

## Modeling forage growth in a Midwest USA silvopastoral system

Tong Zhai<sup>1</sup>, Rabi H. Mohtar<sup>1,\*</sup>, Andrew R. Gillespie<sup>2</sup>, Guntram R. von Kiparski<sup>2</sup>, Keith D. Johnson<sup>3</sup> and Michael Neary<sup>4</sup>

<sup>1</sup>Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN 47907, USA;

<sup>2</sup>Department of Forestry and Natural Resources, Purdue University, IN, USA; <sup>3</sup>Department of Agronomy, Purdue University, IN, USA; <sup>4</sup>Department of Animal Sciences, Purdue University, IN, USA; \*Author for correspondence (e-mail: mohtar@purdue.edu; phone: +1-765-494-1791 fax: +1-765-496-1115)

Received 26 June 2003; accepted in revised form 30 September 2005

**Key words:** Competition, GRASIM, Modeling tree effect, Pasture, SGRASIM, Silvopasture modeling

### Abstract

Tree effects on understory pasture growth in a silvopastoral system were modeled by explicit simulation of tree canopy light and rainfall interception, evapotranspiration, and nutrient uptake. The algorithms to model these effects were incorporated into a multispecies grazing simulation model, GRASIM, to form the Silvopasture GRASIM model (SGRASIM). The new model was evaluated using forage biomass data and soil moisture data collected from a silvopasture field experiment with black walnut (*Juglans nigra* L.). The SGRASIM model performed well in simulating the growth of three competing dominant forage species (orchardgrass [*Dactylis glomerata* L.], Kentucky bluegrass [*Poa pratensis* L.], and tall fescue [*Festuca arundinacea* (Schreb.)]) in the pasture both under tree canopy and in open pasture (linear regression of observed on simulated biomass for the species gave  $r^2$  values above 0.97). Model growth parameters for forage under tree canopy, compared with those for an open pasture, bear testament to the shading effects from the forest canopy in terms of reduced photosynthetic efficiency, increased leaf area ratio, and photosynthate partitioned to aboveground biomass. The new model reasonably followed the soil moisture time series in the upper soil layer (0–30 cm), where the bulk of the forage roots reside.

### Introduction

Silvopasture, one of the oldest agroforestry systems, has been practiced extensively around the world. Within the United States, such practices date back to the early 1900s (Pearson 1990). Shiflet (1980) stated that about 100 million acres of forestland in the southeastern United States have the potential to produce forages for livestock, second to none around the world. The integrated timber and livestock production can generate higher profits, which provide farmers with a means of surviving markets that fluctuate through time.

The successful management of silvopasture, in its various forms (introducing young trees into pasture or grazing natural forest, etc.) for different production goals is determined by the extent of the integration of forest and individual agricultural components (grazing animals and forage, as well as the physical environment). Components are judged by their capacity to produce desired products, and their compatibility with other components. Hence, scientific and quantitative understandings of these interrelated components are needed to replace the commonly relied on empirical experiences.

Comprehensive computer simulation models are best suited for the study of long term interactions among key components of silvopastoral systems, hence can be used to answer important questions like what level of productivity can be achieved or what aspects of forage-tree interaction encountered in various types of silvopasture systems can be further explored to design better management practices (Anderson et al. 1993).

Among others, the Agroforestry Modeling Project (AMP) by the International Center for Research in Agroforestry (ICRAF) established one of the first comprehensive modeling systems, where existing tree growth simulation models are combined with crop growth models to simulate the agroforestry system as a whole. HyPAR (Lawson et al. 1995) and WaNuLCAS (Noordwijk and Lusiana 1999) are the two most prominent models.

These models mainly focused on agronomic cropping system under tree canopy and there have been no reported use of these models for silvopastoral systems with mixed forage species. In addition, these complex models require a large amount of input data for various model components, including many data for tree physiology that are unfamiliar to common landowners and livestock producers. Some of these data are difficult to obtain due to high cost and labor intensity. Existing traditional pasture and grazing models such as GRAZE (Parsch and Loewer 1995) and DAFOSYM (Rotz et al. 1989) don't have a tree component, thus, limiting their application to silvopastoral systems.

In this research, a modeling approach is employed to help investigate the competitive forage growth in a silvopastoral system at farm level. A simple and effective silvopasture model is developed and serves as a research framework to account for the competition among trees and multiple understory forage species under changing environmental conditions. It has long been recognized that the availability of the three most important resources, i.e. light, water and nutrient, and the interrelationships among coexisting species with regard to these resources are at the core of research and design of successful agroforestry systems (Ong 1991). Hence in the current project, a silvopastoral model was constructed by incorporating algorithms for simulating tree competition for light, water and nitrogen into GRASIM, an existing grazing simulation model (Mohtar

et al. 1997a) that is capable of simulating the growth of mixed pastures (Zhai et al. 2004). In the following sections, the structure of the silvopasture GRASIM (SGRASIM) model is presented per its explicit simulation of tree-forage competition for solar radiation, water, and nitrogen. The model was then evaluated using observed forage biomass and soil moisture data from a silvopasture field experiment. The simulated differential forage growth in open pasture and under tree canopy is analyzed to evaluate the effects of the tree canopy.

## Methodology

### *Modeling tree competition and its impact on understory forage growth*

Tree canopy light, rainfall interception, canopy transpiration, and soil nitrogen uptake were explicitly modeled and presented below. It is assumed that the tree canopy is horizontally homogeneous in leaf area distribution, which corresponds to the closely positioned and relatively uniform tree crowns in the experimental field.

