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A model of pecan tree growth for the management of pruning and irrigation

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ABSTRACT

Pecans [*Carya illinoensis* (Wangenh.) C. Koch] are an important cash crop in arid southwestern USA. The pecan is an alternate bearing tree and its water use is greater than that of most row crops. Irrigation, pruning amount, and timing must be effectively managed to reduce alternate bearing for maximum profits. A simulation model of pecan growth and yield is a potential tool for managing irrigation and pruning amounts and timing. An object-based pecan growth model was developed and validated to simulate daily pecan tree dry matter production, biomass allocation to leaves, nuts, trunk, and branches, and alternate bearing according to inputs of weather data, soil condition, irrigation, and pruning operations. Daily dry matter production per unit of evapotranspiration (water use efficiency) was calculated as a function of average vapor pressure deficit. Biomass allocation functions were derived from tree growth measurements at an orchard near Las Cruces, NM. Alternate bearing was simulated as a function of the level of root starch reserves. It was theorized that the setting of pistillate flowers and subsequent nut yields are proportional to the level of root starch reserves in the preceding dormant phase (winter). Mathematical functions for the effects of irrigation and pruning on tree growth and yield were derived from the literature and available data. The model was calibrated using 2002, historical, and literature data and validated against 2003 and 2004 data obtained from a mature pecan (Western Schley cultivar) orchard near Las Cruces, NM. Overall accuracy was above 89% for simulated total dry matter production, nut yield, tree height, and diameter at breast height (DBH). This model was found to adequately simulate the effects of climate, irrigation, and pruning on pecan tree growth, nut yield, and alternate bearing. It can potentially be used to schedule and estimate the amount of irrigation and pruning to optimize pecan nut yield.

1. Introduction

Pecan trees are an important crop in the irrigated agriculture of southwestern US. The main cultivar is 'Western Schley'. The water use of pecan trees is greater than that of most row crops and is estimated to be 100–130 cm per season for mature pecan trees grown in the El Paso, TX–Las Cruces, NM area (Miyamoto, 1983). More recent measurements in 2003 from 21-year-old pecan trees located 7 km south of Las Cruces, NM gave a maximum daily ET of 10.6 mm day^{-1} and a seasonal

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(May 1–November 31) total of 116 cm (Wang et al., 2006). Flood irrigation is the oldest and most common irrigation system used in New Mexico orchards. Typically, annual irrigation is about 2 m for pecan orchards (Wang et al., 2006). Irrigation amount and timing should be based on the ET of the pecan trees to optimize growth and production (Stein et al., 1989; Miyamoto, 1985).

Pecan trees are usually spaced about 9 m $\times$ 9 m for high density planting (Herrera, 2005). Tree crowding and excessive shading reduce productivity (Andersen and Crocker, 2004). Crowded trees also make agricultural operations such as spraying and harvesting more difficult. Pruning can solve these problems. The diameter of branches that are pruned can range from 0.01 to 0.11 m and total dry weight removed can be from 10 to 130 kg tree^{-1}. Pruning includes mechanical hedging and selective pruning. In the southwestern US, hedging is the common pruning practice. In other areas where pecans are grown hedging is not common or less common than selective pruning. Our model work will focus on mechanical hedging pruning practice for the southwestern US. Pruning may reduce the yield and alter the bearing phase (Worley, 1985, 1991).

'Western Schley' is a fairly strong alternate bearer compared to other pecan cultivars (Conner and Worley, 2000). The tendency for alternate bearing increases with age and increasing yield. For example, at Stahmann Farm in Las Cruces, NM, the average yield from a mature orchard is 2500 kg ha^{-1} with yields of 1400 kg ha^{-1} in an off year and 3600 kg ha^{-1} in an excellent year (personal communication). Pecan nut prices are usually low in years of high yield (McEachern et al., 1997). Managing a pecan orchard to adjust alternate bearing to an optimal level (e.g., being out of sync with other orchards) will result in maximum profits.

Modeling pecan yield is complicated by the occurrence of alternate bearing. Several investigators have found that flowering and nut yield are related to the amount of carbohydrate reserves stored from the previous season (Malstrom, 1974; Smith and Waugh, 1938; Wood, 1989, 1991; Wood and McMeans, 1981; Worley, 1979a,b). There was a strong relationship between nut yield and January root starch concentrations and nut yield was not significantly related to shoot carbohydrate reserves (Smith and Waugh, 1938; Smith et al., 1986; Wood, 1989). Irregular bearing in pecan has been attributed to failure of pecan trees to annually initiate and set sufficient numbers of pistillate flowers (Amling and Amling, 1983). Pistillate flower differentiation occurs in the spring, when the outer bud scales are shed and buds are swollen, but before the inner bud scale is broken (Wetzstein and Sparks, 1983).

To simulate pecan tree growth the total dry matter production needs to be calculated. Dry matter production can be estimated from the product of water use efficiency (WUE, kg ha^{-1} cm^{-1}) and ET (cm). Plant WUE variation is strongly affected by vapor pressure deficit (VPD) (Law et al., 2002; Gutschick, in press). Law et al. (2002) analyzed monthly WUE and VPD data for evergreen conifers, deciduous broadleaf forests, crops and grasslands from different AmeriFlux sites, and found that as VPD increased, WUE decreased.

The total dry matter production should appropriately be allocated to different tree components. Lacointe (2000) gave a comprehensive review regarding assimilation–allocation models. The source/sink models have been widely used. The sources are the leaves that assimilate carbon. The sinks are the components (trunk, branches, leaves, nuts, and roots) that consume or store assimilates. Two main subclasses of models can be distinguished in the source/sink model. One is the proportional model that allocates assimilate flux proportional to the sink demand, not exceeding it. The other is the hierarchical model, in which sink strength is defined as a maximum growth rate or demand, and the different sinks are ranked according to a priority-level order or hierarchy. For example, Grossman and DeJong (1994) proposed an approach for peaches with the assumption that sink strength was greatest for organs closest to the source.

The allocation parameters can be measured experimentally. Point and band dendrometers have been used to measure the change in the diameter and growth of trunks and branches for forest trees since the 1950s (Clark et al., 2000). If a very sensitive linear variable differential transducer (LVDT) is used in the dendrometer, a data logger can continuously record the diameter changes throughout the day (Goldhamer et al., 2003). The biomass of new growth can be calculated according to the change in diameter, the length of the trunk or branch, and wood density.

A pecan crop model is needed to understand the complex relationships among weather, irrigation, and pruning timing and amount as it affects growth and nut yield. This model needs to simulate the alternate bearing effects on the pecan yield and be able to allocate the total biomass to major components of the tree.

Passioura (1996) makes the argument that models fall into two categories: (1) mechanistic models developed for scientific understanding of the processes in nature or (2) functional models developed to solve management problems. The mechanistic models are based on hypotheses, which may or may not be correct, of how plants grow. Often these models 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.

A simulation model to be developed as a user-friendly decision support system for irrigated crops should include all objects necessary to simulate crop growth using either mechanistic or empirical functional relationships (Acock and Reynolds, 1989; Reynolds and Acock, 1997). Object-oriented decision support programs model real world objects with software counterparts and 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.

The purpose of this research was to develop and test a user-friendly and object-oriented pecan growth model for the management of irrigation and pruning. Excel (Microsoft Corporation) spreadsheets are the user-interfaces that allow the user to easily change the parameters and mathematical functions in the model. The major processes (e.g., tree growth, irrigation, and pruning) are represented as separate objects, each contained in a worksheet. The entire model is the aggregate of all the worksheets (objects) contained in one workbook and interlinked with appropriate equations and functions. The model can be classified as a functional model and is envisioned to help make management decisions in pecan production.

2. Model description

We developed a pecan model with objects for simulating irrigation, alternate bearing, shoot biomass allocation, and growth by modifying an existing growth-irrigation scheduling model (GISM) (Al-Jamal et al., 2002). The new model simulates pecan tree growth on a daily basis. A flowchart of the model is shown in Fig. 1. Model inputs include daily weather, soil condition, irrigation, and pruning data. The irrigation object simulates pecan evapotranspiration (ET), soil water balance, and water stress. The biomass allocation object calculates the potential biomass allocation ratios to different branches and trunk. The pruning object simulates removal of branches and affects the objects of irrigation, biomass allocation ratios, and alternate bearing. The alternate bearing object simulates CHO reserve (starch) amount in the roots. Finally, the growth object simulates tree growth and nut yield and allocates the biomass to the tree components according to ET, water stress, allocation ratios, pruning effects, and CHO reserve amount.

