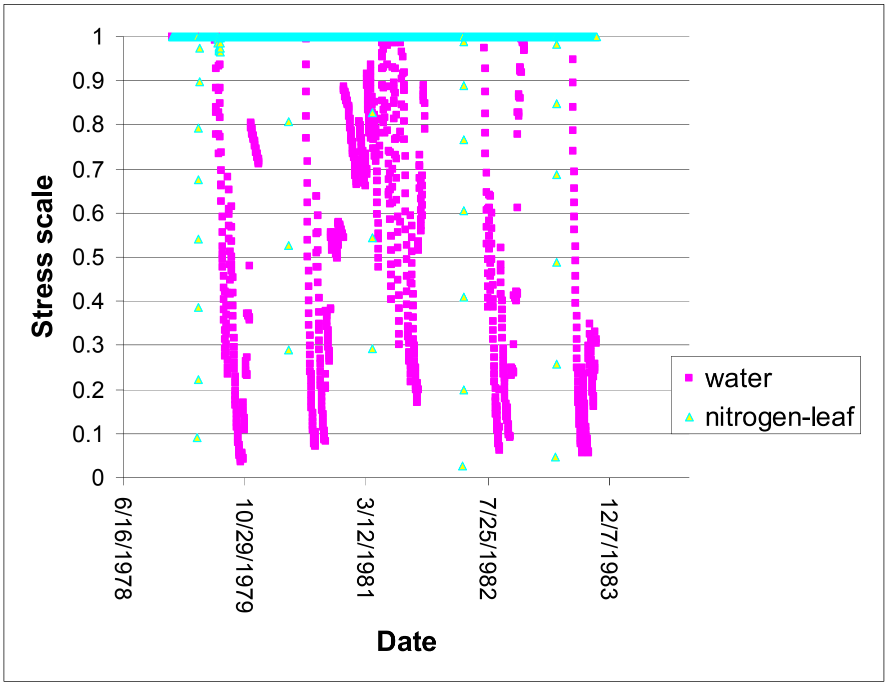

Figure 4. Stress response output from Pecan Growth Model when 0 kg/ha of nitrogen was applied through the growing season at Stillwater, Oklahoma.

The nut yield simulation data under non-water moisture stress where irrigation was applied when moisture stress started to occur ranged from 4500 kg/ha to 3200kg/ha but under rainfall conditions (the actual experimental conditions) the model overpredicted yield by 453 kg/ha in 1979 to under estimation by 703 kg/ha in 1983 (Figure 5). The overestimation in 1979 was due to the initial conditions in the model. A crop simulation model needs to be run for several years prior to the measured data years so that initial conditions can stabilize. In 1983 the water stress could have been greater than at the research site because the rainfall and climate data was from a site 16 km north of the research site which is sufficient distance for a thunderstorm to occur at the research site and not at the weather station site.

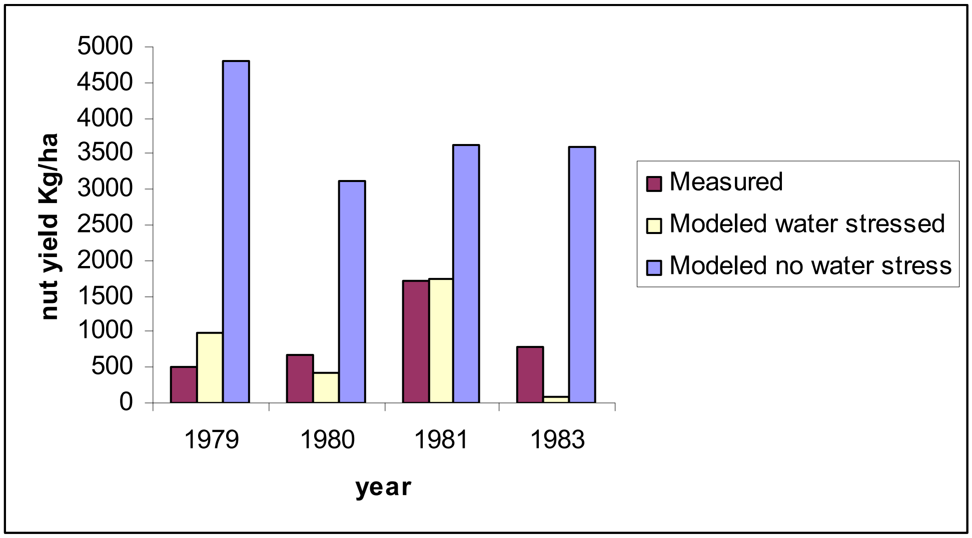

Figure 5. Modeled and measured pecan yield at Oklahoma. Nitrogen was not limiting growth but growth was severely limited by water stress.