### *Solar radiation interception by tree canopy*

Solar radiation intercepted by tree crowns is calculated using Jackson and Palmer's (1981) model applied to a discontinuous forest canopy (Equation 1). The total percentage of solar radiation reaching the understory forage ( $T$ ) is calculated as:

$$T = T_b + (1 - T_b)e^{\frac{-kL}{1-T_b}} \quad (1)$$

where  $k$  is the tree canopy light extinction coefficient,  $L$  is tree leaf area index ( $\text{m}^2$  leaf area per  $\text{m}^2$  ground),  $T_b$  is the percentage of solar radiation transmitted through the gaps between tree crowns, and  $1 - T_b$  is the percentage of solar radiation transmitted through the tree crown that attenuates exponentially down the height of the tree crown.  $T_b$  is a function of cloud cover, tree canopy height ( $h$ ), and tree crown gap ( $g$ ) according to (Equation 2):

$$0.5g/h < T_b < 0.6g/h \quad (2)$$

where the coefficients correspond to cloud cover, with 0.5 for a cloudy overcast sky and 0.6 for a clear bright sky.

The advantage of the above formulation is that it can easily calculate the amount of light inter-

cepted by the tree canopy as a whole,  $I_c$ , to be:

$$I_c = I_0(1 - T) \quad (3)$$

where  $I_0$  is the incident light on the top of tree crown.  $I_c$  is used as the energy input in the transpiration estimation from the tree canopy.

Tree leaf fall phenology was observed, recording the start and end of litter fall from trees in the field, which, in turn, was used to describe the leaf area index seasonal dynamics using the following equation set:

$$\begin{aligned} L_t &= L_{\max} & t < t_{\text{beglf}} \\ L_t &= \left(1 - \left(\frac{t - t_{\text{beglf}}}{t_{\text{endlf}} - t_{\text{beglf}}}\right)^{\text{elf}}\right) * L_{\max} & t_{\text{beglf}} \leq t \leq t_{\text{endlf}} \\ L_t &= BAI & t > t_{\text{endlf}} \end{aligned} \quad (4)$$

where  $L_t$  is the tree canopy leaf area index at time  $t$ ;  $L_{\max}$  is the maximum tree leaf area index;  $BAI$  is the tree canopy branch area index,  $\text{m}^2$  branch area/ $\text{m}^2$  ground area (after leaf fall ceases);  $t_{\text{beglf}}$  is the time tree leaf fall starts;  $t_{\text{endlf}}$  is the time tree leaf fall ends; and  $\text{elf}$  is the exponent term for the leaf fall function. Although the current model is used to simulate forest starting with a full canopy, it has a similar function to describe the leafing process.

The parameters used in Equations 1–4 were determined by optimization. Measured daily incident light during the 2000 growing season above the tree canopy ( $I_0$ ) was multiplied by Equation 1 to calculate the predicted light transmission. Then, the square root of the averaged sum of the differences between predicted and measured transmitted light through the tree canopy was minimized using the parameters as independent variables (Appendix A).

#### Rainfall interception

In this study, only the daily storage capacity of a black walnut canopy is considered in precipitation interception calculations. The maximum canopy storage capacity for precipitation,  $S$ , is first determined and subsequently modified by the changing tree canopy leaf area index over the growing season (Equation 4).

$S$  is determined from a plot of gross rainfall versus throughfall (TF) for individual storms (Rowe 1983). This technique assumes that total rainfall is equal to the sum of throughfall, canopy storage ( $S$ ), and evaporative loss from the wetted canopy. It uses a straight line of unit slope to form an upper envelope of all the data points in a throughfall vs. gross

rainfall plot. This upper envelope of all data points goes through only those points representing conditions with minimal rainfall loss due to evaporation from a wet canopy. Hence, by back extrapolating this line,  $S$  is given by the negative intercept of this line with the throughfall axis (Figure 1), i.e. the amount of rain that falls before throughfall begins (TF = 0). Only those storms that were greater than 1.5 mm and preceded by at least 8 h dry period were used in the estimation of  $S$  to avoid the high potential of evaporative loss during small rainfalls. In this study, the  $S$  of the experimental black walnut canopy was found to be 1.0 mm (Figure 1). Daily rainfall budget is to have tree canopy storage fulfilled before any precipitation is allowed to reach the understory layers.

#### Interaction between trees and understory pasture for water and nutrients

The daily water and nutrient uptake by either trees or crops is determined by their corresponding characteristic root distribution, fine root mass, and the soil water and nutrient content. Tree water and nitrogen daily demand were calculated and used to reduce the availability of soil water and nitrogen for forage growth.

#### Tree daily water demand and forest evapotranspiration (ET). ET is considered to be the driving force for soil water extraction.