2.1. Inputs

Climatic inputs for the model consist of daily maximum and minimum of temperature and humidity, solar radiation, wind speed, rainfall, and soil temperature. These weather parameters are available from the New Mexico Climate Center Web site (http://weather.nmsu.edu). The inputs also include irrigation time and amount, pruning time, maximum diameter of branches to be pruned, and sides to be pruned (east, west, north, south, and top). These pruning operations are hedging. All branches having diameters less than or equal to the maximum pruning diameter are pruned. For example, if we prune the east side of a tree and the pruning diameter is set to 2 cm, then all the branches at the east side with diameters equal to or smaller than 2 cm are pruned (see Section 2.4.1). The growth simulation requires several initial conditions including tree trunk radius, root depth, root CHO reserve amount (starch), and soil moisture (Table 1).

Table 1 – Pecan growth model parameters

Parameter	Value
Wood density (kg m^{-3})	647
Lateral outermost branch angle from horizontal; one value used for all outermost branches to simplify calculation of projected area (degrees)	60
Maximum LAI (m^{-2} m^{-2})	6
Specific leaf area (m^2 kg^{-1})	9.2
Root:shoot biomass ratio	0.34
No. trees per ha	100
Tree spacing (m)	10.0
Soil water holding capacity (m m^{-1})	0.19
Initial trunk radius (m)	0.15
Initial root depth (m)	1.2
Initial carbohydrate (CHO) reserve (kg $tree^{-1}$)	16.0
Initial soil moisture (m m^{-1})	0.19
Maximum root depth (m)	1.5
Optimum CHO reserves in January (kg $tree^{-1}$)	20
Equilibrium RR, RR_e (0–1)	0.85
Reserve ratio (RR) lower limit	0.4
Max. leaf growth rate growth rate (kg $tree^{-1}$ GDD^{-1})	0.0715
Max. bud growth rate in spring (kg $tree^{-1}$ GDD^{-1})	0.30
Max. shell growth rate (kg $tree^{-1}$ GDD^{-1})	0.0106
Max. kernel growth rate (kg $tree^{-1}$ GDD^{-1})	0.0235
Max. husk growth rate (kg $tree^{-1}$ GDD^{-1})	0.0057
Root growth rate (m GDD^{-1})	0.0002
Growing degree days (GDD) to bud break	15
GDDs of leaf photosynthesis beginning	48
GDDs to pollination	210
GDDs to shell hardening	1940
GDDs to leaf fall	2607
GDDs to shuck split	2750

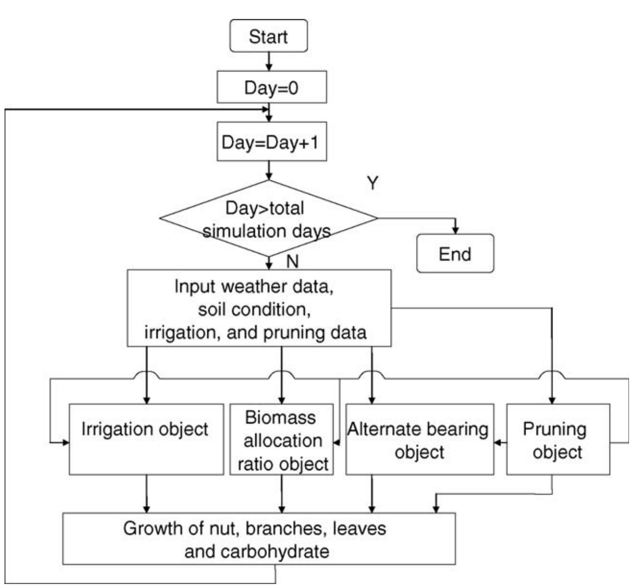

Fig. 1 – Overall flow chart of the pecan model.

2.2. Outputs

The model outputs daily total dry matter production, branch, and trunk growth (dry weight, diameter, and length), tree height, nut, and leaf growth (dry mass). When a predetermined level of water stress occurs, the model will simulate application of the necessary irrigation amount. Also, pruning is simulated when adjacent tree crowns begin to overlap.

2.3. Irrigation object

The irrigation object simulates ET and water stress (Fig. 2). ET is determined by using climate data to calculate a reference evapotranspiration rate (ETo) using the equation developed by Samani and Pessarakli (1986) or Penman (Snyder and Pruitt, 1992) (depending on available climate data), and a crop coefficient (K_c) to scale the daily ETo for non-stressed, closed

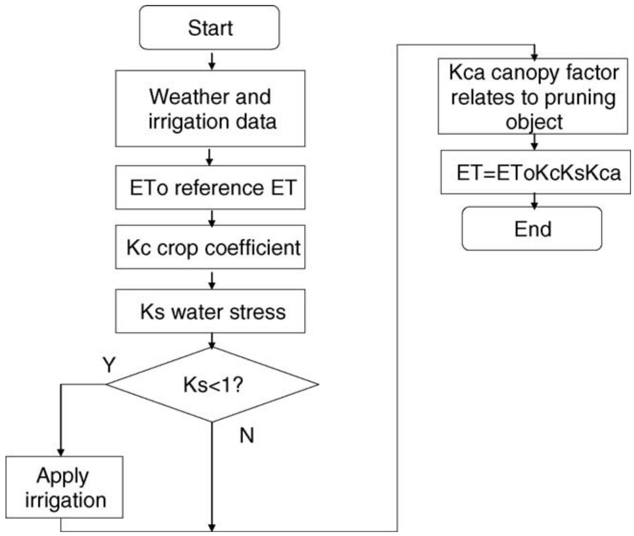

Fig. 2 – Irrigation object flow chart.

canopy pecan conditions. The crop coefficient is the ratio of pecan ET under non-stressed conditions and ETo. The K_c for a closed canopy was obtained from Miyamoto (1983) and then adjusted as follows based on measurements taken in the 2002 experiment (Sammis et al., 2004a).

$$K_c = 0.286 + 0.003\,\mathrm{GDD}_i - 3.02 \times 10^{-6} \times \mathrm{GDD}_i^2 + 1.4 \times 10^{-9} \times \mathrm{GDD}_i^3 - 2.28 \times 10^{-13} \times \mathrm{GDD}_i^4 \quad (1)$$

where GDD_i is growing degree days for day i (°C day)(Al-Jamal et al., 2002) with a cutoff (base) temperature of 15.5 °C for pecan. The calculated non-stressed ET for a closed canopy is reduced by soil moisture stress (K_s) and a canopy scale factor (K_{ca}). Soil moisture stress is a function of the proportional available water in the root zone (Abdul-Jabbar et al., 1983). A canopy scale factor (K_{ca}) decreases ET from a closed canopy to an amount associated with the percent cover at each simulation time interval.

The soil moisture stress function (K_s) scaled from 0 to 1 is:

$$K_s = a + b\frac{\mathrm{Sm}(i)}{\mathrm{WHC} \times \mathrm{Rd}} \quad (2)$$

where a is the y-intercept (0.0), b the slope (2.0), Sm(i) the soil moisture in the root zone on day i (m), WHC the soil water holding capacity (an input to the model, 0.19 m m^{-1}), and Rd is the root depth (m). The value of K_s is set to 1.0 (no stress) when soil moisture remains above 50% of WHC, below which K_s drops linearly to zero as Sm approaches permanent wilting point. Garrot et al. (1993) reported that 45% of the total water-holding capacity could be depleted in a 2.1 m clay loam soil profile with no reduction in pecan yield or nut quality. Irrigation is applied (0.1 m) when Sm falls below the input value of management allowed depletion (MAD), which is set at 50% of WHC × Rd.