A decrease in WUE was not incorporated into the model because the decrease with water stress would have decreased yield even more compared to the measured values. Additional experimental research is needed to verify the mechanistic model estimate of a function of WUE decrease with nitrogen stress before incorporating this function into the pecan plant growth model. The nitrogen content in the model only calculated nitrogen stress when the leaves have below 0.028 g N/g leaf which only occurs when the leaves are just emerging and the nitrogen comes from the carbohydrate reserve pool. As soon as the leaves were budded out then sufficient nitrogen occurred to satisfy the growth of the leaves because of reduced growth due to water stress. The modeled nitrogen content of the leaves increased rapidly to above the 0.028 g N/g leaf (N stress threshold level) but these modeled content was above the measured content with ranged from 0.02 -0.024 in the middle of July (Figure 7). Consequently, based on the leaf nitrogen content there should have been a response in nut yield to nitrogen application but this did not occur in the experimental results. Consequently, it appears that the nitrogen content predicted by the model even under nitrogen stress may be too large but also that the nitrogen stress threshold level derived from seedling experiments in Sparks and Baker (1975) may be too high for pecans. Additional research is needed where mature trees are placed under nitrogen stress and leaf photosynthesis measurements taken to derive the threshold level for mature trees.

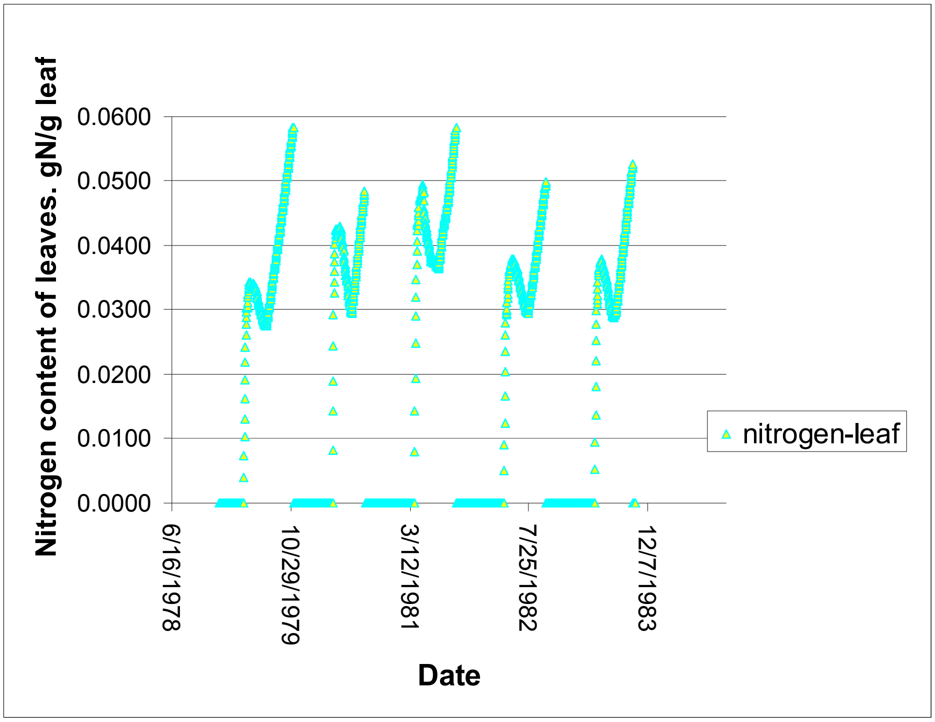

Figure 6 Modeled nitrogen content in leaf with 0 nitrogen application.