The following Penman–Monteith (PM) equation was used to estimate the transpiration

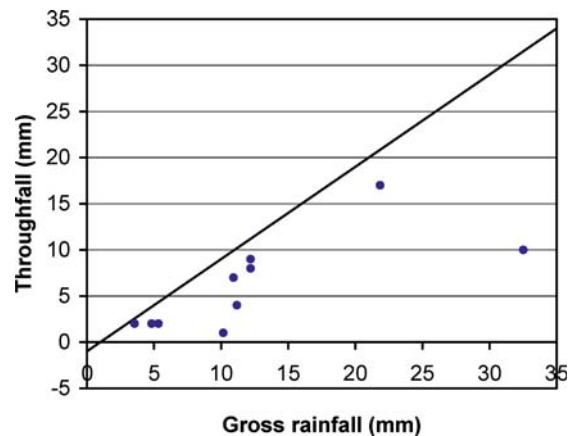


Figure 1. The relationship between storm total rainfall and throughfall at Martell forest, 2000 growing season. The straight line with unit slope forms an upper envelope of data points that intercepts the throughfall axis at  $-1.0$  mm.

capacity of a forest canopy:

$$\lambda \cdot E = \frac{\Delta \cdot R_{\text{net}} + \rho_{\text{air}} \cdot c_p \cdot (e_z^0 - e_z)/r_a}{\Delta + \gamma \cdot (1 + r_c/r_a)} \quad (5)$$

where  $\lambda$  is the latent heat flux density ( $\text{MJ m}^{-2} \text{d}^{-1}$ ),  $E$  is the depth rate evaporation ( $\text{mm d}^{-1}$ ),  $\Delta$  is the slope of the saturation vapor pressure-temperature curve,  $de/dT$  ( $\text{kPa } ^\circ\text{C}^{-1}$ ),  $R_{\text{net}}$  is the net radiation ( $\text{MJ m}^{-2} \text{d}^{-1}$ ),  $\rho_{\text{air}}$  is the air density ( $\text{kg m}^{-3}$ ),  $c_p$  is the specific heat at constant pressure ( $\text{MJ kg}^{-1} ^\circ\text{C}^{-1}$ ),  $e_z^0$  is the saturation vapor pressure of air at height  $z$  ( $\text{kPa}$ ),  $e_z$  is the water vapor pressure of air at height  $z$  ( $\text{kPa}$ ),  $\gamma$  is the psychrometric constant ( $\text{kPa } ^\circ\text{C}^{-1}$ ),  $r_c$  is the plant canopy resistance ( $\text{s m}^{-1}$ ), and  $r_a$  is the diffusion resistance of the air layer ( $\text{s m}^{-1}$ ). All of these terms, except for  $r_c$ , can be calculated or derived from readily available meteorological data (Neitsch et al. 2001).

The air diffusion resistance,  $r_a$ , is also referred to as aerodynamic resistance. It is a function of wind speed and canopy structure. It is calculated as the inverse of the boundary layer conductance (Thornley and Johnson 1990). The canopy resistance,  $r_c$ , is often reported in literature as the inverse of stomatal conductance ( $g_s$ ), i.e.,  $r_c = 1/g_s$ , which is a species specific parameter. In this work, a simple model was used to calculate the stomatal conductance, in which the maximum stomatal conductance ( $g_{\text{smax}}$ ) for black walnut tree was modified by the vapor pressure deficit and then used to calculate the canopy resistance,  $r_c$ . The  $g_{\text{smax}}$  for black walnut trees was found by many researchers to be  $0.01 \text{ m s}^{-1}$  (Le Roux et al. 1999).

In the current model, the daily water demand for trees is considered as the daily transpiration rate from the trees, which is calculated using the PM equation (Equation 5). The total daily ET demand of the forest is satisfied first with forest canopy rainfall storage. Then, the residual ET demand is satisfied with soil moisture.

*Tree daily nitrogen demand.* The following method for the estimation of tree daily nitrogen demand is adapted from the HYBRID model (Mobbs et al. 1998).

$$F_{N,u} = \eta_u \cdot f_T \cdot C_r \cdot N_{\text{min}} \cdot (C_v/N_v) \quad (6)$$

where  $F_{N,u}$  is the daily uptake of nitrogen from soil

by fine roots ( $\text{kg N m}^{-2} \text{day}^{-1}$ ),  $\eta_u$  is a constant with the unit of  $\text{m}^2 \text{kg C}^{-1} \text{day}^{-1}$ ,  $f_T$  is a factor to allow for the effect of soil temperature,  $C_r$  is the fine root carbon mass in  $\text{kg m}^{-2}$ ,  $N_{\text{min}}$  is the soil mineral nitrogen content in  $\text{kg N m}^{-2}$ , and  $C_v/N_v$  is the non-heartwood plant carbon to nitrogen ratio of trees. It is assumed that the tree does not take up any nitrogen if  $C_v/N_v$  is lower than  $10 \text{ kg C kg N}^{-1}$ .  $\eta_u$  is set at  $0.036 \text{ m}^2 \text{kg C}^{-1} \text{day}^{-1}$  (ignoring C:N ratio units) for all trees (Mobbs et al. 1998). The following set of equations is used to estimate  $C_r$ :

$$\begin{aligned} C_r &= \eta_{r/f} \cdot C_f \\ C_f &= \eta_f \cdot \frac{A_{\text{sw}}}{\text{sla}_t} & t < t_{\text{beglf}} \\ C_f &= \eta_f \cdot \frac{A_{\text{sw}}}{\text{sla}_t} \cdot \left(1 - \left(\frac{t - t_{\text{beglf}}}{t_{\text{endlf}} - t_{\text{beglf}}}\right)^{\text{elf}}\right) & t_{\text{beglf}} \leq t \leq t_{\text{endlf}} \\ C_f &= 0 \quad \text{tree } N \text{ uptake ceases} & t > t_{\text{endlf}} \end{aligned} \quad (7)$$