The canopy factor is derived from Snyder's work (Sammis et al., 2004b) and has the form:

$$K_{ca} = \sin\left(\frac{\mathrm{ECC}}{0.7} \times \frac{\pi}{2}\right) \quad \text{when} \quad \mathrm{ECC} < 0.7 \quad (3)$$

where K_{ca} is the canopy factor that ranges from 0 to 1 and ECC is the effective canopy cover, which is the percent projected canopy area divided by the growing area occupied by each tree. $K_{ca} = 1$ when ECC is greater than or equal to 0.7. The canopy factor is decreased by pruning operations.

2.3.1. Soil moisture

The soil moisture at the root zone on day i is calculated as:

$$W_i = W_{(i-1)} + I_i + R_i - \mathrm{ET}_i \quad \text{for} \quad W_{(i-1)} + I_i + R_{ii} < \mathrm{WHC} \times \mathrm{Rd}_i \quad (4)$$

$$W_i = \mathrm{WHC} \times \mathrm{Rd}_i - \mathrm{ET}_i \quad \text{for} \quad W_{(i-1)} + I_i + R_i > \mathrm{WHC} \times \mathrm{Rd}_i \quad (5)$$

where W_i is the water in the root zone on day i (m), W_{i-1} the water in the root zone in day $i-1$, ET_i (m) the evapotranspiration on day i calculated by the irrigation object, I_i the irrigation on day i (m), R_i the precipitation on day i (m), WHC is soil water holding capacity in Eq. (2), and Rd_i is the root depth on day i (m). When $(W_{(i-1)} + I_i + R_i) > (\mathrm{WHC} \times \mathrm{Rd}_i)$, drainage will occur and W_i will be calculated by Eq. (5).

The drainage on day i will be

$$D_i = W_{(i-1)} + I_i + R_i - \mathrm{WHC} \times \mathrm{Rd}_i \quad (6)$$

where D_i (m) is the drainage on day i.

2.4. Shoot biomass allocation ratio object

This object simulates the crown distribution and the allocation ratios to different size branches and the trunk (Fig. 3).

2.4.1. Crown distribution

According to the given diameter at breast height (at 1.4 m height) (DBH) at the beginning of the simulation, the object obtains the diameter, length, and number of trunk and branches, and tree height. The branch angle (from horizontal) of the outer branches in the crown is set (60°) so that the projected area on the ground can be calculated. The model numbers trunk and branches at different levels. The trunk is level 1 and branches directly grown from it are set to level 2, and then branches grown from level 2 are set to level 3 and so on. On the first day of simulation, the model calculates trunk cross-section area according to DBH; then each higher level branch cross-section area is calculated as half of the branch's one level below. The highest branch level is determined by the branch diameter (<1 cm). New branches have diameters of 0 cm at the beginning of each growing season. Each branch length is calculated by a regression equation (Eqs. (13) and (14)).

The branch number in each level was determined by measurements (Table 2, details given in Section 3.2.2). The branches are distributed uniformly among east, west, south, north, and top sides; i.e., in each level, 20% of the number of branches is distributed to each side. The small branches (level 11) can range in diameter from 0.002 to 0.011 m. To obtain reasonable height and projection area, the branch diameter is set to the outer boundary (about 0.009 m, relatively larger than inside branch of the same level). Consequently, the branch number is set to 720 so that the branch yearly growth biomass

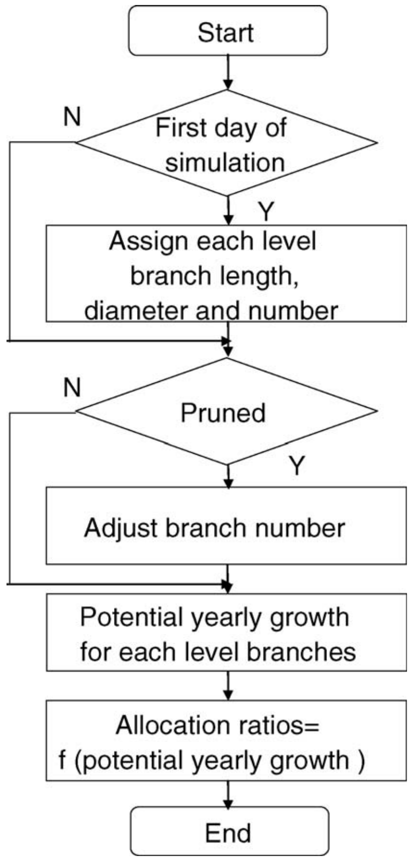

Fig. 3 – Flow chart of the shoot biomass allocation ratio object.

can be reasonable. For the same reason as above, the new branch number is conceptually set to 720.

2.4.2. *Shoot allocation ratios*

Daily growth biomass allocation was assigned according to the allocation ratios of potential yearly growth biomass for each level branch and trunk. To obtain the allocation ratio, first, the potential yearly growth cross-section was calculated using a regression equation (Eq. (16)) for each branch and trunk according to the branch original cross-section area. The potential of new branch yearly growth is set to 1 cm of diameter growth, i.e., the new growth cross-section area is ($3.14 \times 1^2/4 = 0.785$ cm^2). Each level branch or trunk yearly potential growth biomass was calculated according to branch new growth cross-section area, branch length, number, and density. The allocation ratio for each level branch or trunk was calculated as the ratio of potential growth biomass for the corresponding level branches or trunk to the total potential new biomass for all branches and trunk (Table 2).

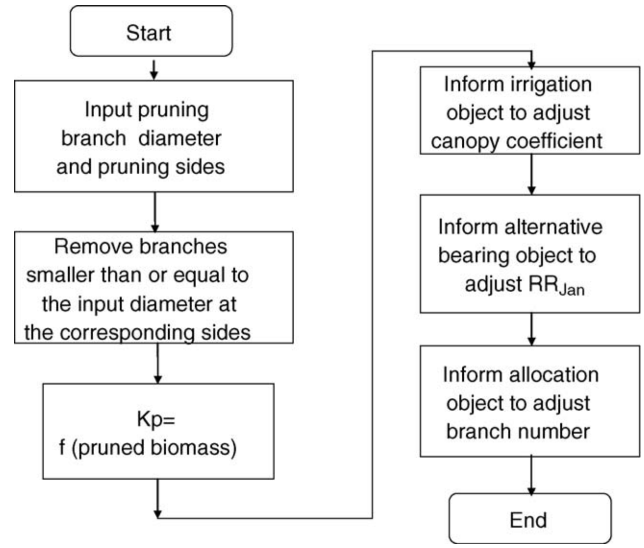

Fig. 4 – Flow chart of the pruning object.

2.5. *Pruning object*

The pruning object reduces the tree biomass and adjusts nut yield (Fig. 4). According to the pruning inputs: pruning diameter, pruning side or sides (east, west, north, south, or top), the branches smaller than or equal to the pruning diameter at the corresponding side are removed (mechanical

Table 2 – The mean diameter, length, and number of branches at each level for an average tree and corresponding shoot biomass allocation ratios at the beginning of the growing season when DBH = 0.3 m

Level[a]	Diameter (m)	Length (m)	Number	Allocation ratios
1 (trunk)	0.300	1.653	1	0.050
2 (scaffold)	0.212	1.544	7	0.200
3 (sub-scaffold)	0.150	1.433	10	0.153
4	0.106	1.322	13	0.076
5	0.075	1.212	13	0.046
6	0.053	1.105	14	0.025
7	0.038	0.996	16	0.015
8	0.027	0.826	80	0.045
9	0.019	0.718	129	0.046
10	0.013	0.613	129	0.032
11	0.009	0.509	720	0.124
12 (new)	0	0	720	0.179

[a] Branch levels range from the largest branch level (trunk) to the smallest (youngest) branch level.

hedging practice). Then the shoot biomass allocation ratios are adjusted accordingly in the shoot biomass allocation ratio object. The current-year nut yield is adjusted by multiplying with the pruning coefficient K_p (from 0 to 1, Eq. (15)). The bud growth rate is adjusted by multiplying with K_p because bud number is reduced (see Section 2.6).