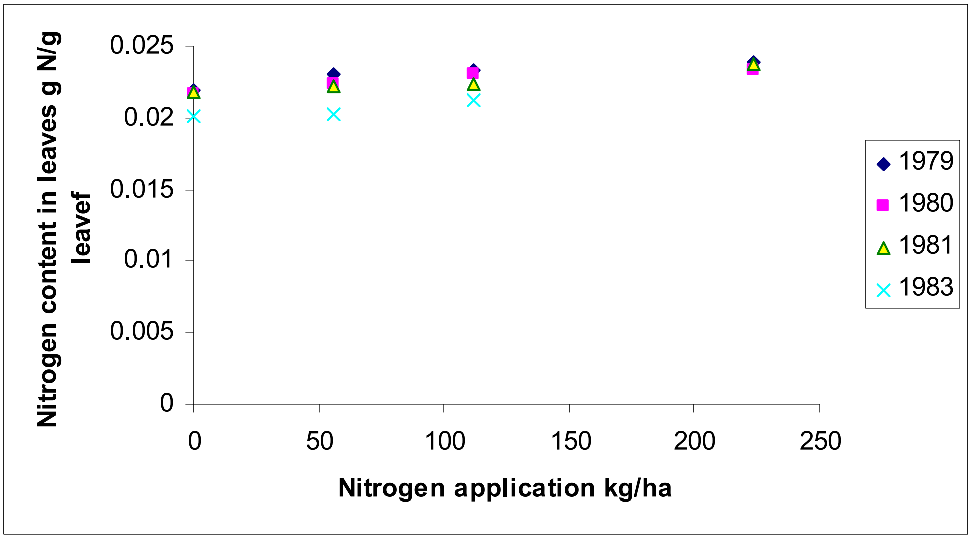

Figure 7. Measured nitrogen content in leaves during the middle of July.

Conclusion

Because nut trees are perennials and the previous year's management can have an impact on nut yield three to four years in the future, a modeling approach to understand the physiological response of a nut tree to inputs of water, nutrients, salinity, cultivation, and pruning offers the only way to understand the complex interaction of these management decisions on nut production. However, any tree model must be verified by controlled field experiments under different environmental conditions. The future of nut tree models will be the development of realistic modules that can be linked together quickly to build a nut tree model appropriate for the management options available to growers. Also, building models using spreadsheet tools will allow more researchers and students to become involved with the development of tree models without having to become computer programmers. The current pecan growth functional model appears to simulate water stress reasonably well but may overestimate the nitrogen uptake and the threshold level of nitrogen stress in the model may be larger than the true value. More field experiments need to be conducted to calibrate the related parameters.

References

Allen, M. T., Prusinkiewicz, P., & DeJong, T. M. (2005). Using L-systems for modeling source-sink interactions, architecture and physiology of growing trees: The L-PEACH model. *New Phytologist*, *166*(3), 869–880.

Andales, A., Wang, J., Sammis, T. W., Mexal, J. G., Simmons, L. J., Miller, D. R., et al. (2006). A model of pecan tree growth for the management of pruning and irrigation. *Agricultural Water Management*, *84*(1–2), 77–88.

Ball, J.T., Woodrow, I.E., Berry, J.A., 1987. A model predicting stomatal conductance and its contribution to the control of photosynthesis under different environmental conditions. In: Biggins, J., Nijhoff, M. (Eds.), Progress in Photosynthesis Research, vol. 4. Dordrecht, pp. 221–224.

Brown, P. H., & Zhang, Q. (2008). Nitrogen fertilization recommendation model for almond [Microsoft Excel spreadsheet model]. Retrieved from http://www.sarep.ucdavis.edu/grants/reports/brown/nmodel.html

Farquhar, G. D. ,S. von Caemmerer, J. A. Berry. 1980. A biochemical model of photosynthetic CO_2 assimilation in leaves of C_3 species. *Planta* 149(1):78-79

Gary, C., Jones, J. W., & Tchamitchian, M. (1998). Crop modeling in horticulture: State of the art. *Scientia Horticulturae*, *74*(1–2), 3–20.

Greene, J. 1983. Simulation of Denitrification in a forest soil. M.S. Thesis Washington State Univeristy, Pullman.

Gijón, M. C., Guerrero, J., Couceiro, J. F., & Moriana, A. (2008). Deficit irrigation without reducing yield or nut splitting in pistachio (*Pistacia vera* cv Kerman on *Pistacia terebinthus* L.). *Agricultural Water Management*. (In press).