where  $C_f$  is foliage carbon mass ( $\text{kg m}^{-2}$ );  $\eta_{r/f}$  is the ratio between fine root carbon and foliage carbon and is assumed to be 1 (Pearson et al. 1984);  $\eta_f$  is the foliage to sapwood area ratio, which is estimated as  $4167 \text{ m}^2 \text{m}^{-2}$  (Young et al. 1980);  $\text{sla}_t$  is the tree specific leaf area ( $\text{m}^2 \text{kg}^{-1}$ ), which was determined to be  $36 \text{ m}^2 (\text{kg carbon})^{-1}$  for most deciduous broadleaved trees (Friend et al. 1997) and could be measured where possible; and  $A_{\text{sw}}$  is the average tree sapwood area at breast height (1.3 m above tree base). It is the cross sectional area of tree trunk at breast height less the heartwood area, which was estimated to be 60% of the cross sectional area of a mature black walnut tree trunk at breast height (Phelps and Chen 1989);  $t_{\text{beglf}}$  is the time tree leaf fall starts;  $t_{\text{endlf}}$  is the time tree leaf fall ends; elf is the exponent term for the leaf fall function.

The soil temperature factor,  $f_T$ , is given by Thornley (1991) as follow:

$$\begin{aligned} f(T) &= \frac{(T - T_{\text{min}})(2T_{\text{max}} - T_{\text{min}} - T)}{(T_{\text{ref}} - T_{\text{min}})(2T_{\text{max}} - T_{\text{min}} - T_{\text{ref}})} \\ f(T_{\text{max}}) &= f_{\text{max}} \\ f(T_{\text{ref}}) &= 1.0 \\ f(T_{\text{min}}) &= f_{\text{min}} \\ T_{\text{min}} &< T_{\text{ref}} < 2T_{\text{max}} - T_{\text{min}} \end{aligned} \quad (8)$$

where,  $T_{\text{min}}$ ,  $T_{\text{max}}$ , and  $T_{\text{ref}}$  are the minimum, maximum, and reference temperature for nutrient

uptake, and are set to be 0, 20, and 40 °C, respectively.  $T$  is the current daily temperature.

Considering the dominant canopy position and the deeper rooting depth of trees compared to grasses, it is likely that tree nutrient uptake will not be severely limited, hence, the tree C:N ratio is assumed to be maintained at optimum at all times and tree N demand can be satisfied from deeper soil depth in case of nutrient shortage (Berendse 1979; Kang et al. 1985). In equation 6,  $C_v/N_v$  is the ratio of carbon to nitrogen content in sapwood and foliage and is calculated based on the HyPAR model method (Mobbs et al. 1999 equation 4:29–4:34).

*Tree-forage competition for water and nutrients.* Black walnut is a deep-rooted species. Black walnut trees have roots capable of growing to a depth of 3.6 m, and water usage is mainly concentrated in the first 1.8 m, with 50% of the water usage from 0 – 1 m beneath the soil surface (Thompson 1976). Thus, assuming that water usage is uniformly distributed in the first 1 m of the soil profile, one half of the daily water demand of black walnut trees is to be satisfied by the soil water in the first 1 m of soil profile, which is considered as the maximum effective rooting depth for forage crops.

In the current model, the distribution of nitrogen uptake demand across the soil profile adopts the same strategy as that for soil water uptake. First, daily tree nitrogen demand is calculated using equation 6. Then, based on Thompson's (1976) description of mature black walnut tree root distributions, half of the N uptake demand is to be satisfied by soil nitrogen content in the first 1 m of the soil profile. If the combined nitrogen demand from forage and tree roots is less than available soil nitrogen content, then both demands will be satisfied and soil N content will be reduced accordingly. If not, forage N uptake is not affected, assuming tree N demand can be satisfied from deeper soil layers (Berendse 1979; Kang et al. 1985).

A schematic of the soil water and nitrogen uptake processes for trees and the understory crop (forage) is shown in Figure 2. Daily water and nitrogen demands from trees and forage are calculated based on growth and/or environmental conditions. Final uptake of water and N are

determined taking into consideration the rooting depth, species composition (among understory crops), and soil available water and nitrogen contents.

*The model.* GRASIM is a field-scale, physically based computer model designed for typical pastoral systems (Mohtar et al. 1997a, b; Mohtar et al. 2000). It is comprised of four major components: forage growth, water cycling, nitrogen cycling, and harvest/or grazing. It operates on a daily time step to predict forage biomass, soil water content, soil nitrogen content, and leaching dynamics. It models soil water and nutrient cycling in a two-layer (top and bottom) soil structure. GRASIM was later developed to simulate mixed pasture where multiple forage species grow and compete at the same time and across multiple fields (Zhai et al. 2004).

In this work, new tree modules as introduced above were incorporated into the multispecies GRASIM to form a silvopasture model (SGRASIM). Figure 3 shows the overall schematic of the SGRASIM model. Trees negatively affect understory pasture growth through the canopy filtering effects of precipitation and solar radiation as well as through competition for nutrients and water. The trees take part in water cycling through transpiration, and nitrogen cycling through nitrogen uptake. Currently, there is no feedback effect on tree processes due to the lack of a detailed tree growth model. Only the effects of environmental conditions such as soil water content and daily temperature on stomatal conductance of tree leaves are represented.

#### *Field experiment and data collection*

A silvopasture experiment were conducted at the Martell Forest experimental station of Purdue University, located about 13 km west of the Purdue campus in West Lafayette, Tippecanoe County, Indiana, USA. It was conducted on naturalized grassland in a black walnut (*Juglans nigra* L.) forest plantation. During the 2000 growing season, data were collected on tree physical dimensions, forage growth, soil water dynamics, and weather conditions from both open pasture and under tree canopy.