2.6. Alternate bearing object

We hypothesized that the level of carbohydrate reserves in the roots during the dormant season (prior to floral differentiation) would affect the setting of pistillate flowers and subsequent nut yield. This is conceptualized in the alternate bearing object using a carbohydrate level factor (0–1) as follows:

$$RR_i = \frac{CHO_i}{CHOOpt} \quad (7)$$

where RR_i is the carbohydrate reserve ratio (0–1) on day i, CHO_i the level of carbohydrate (starch) reserves (kg tree^{-1}) in the roots on day i, and CHOOpt is the optimum level of carbohydrate (starch) reserves in the roots during the dormant phase that will not limit pistillate flower differentiation (kg tree^{-1}). Fig. 5 shows the flowchart of the alternate bearing object. CHOOpt (starch) is set to 20 kg for mature pecan trees (DBH = 0.3 m) based on Smith and Waugh (1938) and Wood (1989). Smith and Waugh (1938) reported that the weight of dry root starch in a mature pecan tree in winter before an on year was about 1/12 of the total root dry weight. When DBH = 0.3 m, the total shoot dry weight is about 692 kg tree^{-1} (calculated from the method in Section 2.4.2) and root dry weight is about 237 kg tree^{-1} (calculated from the method in Section 2.7). Therefore, the estimated CHOOpt (starch) is 20 kg tree^{-1} (237/12 = 20). The January 1 value of RR (taken to represent the dormant phase), herein referred to as RR_{Jan}, is specifically used to scale the growth of the shuck, shell, and kernel (the GF_j value in Eq. (10) in Section 2.7). Thus, RR_{Jan} is used to scale nut yield based on the level of carbohydrate reserves during pistillate flower differentiation. The level of carbohydrate reserves (root starch) during the dormant phase determines the pecan nut yield and its fluctuation from year-to-year as the primary mechanism by which the model simulates alternate bearing. If pruning occurs, the pruning may affect nut yield. Then RR_{Jan} is adjusted and multiplied by the pruning coefficient (K_p, in Eq. (15)). The bud growth rate is adjusted and multiplied by K_p assuming reduced bud numbers reduces CHO usage (see Section 2.7 for bud growth).

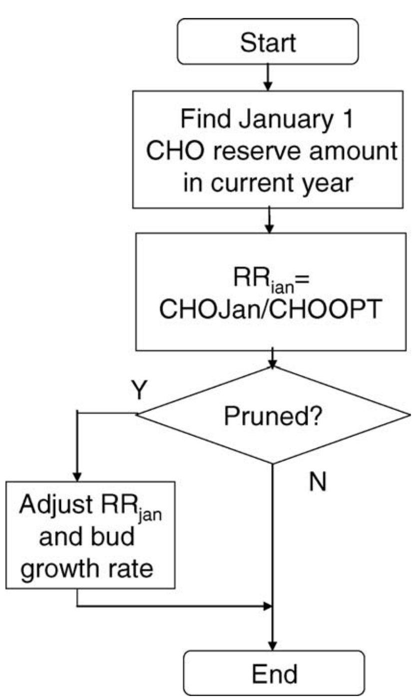

Fig. 5 – Flow chart of the alternate bearing object.

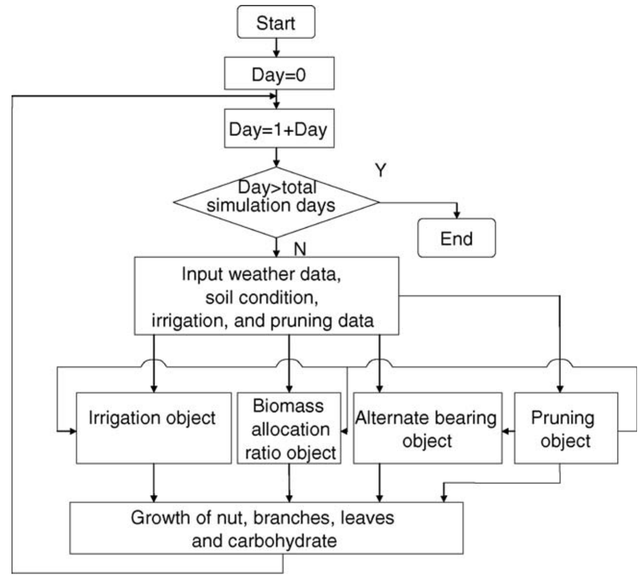

Fig. 6 – Flow chart of the growth object.

2.7. Growth object

This object calculates total dry matter, leaf, CHO reserve, branch, and root growth (Fig. 6). ET calculated and scaled by water stress, and canopy factor from the irrigation object, is used to calculate total net dry matter production. Daily net dry matter gain per tree (DM) is estimated as the product of the ET and WUE. WUE, the carbon assimilation rate (dry matter accumulation per unit area per unit water used) (kg ha^{-1} cm^{-1}), was measured in 2002 (off year) and 2003 (on year) by Wang et al. (2006). The daily WUE is calculated as a function of VPD (kPa) given by Wang et al. (2006).

$$WUE = 28.66 - 3.51 \times VPD \quad (8)$$

The daily VPD is calculated as the average of the daily maximum and minimum of VPD, which are calculated from maximum and minimum air temperature and humidity:

$$VPD = \frac{0.6108 \times 2.72^{(17.269 \times T_{max})/(T_{max}+237.3)} \times (100 - RH_{min})/100 + 0.6108 \times 2.72^{(17.269 \times T_{min})/(T_{min}+237.3)} \times (100 - RH_{max})/100}{2} \quad (9)$$

where T_{max} and T_{min} are the maximum and minimum temperatures (°C), and RH_{max} and RH_{min} are the maximum and minimum relative humidities (%).

According to oak tree measurements by King and Schnell (1972), the root biomass to shoot biomass ratio was 0.34. The WUE for above ground biomass (mainly shoots) is calculated assuming the new biomass is proportionally allocated to root and shoots. The root biomass growth is the product of total shoot biomass growth and the root biomass to shoot biomass ratio (0.34).

The allocation of the above ground DM is modeled in a cascading manner, where DM is allocated first to leaves, then to nuts, then to the carbohydrate reserve pool and lastly to branches and the trunk. The daily allocation to leaves and nuts (further separated into shuck, shell, and kernel) is estimated as:

$$DM_j = GR_j(GDD_i)(GF_j) \tag{10}$$

where DM_j is the daily dry matter gain of organ j (kg tree^{-1}), GR_j the maximum growth rate of organ j (kg tree^{-1} GDD^{-1}), GDD_i the growing degree days for day i (°C day), and GF_j is the limiting growth factor (0–1) for organ j. The GF is assumed to be 1.0 for leaves. GF is equal to the carbohydrate reserve ratio on January 1 (RR_{Jan}) for shuck, shell, and kernel. The DM_j for any given organ j is limited by the remainder of DM after allocation to organs of higher sink strength. For example, allocation to nuts cannot exceed the amount of remaining DM after allocation to leaves. GR_j was calibrated using 2002 measurements and data from the literature (see Section 3).

Daily dry matter allocation to the carbohydrate reserve pool, DM_{CHO} (kg tree^{-1}), is calculated after allocation to leaves and nuts and is conceptualized as:

$$\begin{aligned} DM_{CHO} &= [DM - DM_{leaves} - DM_{husk} - DM_{shell} - DM_{kernel}] \\ &\quad \times RA; \quad RR_{Jan} < RR_e \\ DM_{CHO} &= 0; \; RR_{Jan} = RR_e \end{aligned} \tag{11}$$

where DM is the total daily dry matter gain per tree (kg tree^{-1}), DM_{leaves} the dry matter gain of leaves (kg tree^{-1}), DM_{shuck} the dry matter gain of shucks (kg tree^{-1}), DM_{shell} the dry matter gain of shells (kg tree^{-1}), DM_{kernel} the dry matter gain of kernels (kg tree^{-1}), RR_e the equilibrium carbohydrate reserve ratio (0–1), and RA is the allocation ratio of the remaining dry matter to reserves [0.03 according to Wood (1989), it is 1/12 of root biomass growth]. The RR_e (0.85) corresponds to the RR that would result in an average pecan nut yield that was determined from data reported by Wood (1989). Eq. (11) indicates that the carbohydrate reserve pool is only refilled if the current RR_{Jan} is below RR_e because when RR_{Jan} is greater than RR_e, the year will be an on-year and the photosynthate will be allocated to nut production and may not increase the reserve (Smith and Waugh, 1938). The reserve is drawn down by the amount of dry matter allocated to bud development (implicitly includes pistillate flower formation) and initial leaf expansion in spring. The bud growth rate was parameterized from 2002 bud growth measurements (0.3 kg tree^{-1} GDD^{-1}).