Jones, C.A. and J.R. Kiniry. 1986. CERES-Maize: A simulation model growth and development. College Station: Texas A&M University Press.

Kallestad, J. C., Sammis, T. W., Mexal, J. G., & Gutschick, V. (2007). The impact of prolonged flood irrigation on leaf gas exchange in mature pecans in an orchard setting. *International Journal of Plant Production*, *1*(2), 163–178.

Le Roux, X., Lacointe, A., Escobar-Gutiérrez, A., & Le Dizès, S. (2001). Carbon-based models of individual tree growth: A critical appraisal. *Annals of Forest Science*, *58*(5), 469-506.

Lescourret, F., Mimoun, M. B., & Génard, M. (1998). A simulation model of growth at the shoot-bearing fruit level: I. Description and parameterization for peach. *European Journal of Agronomy*, *9*(2–3), 173–188.

Mehran, M. and K.K. Tanji. 1974. Computer modeling of nitrogen transformation in soils. *J. Environ. Quality* 3(4):391-396.

<u>Norman and Welles, 1983.</u> J.M. Norman and J.M. Welles, Radiative transfer in an array of canopies. *Agron. J.* 75 (1983), pp. 481–488.

Passioura, J. B. (1996). Simulation models: Science, snake oil, education, or engineering? *Agronomy Journal*, *88*(5), 690–694.

Pilot, L. and W.H. Patrick, Jr. 1972. Nitrate reduction in soils: effect of soil moisture tension. *Soil Sci.* 114:213-216.

Pokovai, K., & Kovacs, G. J. (2003). Development of crop models: A critical review. *Novenytermeles*, *52*, 573–582.

Reynolds, J. F., & Acock, B. (1997). Modularity and genericness in plant and ecosystem models. *Ecological Modelling*, *94*(1), 7–16.

Seem, R. C., Oren, T. R., Eisensmith, S. P., & Elfving, D. C. (1986). A carbon balance model for apple tree growth and production. In F. Winter (Ed.), *ISHS Acta Horticulturae 184: I International Symposium on Computer Modelling in Fruit Research and Orchard Management* (pp. 129-138). Hohenheim, Germany.

Sharma, P., M. K. Shukla, T. W. Sammis 2009. Predicting soil temperature using air temperature and soil, crop and meteorological parameters. ASABE Transaction. In Press.

Smith, M. W., P. L. Ager, and D. S. W. Endicott. 1985. Effect of nitrogen and potassium on yield, growth and leaf elemental concentration of pecans. *J. Amer. Soc. Hort. Sci* 110:446-450.

Sparks, D. and D. H. Baker. 1975. Growth and nutrient response of pecan seedlings, Carya Illlinosensis Koch, to nitrogen levels in sand culture. *Journal of Amer. Soc. of Hort. Sci.* 100:392-399.

Stanford, G. and E. Epstein. 1974. Nitrogen mineralization-water relations in soils. *Soil Sci. Soc. Am. Proc.* 38: 103-107.

Stanford, G. and S. J. Smith. 1972. Nitrogen mineralization potential of soils. *Soil Sci. Soc. Am. Proc.* 36:465-472.

Stanford, G., M.H. Frere, and D.H. Schwaniger. 1973. Temperature coefficient of soil nitrogen mineralization. *Soil Sci.* 115:321-323.

Stockle, C. O. and G.S. Campbell. 1989. Simulation of crop response to water and nitrogen: an example using spring wheat. *Trans. ASAE* 32:66-74.

Wang, J., D.R. Miller, T.W. Sammis, V.P. Gutschick, L.J. Simmons, A.A. Andales. 2007. Energy Balance Measurements and a Simple Model for Estimating Pecan Water Use Efficiency. *Agr. Water Manag.* 91:92-101.

Watts, D.G. and R.J. Hanks. 1978. A soil-water-nitrogen model for irrigated corn on sandy soils. *Soil Sci. Soc. Am. J.* 42:492-499.

Whiley, A. W., Saranah, J. B., Cull, B. W., & Pegg, K. G. (1988). Manage avocado tree growth cycles for productivity gains. *Queensland Agricultural Journal*, *114*, 29-36.

Yanai Ruth D 1994. A Steady-State Model of Nutrient Uptake Accounting for Newly Grown Roots. *Soil Sci. Soc. Am. J.* 58 (5): 1562–1571.