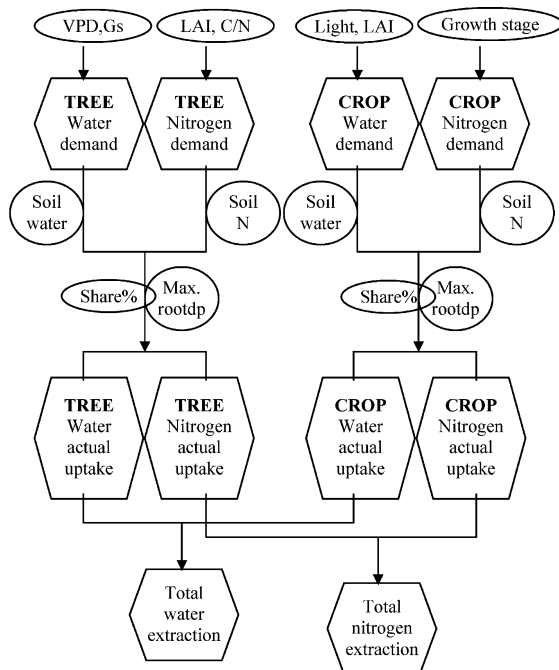


Figure 2. Schematic of tree crop water and nitrogen uptake processes in the present agroforestry model. VPD: vapor pressure deficit (used in the PM model for estimation of tree transpiration demand); Gs: stomatal conductance (used in the PM model for estimation of tree transpiration demand); rootdp: rooting depth of a crop species; Share%: species composition (dry mass based); LAI: leaf area index of a species.

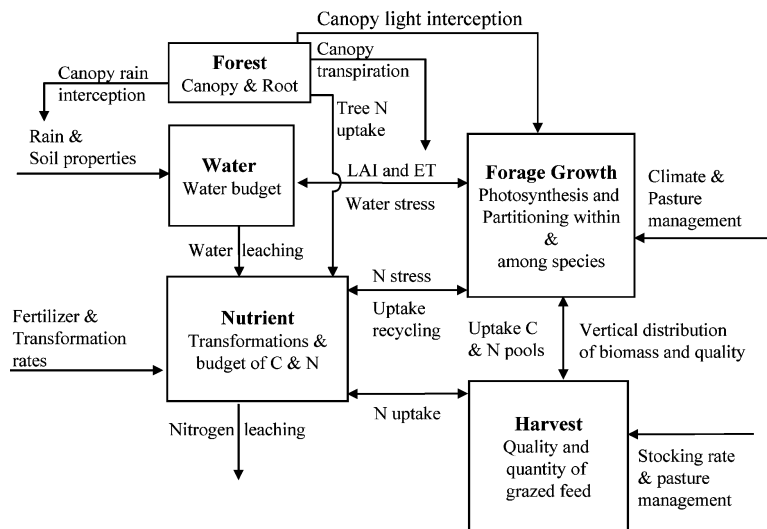


Figure 3. Schematic of the silvopasture GRASIM model.

Forage aboveground biomass was collected with 0.5 m<sup>2</sup> frame by hand clipping to about 7 cm above ground. Samples were oven dried at 60 °C for 7 days and weighed. Forage species composi-

tion was estimated from subplots within each sampling plot at three dates (June 13, August 10 and October 18, 2000) (Table 1), which was used to calculate individual species biomass. The three

perennial species that had been present during the entire growing season and, hence, included in our simulations are orchardgrass (OG, *Dactylis glomerata* L.), Kentucky bluegrass (BG, *Poa pratensis* L.), and tall fescue (TF, *Festuca arundinacea* (Schreb.)).

At early growing season, tree physical dimensions were measured including average diameter at breast height (dbh at 1.3 m above the base of tree trunk), total tree height, canopy height, and canopy crown base diameter. These were measured once and considered as constant throughout a single growing season, considering the relatively slower growth of trees compared with that of understory forage.

Continuous measurement of volumetric soil water content was done throughout the 2000 growing season using frequency domain reflectometer (FDR) unit in each sampling plot and recorded by an automated data logger. Soil physical properties and water and nutrient contents were measured from soil core samples taken from 0 to 30 cm and 30 to 100 cm depths from each plot. Crop residue data on the ground surface was recorded by excavating a 10×10×15 cm soil cube from each plot on May 8, 2000, which were saved in plastic bags and stored in a freezer at -5 °C after collection. In laboratory, surface live (green) plant tissue and dead plant material on the surface was picked out and dried at 60 °C for 48 hours and weighed.

Weather data included daily minimum, maximum air and soil temperatures, photosynthetically active radiation (PAR), precipitation and wind speed. All weather data were recorded continuously using automated data loggers and retrieved weekly (Figure 4).

### Model simulation

The SGRASIM model was applied to simulation of an open pasture and a pasture under black walnut tree canopy during the 2000 growing season. Model simulated growth of three dominant forage species and soil water contents were compared against measured data.

Model parameter estimation was conducted to minimize the difference between measured and simulated data. Optimization of default forage growth parameters were done for the open pasture simulation initially. Additional changes were made to photosynthetic efficiency, specific leaf area and the proportion of photosynthate partitioned to above ground biomass according to reported findings of forage growth under shading from forest canopy. Parameters used in tree canopy solar radiation (Equations 1–4) and rainfall interception routines in the simulation of pasture under tree canopy were estimated by methods introduced in the corresponding sections above. All optimized parameters and model simulation initial conditions are listed in Appendix A.

Table 1. Pasture forage species composition across 2000 growing season at Martell Forest experimental station, presented as the fraction of each species in total dry weight of all species sighted on each sampling date.