Any residual DM is allocated to branches and trunk based on their allocation ratios (details in Section 2.4). The tree height is calculated as the sum of each layer branch and trunk length, and the tree crown projection area is calculated using the outer branch length and angle. The maximum projection radius is half of the tree spacing. The leaf area per tree (m^2 tree^{-1}) is modeled by multiplying the total leaf biomass per tree by the specific leaf area, SLA (m^2 kg^{-1}).

Critical growth stages, expressed in terms of thermal time (i.e., cumulative growing degree days), are used to control seasonal growth duration of each organ in the model. Dry matter gain of leaves commences after budbreak and seizes after reaching a specified maximum leaf area index (MaxLAI, m^{-2} m^{-2}). Simulation of shuck and shell growth begins after pollination. Shell growth seizes in the model after reaching the shell hardening stage, which marks the start of DM accumulation in the kernel. Shuck and kernel growth stops after shuck split. Accumulation of DM in the whole tree starts when leaves start photosynthesizing and ceases after leaf fall.

3. Materials and methods

A 5.1 ha pecan orchard located 7 km south of Las Cruces was planted in 1970 at 10.0 m × 10.0 m tree spacing. In 2002, average orchard height was 11.3 m with an average DBH of 0.3 cm. The soil is Harkey loam (coarse-silty, mixed, calcareous, thermic typic Torrifluvents). The orchard area was determined from aerial photographs using ArcView software. The farmer applied 320 kg ha^{-1} of actual nitrogen through the irrigation system throughout the growing season. The orchard was pruned in February of 2002 and 2003. Branches pruned had an average diameter of 2 cm. In 2002, south and north sides and top were pruned with a mechanical hedger; in 2003, east and west sides were pruned. Since 1990, the pruning data (pruned biomass and nut yield) have been recorded.

3.1. *Irrigation and biomass measurements*

The orchard was flood-irrigated from two wells where the water was discharged into the orchard through a high-flow turnout. Sparling Propeller flow meters (Sparling Instruments, Inc., CA) were installed on the pumps to measure the irrigation amounts. A Hobo H8 (Onset Computer Corporation, MA) irrigation gate data logger was connected to a magnetic switch that recorded when the irrigation gate on the high-flow turnout was raised and lowered to measure when the water was turned into the orchard and to verify the Sparling meter readings. Table 3 lists the dates and amounts of flood irrigation applied during 2002 through 2004.

In 2002–2004, the orchard was instrumented with a Li-Cor eddy correlation system to obtain water use and total dry matter production through vapor and CO_2 flux measurements above the orchard from a 16 m tower. The daily total dry matter production and ET were estimated from the measurements (Wang et al., 2006).

The biomass of leaves and nuts were estimated from weekly samples from 2002 through 2004. On each sampling date, two small branches (diameter about 1.5 cm) were randomly clipped. A total of 25 leaves from each branch were randomly selected for measurements of leaf area and dry weight. The specific leaf area (m^2 kg^{-1}) was then calculated from these measurements. Also, the nut dry weight and number on the two branches were measured. The farmer measured nut yield at the end of each growing season. The nut yield per tree was estimated according to the number of trees

Table 3 – Flood irrigations applied to the pecan orchard in 2002–2004

Date 2002	Depth (mm)	Date 2003	Depth (mm)	Date 2004	Depth (mm)
3/14	115.0	3/24	120.4	3/22	116.8
4/17	114.4	4/28	135.4	4/25	111.8
5/5	203.6	5/14	139.8	5/16	134.6
5/21	122.1	5/20	151.8	5/30	109.2
6/3	114.3	5/28	124.3	6/10	160
6/14	125.2	6/10	124.2	6/21	152.4
6/23	115.0	6/16	147.0	7/6	139.7
7/4	111.3	6/22	195.9	7/14	127
7/15	96.8	7/1	119.5	7/23	127
7/25	95.0	7/9	93.0	8/2	111.8
8/5	94.0	7/17	88.0	8/11	111.8
8/14	87.9	7/25	93.2	8/24	99.1
8/23	81.3	8/2	87.6	9/2	101.6
8/30	94.3	8/14	94.2	9/9	96.5
9/14	107.2	8/21	92.0	9/17	101.6
9/23	80.4	8/28	49.7	9/28	101.6
10/4	112.8	9/5	107.1	10/14	88.9
10/22	83.6	9/13	101.0	10/27	68.6
		9/23	75.6		
		10/6	95.4		
		10/22	94.2		
Totals	1870.6		1963.21		2060

per hectare. The weekly nut biomass (kg ha^{-1}) was estimated as the measured nut yield scaled by the ratio of corresponding weekly measured average weight per nut to the value at the harvest time. Total leaf biomass of pecan trees was difficult to measure because of their large canopies. In lieu of total leaf biomass, a leaf growth ratio was calculated for each weekly measurement by dividing the weekly sample weight by the October's leaf weight (in October, pecan trees obtain maximum leaf weight).

3.2. *Measurements of shoot biomass allocation*

To obtain shoot biomass allocation, the wood density, crown distribution, and branch growth were measured and analyzed.

3.2.1. *Wood density measurement*

Four pecan branch segments (diameter: 1.5–6 cm; length: 15–25 cm) were sampled in November 2004. The segments were dried and weighed. The volumes of the segments were measured by water displacement in a graduated cylinder. The density of each segment was calculated as the weight divided by the volume. The mean density from the four segments was used in the model as pecan wood density.

3.2.2. *Crown distribution measurement*

Crown distribution was estimated in November 2004 from three pecan trees. DBHs were about 0.3 m. The number, length, and diameter of all the branches (>3.5 cm diameter) were measured. The branch angle from horizontal of outer branches (the outermost branches at the lateral sides) in the crown was obtained. For small branch diameter and length measurements, sub-sampling was used. Each cluster of small branches on three branches of diameter 3.5 cm, were sampled. The clusters of branches ranged from 0.4 to 3.5 cm. The clusters of branches were sorted into categories (<1.1, 1.2–1.6, 1.7–2.3, and 2.4–3.4 cm). The average number of branches in each category for each 3.5 cm—diameter branch was calculated. The total number of branches for each tree and each category was calculated using the average number in each category multiplied by the total number of 3.5 cm branches per tree. The relationship of branch diameter and length was analyzed by regression (Minitab, 2000).

3.2.3. *Trunk and branch growth*

The radial growth of trunk (diameter about 30 cm), primary (diameter about 20 cm), and secondary branches (diameter about 15 cm) in 2004 were measured by 24 automated point-dendrometers on four trees. Each trunk or branch had two duplicate dendrometer measurements. The dendrometers were constructed using a linear motion position sensor (Model 9605, BEI Duncan Electronics) fixed on the trunk and branches by clamps using mounting bolts (Fig. 7). Hourly measurements were recorded by a CR23X data logger (Campbell Scientific). The average and standard deviation of diameter growth for each size branch or trunk were calculated for future comparisons. The annual growth of smaller branches, having diameter of 1–15 cm, was measured manually by cutting off the branches and measuring the diameter growth according to growth rings. The average tree height was obtained by measuring four trees annually in the end of each year or after a top pruning.

3.2.4. *Shoot biomass allocation*

The 2004 yearly cross-section growth area for each measured branch and trunk was calculated according to the diameter growth. The relationship between cross-section growth area and original area was analyzed by regression (Minitab, 2000). Then the shoot allocation ratios were calculated for branches and trunk (see Section 2.4). For future comparisons, the average and standard deviation of dry biomass for primary and secondary branches, and trunk were calculated, respectively, according to the branch or trunk number, cross-section area, length, and density.