Species	Sampling date		
	6/13/00	8/10/00	10/18/00
Big blue stem	0.0003	0	0
Bluegrass	0.4778	0.4311	0.6089
Black medic	0.0582	0	0
Nimble will	0	0.0527	0.0689
Orchardgrass	0.0288	0.0282	0.0240
Purple top	0.0307	0.1167	0
Red clover	0.0138	0.0093	0.0013
Red top	0.0018	0	0
Smooth brome	0	0.0033	0.0045
Sweet clover	0.0025	0.0033	0.0017
Tall fescue	0.2329	0.1849	0.2671
Timothy	0.0060	0.0038	0
White clover	0.0033	0.0100	0.0037
Weeds	0.1484	0.1724	0.0247

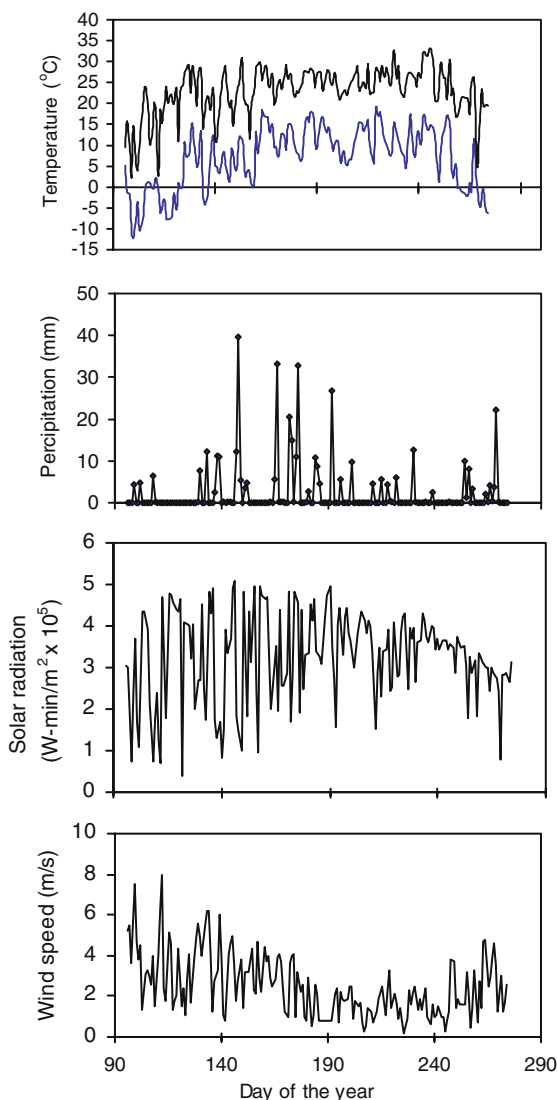


Figure 4. Daily weather data during the 2000 growing season.

## Results

The optimized tree canopy solar radiation interception routine (Equations 1–4) fitted measured light transmission data with a correlation coefficient of 0.6 (Figure 5). Linear regression of predicted on measured light transmission yielded a regression line with a slope of 0.59 and an intercept of 41258 W-min/m<sup>2</sup> ( $R^2 = 0.6$ ). The optimized tree parameters were applied in the subsequent simulation of pasture under tree canopy.

The SGRASIM model closely simulated forage growth of the three dominant species in the mixed

pasture in both open field (Figure 6a) and under the tree canopy (Figure 6b), with  $R^2$  greater than 0.97 for all species. Soil water contents simulations for the two treatments revealed that SGRASIM's soil water module reasonably followed the seasonal dynamics in the top 30 cm soil layer (Figure 7) while its prediction of the soil moisture in the lower 70 cm soil layer are significantly different from the observed in both cases. It prompts investigation of the soil water module's model structure, hence its capability of taking into account of subsurface soil water movements other than gravitational flow. The local topography and the lack of detailed knowledge of subsurface soil structure could also played role in the significant deviation of model simulated soil moisture in the deeper soil layer from those observed.

## Discussion

### *Forest canopy light interception*

Solar radiation attenuation and distribution in a forest exert crucial impact on understory growth and hence it is an important component in the modeling of agroforestry systems. The tree canopy light interception functions (Equation 1–4) in the current model tends to underpredict light transmission under high light and overpredict under low light (Figure 5). This could be due to the inadequacies in the model to account for direct light penetration through canopy gaps, i.e. sunflecks, under high light conditions and to account for cloud cover dynamically under low light conditions. It is known that sunflecks under the forest canopy can be highly variable and that it can contribute a significant amount of light to the understory (Chazdon 1988). Canham et al. (1990) reported that between 46% and 80% of the growing season PAR in the understory of a northern hardwood forest was due to sunflecks with durations of 4–8 min and that southern hardwoods had similar values. Thus, future model needs to better account for such energy burst from sunflecks. Cloud cover is another highly variable factor by nature, and could be simulated more dynamically than assuming a constant overcast weather condition. Nevertheless, the current light interception model is based on simple and commonly reported geometric characteristics of forest



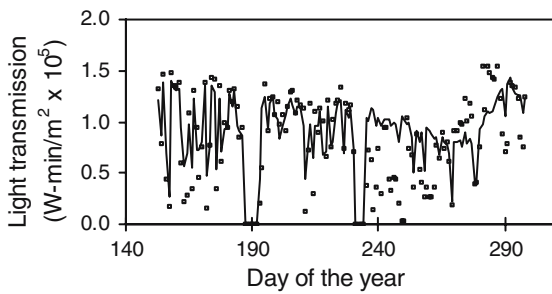


Figure 5. Simulated (line) and observed (points) solar radiation transmitted through a black walnut tree canopy in the 2000 growing season. The regression line of simulated vs. measured solar radiation transmission data under the tree canopy is of a slope of 0.59 and an intercept of 41258 W-min/m<sup>2</sup> ( $R^2 = 0.6$ ).

canopy. It is suitable for forest plantation where tree distribution can be considered as uniform. In this research, the experimental black walnut forest was estimated to have a leaf area index of 2.92 at full canopy (Appendix A). This estimate is within the range of 2.6 for forest on dry slopes and 4.5 for those on bottomlands reported by Jose and Gillespie (1997) in their study of forest leaf area-productivity relationship in Indiana, USA. The experimental site at Martell forest is situated on a terrace above the bank of Indian Creek. Thus, a LAI in the middle of the above range is plausible.

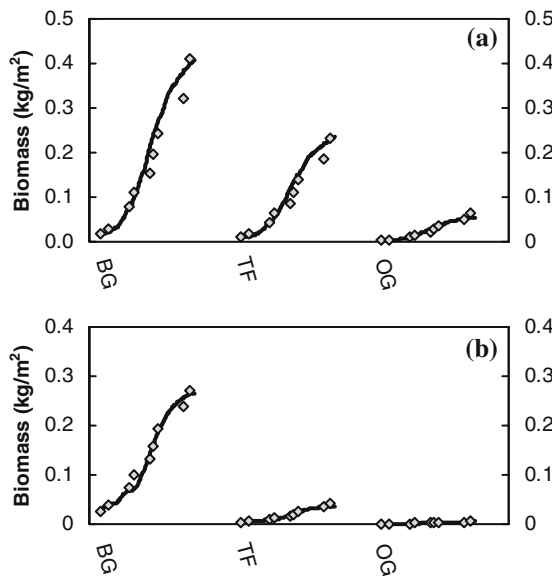


Figure 6. Simulated (lines) and measured (points) forage growth for the three perennial grass species across the 2000 growing season. (a) Simulation of open pasture. (b) Simulation of pasture under tree canopy. OG: orchardgrass, BG: bluegrass, TF: tall fescue.

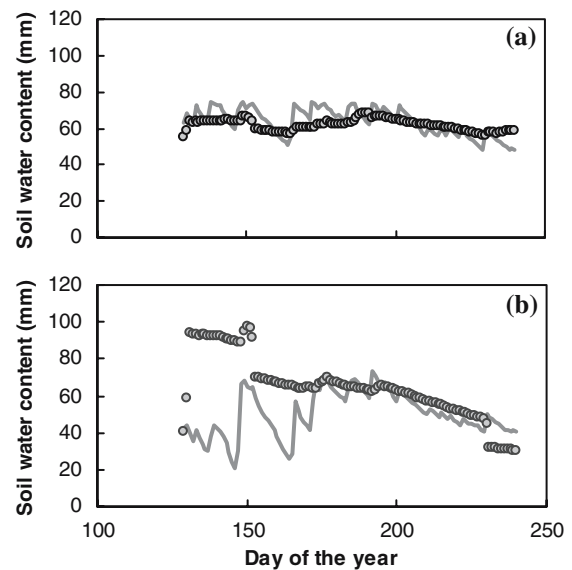


Figure 7. Simulated (lines) and observed (points) soil water contents in the top 30 cm soil layers of open pasture (a) and pasture under tree canopy, (b) during the 2000 growing season.

The estimated black walnut forest canopy light extinction coefficient is also close to the typical 0.5 for broadleaved forest (Mobbs et al. 1998).

#### Forest rainfall interception

Rainfall interception by a tree canopy and subsequent loss due to evaporation have been reported to account for a significant percentage of annual precipitation in some forested areas (Zinke 1967), especially in the tropics (Bruijnzeel 2001). The Gash and Rutter's model provided a framework for detailed examination of the physical processes during precipitation event in a forest. Subsequent efforts by Teklehaimanot and Jarvis (1991a, b) further validated and provided new insights into physical properties of these two models. Among others, the two most important parameters for estimation of rainfall interception loss by forest canopy are the boundary layer conductance, which also determines the tree spacing effects (Teklehaimanot et al. 1991), and canopy storage capacity. Both models could give good estimate of rainfall interception loss in short term experiments (Teklehaimanot and Jarvis 1991a). The adaptation of the two models in the current SGRASIM model would have been ideal provided more readily available detailed model input parameters for

deciduous hardwood forest. In this study, the estimated  $S_{\max}$  of 1 mm for the experimental black walnut canopy is similar to values found by several other studies on evergreen hardwoods and deciduous forests where  $S$  was found to range up to 2 mm (Prebble and Stirk 1980; Rowe 1983) and between 1.0 and 1.2 mm in a mixed beech stand (Pearce et al. 1980).