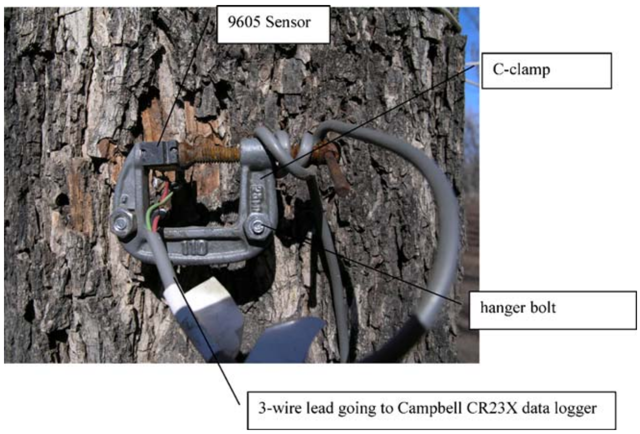

Fig. 7 – Automated point dendrometer used to measure trunk and branch diameter growth.

3.2.5. *Calibration and validation*

Measurements of GDDs in 2002 for critical growth stages were used to calibrate the pecan model. The maximum nut growth rate was calculated from historical maximum nut yield in the orchard and the corresponding GDDs (Table 1). The maximum component growth rate of kernel, shell and shuck was obtained using the maximum nut growth rate multiplied by the component weight ratios measured in 2002. The maximum growth rate of leaves was obtained using leaf weight ($64\,kg\,tree^{-1}$) from Kraimer (1998) and the corresponding growing-season GDDs. The measured SLA in 2002 was used in the model ($9.2\,m^{-2}\,kg^{-1}$). The maximum leaf area index (MaxLAI) was calculated ($6\,m^{-2}\,m^{-2}$) according to SLA, leaf weight per tree, and tree spacing ($MaxLAI = 64 \times 9.2/10^2$). The historical pruning data (pruned biomass and nut yield) in the orchard taken before 2002 were used to calibrate the pruning coefficient K_p by regression. Other parameters were taken from the literature. The 2003 and 2004 growing season data were then used to validate the model. The accuracy for each organ growth simulation (DM, nut, DBH, and height) at the end of each simulation year was calculated as:

$$\text{accuracy} = 1 - \left|\frac{\text{simulation} - \text{observation}}{\text{observation}}\right| \quad (12)$$

The time series of simulated and observed plant components was also plotted for visual analysis.

For this study, it was assumed that the pecan trees were subjected to insignificant N stresses during the growing season because of frequent applications of N fertilizer along with the irrigation water. Thus, N stress and its effect on growth were not considered in the simulations.

4. Results and discussion

4.1. *Calibration parameters*

Table 1 shows the pecan model parameters that were best estimates from literature and measured data. The measured wood density was $647\,kg\,m^{-3}$. The branch number in each level is shown in Table 2. The relationship between diameter and branch length is

$$y = 0.33\ln(x) + 2; \quad x > 0.01\,m \quad (13)$$

where x is the diameter (m) and y is the length (m) ($F = 503.6$, $P < 0.001$, $\ln(x)$ used as the independent variable in regression analysis).

When $x < 0.01$ m, Eq. (13) will give a negative value so we used the following equation instead.

$$y = 44.5x \quad (14)$$

Table 2 shows the calculated length for each level branch when DBH = 0.30 m.

The pruning coefficient is expressed as:

$$K_p = (1 - PR)^2 \quad (15)$$

where PR is the ratio of pruned biomass to the total shoot biomass, which includes level 2 and higher level branches ($F = 13006$, $P < 0.001$, regression analysis used $(1 - PR)$ as the independent variable). When there is no pruning, $K_p = 1$. When all the branches with diameter of 0.2 m (the level 2 branch) is pruned, PR = 1 and $K_p = 0$.

The relationship of yearly new growth cross-section area and original area in 2004 is shown in Fig. 8. The equation is

$$y = 0.011x^{0.54} \quad (16)$$

where x is the original cross-section area (m^2) and y is the yearly growth cross-section area (m^2). The equation is significant ($F = 159.6$, $P < 0.001$, regression analysis used $x^{0.54}$ as the independent variable). The shoot allocation ratios were obtained for each level branches and trunk according to this equation, shoot number, diameter, and length (Table 2). The tree height of about 11.3 m was estimated by summing all the lengths. This estimate is reasonable compared to the measured tree height of around 11.1 m at the beginning of 2002 when DBH was 0.30 m. The radius of the projected canopy area

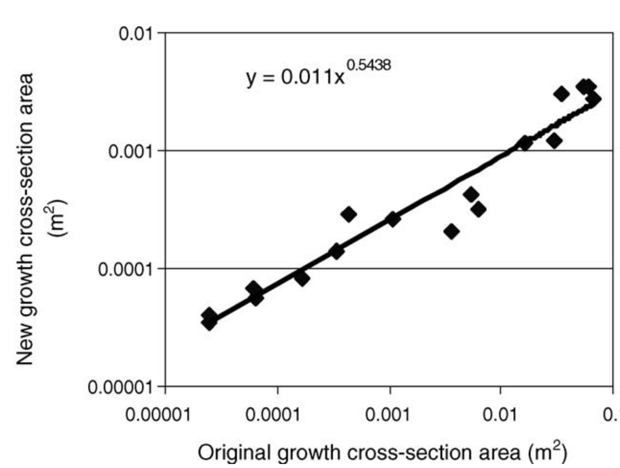

Fig. 8 – Relationship between yearly new growth cross-section area and original cross-section area measured in 2004.

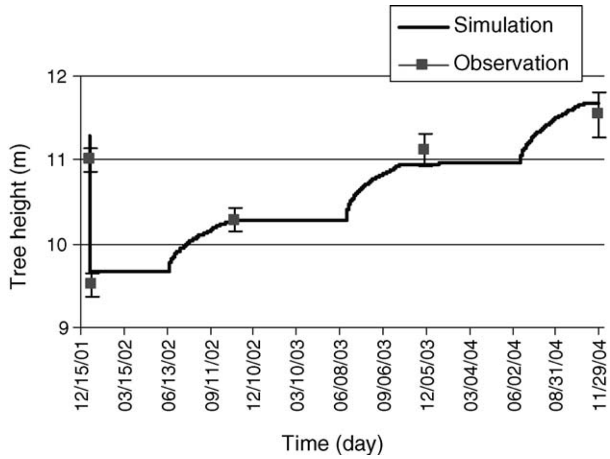

Fig. 9 – Variation of pecan tree height with time. Top pruning occurred in January 2002. Vertical bars are standard deviations.

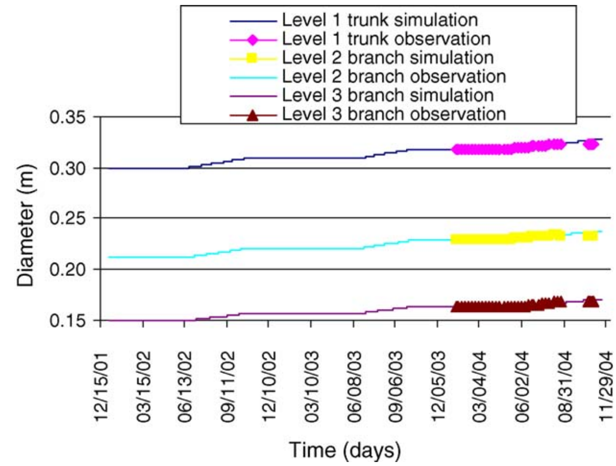

Fig. 10 – Comparison of simulated and observed diameters for level 1 (trunk), level 2 (primary), and level 3 (secondary) branches.

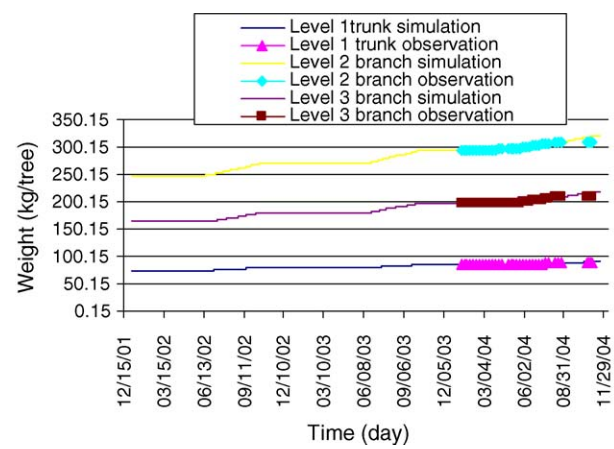

Fig. 11 – Comparison of simulated and observed biomass for level 1 (trunk), level 2 (primary), and level 3 (secondary) branches. There were some data gaps because of data logger power problems.

(i.e., projected to the ground) calculated using the branch length and the outer branch angle was 5.0 m, also deemed reasonable when the canopy fully covered the ground at the beginning of 2002.

4.2. *Simulation*

4.2.1. *The growth of tree height, trunk, primary, and secondary branches*

The tree grew in height about 0.7 m every year from 2002 through 2004 (Fig. 9). At the beginning of 2002, the trees were 11.1 m tall. In January 2002, a top pruning occurred and the height decreased to 9.5 m. It grew to 11.5 m at the end of 2004. The growth in height was not affected by the light pruning operations in 2003 because the tops of the trees were not pruned. The simulation was accurate with accuracy over 95%.

The simulated diameter growth of level 1 (trunk), level 2 (primary) and level 3 (secondary) branches tracked the dendrometer measurements very well (Fig. 10). The standard deviation of the measured diameter growth was less than 0.002 m, which was too small to be shown in the figure. The DBH increased from 0.3 m in 2002 to 0.327 m in 2004 based on the model simulation (level 1 trunk in Fig. 10). The DBH grew about 9.0 mm each year on average and 27 mm total over the 3 years. The predicted diameter of primary branches increased from 0.212 to 0.237 m from 2002 to 2004. Thus, average increase in primary branch diameter was 8.3 mm per year. The diameter of secondary branches increased from 0.150 to 0.170 m from 2002 to 2004, with an average increase of 6.6 mm per year.

Nelson (1965) reported that mature pecan trees could grow about 0.9 m per year in height in loamy soil and average 7 mm per year increase in DBH for trees of DBH = 35 cm. The height and DBH simulation results are comparable with Nelson's (1965) observations.

The simulation of biomass in the trunk, primary, and secondary branches agreed well with the measurements (Fig. 11). The standard deviation of the measured biomass growth was less than 0.5 kg tree^{-1}. The trunk grew from 74.5 to 88.0 kg tree^{-1} from 2002 to 2004; primary branches (level 2) from 248.4 to 319.4 kg tree^{-1}; and secondary branches (level 3) from 163.5 to 217.4 kg tree^{-1}.

This model had better accuracy in predicting height and DBH compared with the eucalyptus model (*Eucalyptus camaldulensis*) of Al-Jamal et al. (2002), upon which this pecan model was based. The eucalyptus model overestimated height by 14% in 3 years of simulations. It overestimated DBH growth by 58% in the first simulation year and 14% in second and third years. The reason for the overestimation may be that the shoot structure in the eucalyptus model was not detailed, i.e., the model did not divide the shoots into different diameter levels, instead the model only divided the shoots in two parts: a trunk and the rest of the shoot.

4.2.2. *Dry matter, leaf, and nut growth*

Simulated values of total dry matter production per tree (254.3 kg tree^{-1}) in 2002 were very close to estimates derived from eddy covariance measurements (250.2 kg tree^{-1}) (Fig. 12). The simulated values in 2003 and 2004 were also accurate

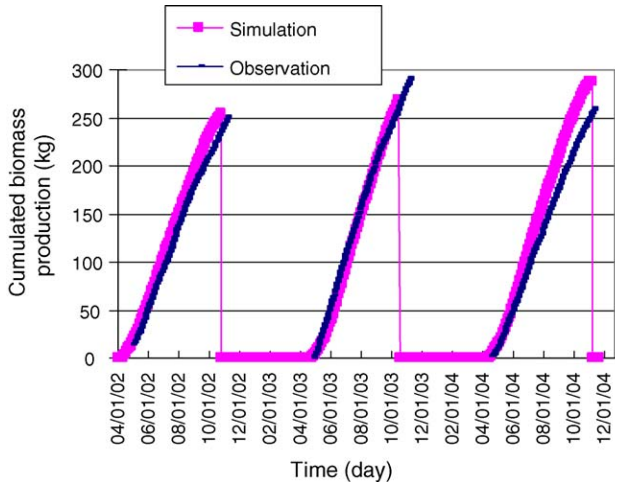

Fig. 12 – Simulated and observed total dry matter production per tree in 2002–2004.

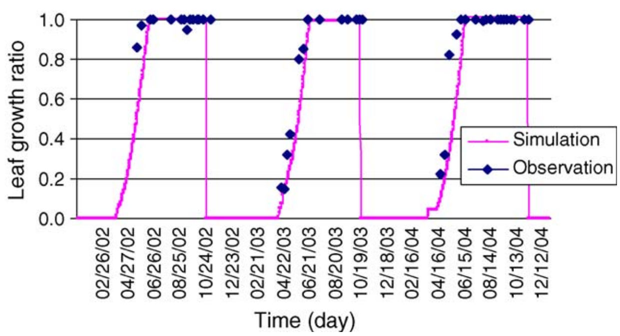

Fig. 13 – Simulated and observed leaf growth ratios in 2002–2004.

compared with the measurements (266.0 kg tree^{-1} versus 290.7 kg tree^{-1} and 287.4 kg tree^{-1} versus 259.1 kg tree^{-1} in 2003 and 2004, respectively). The accuracy in the 3 years was 98.4, 91.6, and 89.1%, respectively. Pecan trees began to increase in dry matter around the middle of April, a couple of weeks after the leaves had emerged. The dry matter increase ceased by the end of October or the beginning of November when the leaves fell.

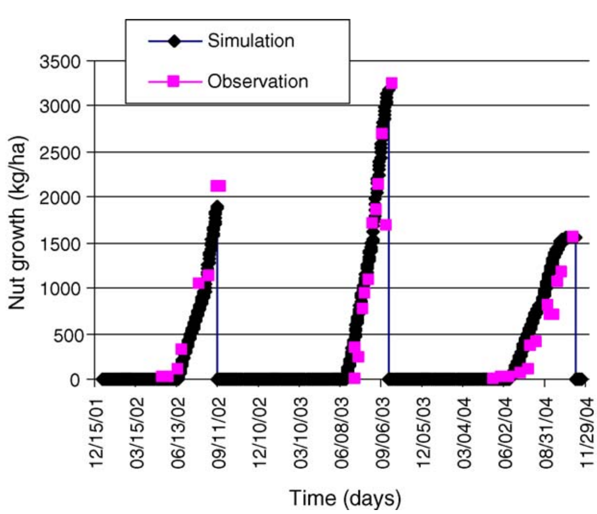

Fig. 14 – Simulated pecan nut biomass compared with observations in 2002–2004.

The model simulated the trends in leaf growth (i.e., leaf growth ratio) accurately (Fig. 13). The leaves emerged at the end of March or beginning of April, with maximum LAI attained by the middle or end of June.

The model accurately simulated alternate bearing from 2002 to 2004 (Fig. 14). The model accuracy was above 89.7%. Nut growth began at the start or middle of May. At this phase, the nuts grew slowly because leaves were not fully developed. In the middle of June, the leaves were fully developed and nuts grew at a faster rate. Nut growth ended shortly after shuck split in October.

This newly developed model has similar capabilities and accuracy compared to the peach growth model by Grossman and DeJong (1994) that simulates dry matter production of fruits, leaves, branches, and trunk.

5. Conclusion

A pecan model was developed with objects for simulating irrigation, pruning, alternate bearing, shoot biomass allocation, and growth by modifying an existing growth-irrigation scheduling model (GISM) (Al-Jamal et al., 2002). The model simulated dry matter production, nut yield, and alternate bearing accurately from 2002 to 2004. The accuracy was above 89% for total dry matter production and nut yield. The model also simulated the trends in leaf growth accurately. Overall, this model was found to adequately simulate the effects of climate, irrigation, and pruning on pecan tree growth and nut yield, including alternate bearing. However, the model should be tested with more years of data at multiple locations to gain a better assessment of its robustness. It can potentially be used to schedule and estimate the amount of irrigation and pruning to optimize pecan nut yield.

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REFERENCES

Abdul-Jabbar, A.S., Sammis, T.W., Lugg, D.G., Kallsen, C.E., Smeal, D., 1983. Water use by alfalfa, corn and barley as influenced by available soil water. Agric. Water Manag. 6, 351–363.

Acock, B., Reynolds, J.F., 1989. The rationale for adopting a modular generic structure for crop simulators. Acta Horticult. 248, 391–396.

Al-Jamal, M.S., Sammis, T.W., Mexal, J.G., Picchioni, G.A., Zachritz, W.H., 2002. A growth-irrigation scheduling model for wastewater use in forest production. Agric. Water Manag. 56, 57–79.
Amling, H.J., Amling, K.A., 1983. Physiological differentiation of pistillate flowers of pecan and cold requirements for their initiation. J. Amer. Soc. Hort. Sci. 108, 195–198.
Andersen, P.C., Crocker, T.E., 2004. The pecan tree. Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, First published May 2004, HS984, http://edis.ifas.ufl.edu.
Clark, N.A., Wynne, R.H., Schmoldt, D.L., 2000. A review of past research on dendrometers. For. Sci. 46, 570–576.
Conner, P.J., Worley, R.E., 2000. Alternate bearing intensity of pecan cultivars. HortScience 35, 1067–1069.
Garrot Jr., D.J., Kilby, M.W., Fangmeier, D.D., Husman, S.H., Ralowicz, A.E., 1993. Production, growth, and nut quality in pecans under water stress based on the crop water stress index. J. Amer. Soc. Hort. Sci. 118, 694–698.
Goldhamer, D.A., Fereres, E., Salinas, M., 2003. Can almond trees directly dictate their irrigation needs? California Agriculture, http://californiaagriculture.ucop.edu/.
Grossman, Y.L., DeJong, T.M., 1994. Peach: a simulation model of reproductive and vegetative growth in peach trees. Tree Physiol. 14, 329–345.
Gutschick, V.P. Plant acclimation to elevated CO_2—from simple regularities to biogeographic chaos. Ecol. Model., in press.
Herrera, E., 2005. Historical Background of Pecan Plantings in the Western Region. College of Agriculture and Home Economics, New Mexico State University Guide H-626 (May 2005).
King, W.W., Schnell, R.L., 1972. Biomass estimates of black oak tree components. TVA Div. of Forests, Fisheries, and Wildlife Mgt. Tech. Note B1. Norris, Tenn.
Kraimer, R.A., 1998. Fate of labeled fertilizer applied to pecan. M.S. thesis. New Mexico State University, Las Cruces, New Mexico.
Lacointe, A., 2000. Carbon allocation among tree organs: a review of basic processes and representation in functional-structural models. Ann. For. Sci. 57, 521–534.
Law, B.E., Falge, E., Gu, L., Baldocchi, D.D., Bakwin, P., Berbigier, P., Davis, K., Dolman, A.J., Falk, M., Fuentes, J.D., Goldstein, A., Granier, A., Grelle, A., Hollinger, D., Janssens, L.A., Jarvis, P., Jensen, N.O., Katul, G., Mahli, Y., Matteucci, G., Meyers, T., Monson, R., Munger, W., Oechel, W., Olson, R., Pilegaard, K., Paw, U.K.T., Thorgeirsson, H., Valentini, R., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2002. Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation. Agric. For. Meteorol. 113, 97–120.
Malstrom, H.L., 1974. The relationship of stored reserves to yield in mature pecan trees. Proc. West. Pecan Conf. 8, 65–69.
McEachern, G.R., Stein L.A., Sauls, J.W., 1997. Texas Pecan Orchards. Extension publication. Texas A&M University, College Station, Texas 77843-2134, January 27, 1997, http://aggie-orticulture.tamu.edu/extension/fruit/pecanorchard/pecanorchard.html.
Minitab, 2000. Minitab Reference Manual, Release 13.3. Minitab Inc., State College, PA.
Miyamoto, S., 1983. Consumptive water use of irrigated pecans. J. Amer. Soc. Hort Sci. 108, 676–681.
Miyamoto, S., 1985. Water consumption: growers need to know this to plan irrigation. Pecan S. Pecan Quart. 19 (3), 8 10, 12–13.
Nelson, T.C., 1965. Silvical characteristics of the commercial hickories. USDA Forest Service, Hickory Task Force Report 10, Southeastern Forest Experiment Station, Asheville, NC, 16.
Passioura, J.B., 1996. Simulation models: science, snake oil, education, or engineering? Agron. J. 88, 690–694.
Reynolds, J.F., Acock, B., 1997. Modularity and genericness in plant and ecosystem models. Ecol. Model. 94, 7–16.
Samani, Z.A., Pessarakli, M., 1986. Estimating potential crop evapotranspiration with minimum data in Arizona. Trans. Aer. Soc. Agro. Eng. 29, 522–524.
Sammis, T.W., Mexal, J.G., Miller, D.R., 2004a. Evapotranspiration of flood-irrigated pecans. Agric. Water Manag. 69, 179–190.
Sammis, T.W., Andales, A., Simmons, L., 2004b. Adjustment of closed canopy crop coefficients of pecans for open canopy orchards. In: Thirty-eighth Western Pecan Conference Proceedings, Las Cruces Hilton, Las Cruces, New Mexico, March 7–9, 2004, pp. 28–32.
Smith, C.L., Waugh, J.G., 1938. Seasonal variations in the carbohydrate and nitrogen content of roots of bearing pecan trees. J. Agric. Res. 57, 449–460.
Smith, M.W., McNew, R.W., Ager, P.L., Cotton, B.C., 1986. Seasonal changes in the carbohydrate concentration in pecan shoots and their relationship to flowering. J. Amer. Soc. Hort. Sci. 111, 558–561.
Stein, L.A., McEachern, G.R., Storey, J.B., 1989. Summer and fall moisture stress and irrigation scheduling influence pecan growth and production. HortScience. 24, 607–611.
Snyder, R.L., Pruitt, W.O., 1992. Evapotranspiration data management in California. In: Presented at the Am. Soc. Civil Engr. Water Forum '92', Baltimore, MD, August 2–6.
Wang, J., Miller, D.R., Sammis, T.W., Gutschick, V.P., Simmons, L.J., 2006. Measurement and simple model for pecan water use efficiency. Agric. Water Manage. submitted for publication.
Wetzstein, H.Y., Sparks, D., 1983. The morphology of pistillate flower differentiation in pecan. J. Amer. Soc. Hort. Sci. 108, 997–1003.
Wood, B.W., 1989. Pecan production responds to root carbohydrates and rootstock. J. Amer. Soc. Hort. Sci. 114, 223–228.
Wood, B.W., 1991. Alternate bearing in pecan. In: Wood, B.W., Payne, J.A. (Eds.), Pecan Husbandary: Chanllenges and Opportunities. First National Pecan Workshop Proceedings, U.S. Dept. Agri., Agri. Res. Serv., ARS-96, pp. 180–190.
Wood, B.W., McMeans, J.L., 1981. Carbohydrate changes in various organs of bearing and nonbearing pecan trees. J. Amer. Soc. Hort. Sci. 106, 758–761.
Worley, R.E., 1979a. Pecan yield, quality, nutlet set, and spring growth as a response of time of fall defoliation. J. Amer. Soc. Hort. Sci. 104, 192–194.
Worley, R.E., 1979b. Fall defoliation date and seasonal carbohydrate concentration of pecan wood tissue. J. Amer. Soc. Hort. Sci. 104, 195–199.
Worley, R.E., 1985. Effects of hedging and selective limb pruning of Elliott, Desirable, and Farley pecan trees under three irrigation regimes. J. Amer. Soc. Hort. Sci. 110, 12–16.
Worley, R.E., 1991. Selective limb pruning intensity influences mature pecan tree and nut characteristics. J. Amer. Soc. Hort. Sci. 26, 126–129.