#### *Forest canopy transpiration*

For estimating forest ET potential, the strength of the Penman–Monteith equation lies in the incorporation of the canopy resistance term,  $r_c$ , to describe the effect that partially closed stomates have on evapotranspiration (Stannard 1993). In two-layered systems where vegetation grows under a sparse tree canopy, McNaughton and Jarvis (1983) suggested that tree transpiration is advectively controlled by the imposed air saturation deficit as stomata close in response to increasing air saturation deficit ( $D$ ) and the understory transpiration might tend toward the local equilibrium rate determined by the net radiation incident below the tree canopy, unless otherwise constrained by low soil water availability. Thus, it is a sensible choice in this modeling effort to use an energy-based ET model (Ritchie 1972) for understory forage and the Penman–Monteith model for overstory tree canopy transpiration simulation with stomatal control. Such combination could provide a venue for research of the productivity of agroforestry systems from the physiological perspective (Whitehead and Kelliher 1991; Köstner et al. 1992; Arneeth et al. 1996). In the cases where large understory areas are bare soil such as in row crop, the two-source (crop and soil) ET model by Shuttleworth and Wallace (1985) could be used to explicitly estimate the moisture flux from bare soil. Additionally, a Penman type of equation was also found to better estimate the evaporation from the wet forest canopy (Teklehaimanot and Jarvis 1991b), as is implemented in the SGRASIM model.

#### *Tree-forage interaction in terms of water and nutrient uptake*

In this modeling project, black walnut trees are assumed to have no direct competitive advantage

against forage crop roots during extreme soil water and nitrogen shortage in a given soil layer. The assumption is based on reported black walnut water use research such as the one conducted by Kuhns et al. (1985), who in a study of mature black walnut tree root growth relative to other species, found that black walnut can maintain higher leaf water potential than other tree species under stress by tapping deeper soil layers via its deep rooting system. They also found that the root growth of black walnut stopped during dry season when soil water potential fell below  $-1.0$  MPa, but continued in the deeper, wetter soil layer. This characteristic of black walnut tree roots to avoid dry conditions and the ability to explore moisture source in deeper soil layers in part support the assumption that there could be no significant competition in the effective forage rooting depth in the soil profile between tree and forage roots under water limiting conditions. However, such assumption is unlikely to hold in the more general use of the SGRASIM model in other types of silvopasture. More detailed plant water uptake model will need to take into account of the simultaneous interaction of potential transpiration demand, root distribution and soil hydraulic structures (Ozier-Lafontaine et al. 1997). Works done by Lafolie et al. (1991) represents a new generation of plant water uptake model based on root water potential and its distribution in the soil profile.

The method used here for tree N uptake assumes that daily N uptake by trees is related to fine root biomass, soil mineral N content, and the C:N ratio of the entire plant (Equation 6). It was also assumed that N uptake by trees ceases after leaf fall completion (Equation 7), as reported by other researchers (Weinbaum and Van Kessel 1998; Polanin et al. 1999) that N uptake by trees is minimal after leaf fall or during dormancy and that black walnut fine roots stopped growing after leaf fall completion (Kuhns et al. 1985). Dong et al. (2001) found that the N uptake by young apple trees was not significant due to the combined effect of low soil temperature and delayed leafing during spring. Wallach et al. (1990) found that the N uptake efficiency of peach tree increased from near zero in mid-April to a maximum in late May, and then decreased again to near zero in late September, corresponding to the canopy dynamic in a growing season. The positive linear relationship between tree N uptake and tree fine root

biomass is based on the assumption that uptake is limited by the volume of soil that can be explored by roots, and by root abundance (Landsberg 1986), which determines the absorbing surface area per unit volume of soil. There are a number of other factors influencing tree N uptake such as transpiration status and foliage N content that could be included in the model in the future.

### *Forage growth under tree canopy*

Examining the growth parameters for the three dominant forage species in open pasture and under tree canopy (Appendix A) revealed shading effects from tree canopy on the physiology of the understory vegetation. All three species have lower photosynthetic efficiency ( $\alpha$ ), larger specific leaf area (sla), higher leaf light transmission coefficient ( $m$ ) and higher proportion of photosynthate partitioned to aboveground biomass ( $\phi$ ) under tree canopy than in open pasture. These changes in the physical parameters corroborate reported shading effects on understory forage growth in that forage grown under shading tends to have lower photosynthetic efficiency (Peri et al. 2005), more air space in leaf lamina and thinner, wider leaf blades (Allard et al. 1991), decreasing leaf-area ratio (Kephart et al. 1992) and partition of dry matter in favor of leaf production (Allard et al. 1991). Yet, shading effects on forage growth are far from definite. For example, Malkin and Fork (1981) reported that shade plants had larger chlorophyll reaction centers. Watson et al. (1984) found that shade reduced the height of species with an upright growth habit more than it did the sod-forming species. Other factors such as the temporal dynamic in soil moisture or organic matter breakdown were also found to promote herbaceous plant growth under shade or in full sunlight (Wilson, 1996). Hence, future development of the SGRASIM model should continuously draw on these findings to help evaluate the compatibility of forage and trees as well as among forage species.

### *Model limitations*

The current SGRASIM model's soil water model adopts an over simplistic two-layered, free drainage representation of soil rooting zone. It lacks the

mechanism for simulating stream recharge, subsurface flow, and hydraulic lift near tree roots. A more layered soil profile could also help better represent forage and tree root distribution, hence water and nutrient uptake.

Other limitations of the current SGRASIM model include the assumed spatial homogeneity of species distribution and the lack of influence from plant phenology on model growth parameters. Existing complex agroforestry models such as HyPAR can deal with varying spatial distribution of trees within a field while assuming uniformity in understory crops. Few models have yet successfully accounted for the species heterogeneity found in naturalized grassland. Recent trend in modeling plant population dynamic is to use the cellular automata method based on resource availability in a network of interdependent grid cells, each evolves from an initial distinct species composition and environmental conditions (Baltzer et al. 1998; Bandini and Pavesi 2004). The use of Geographic Information System (GIS) with these cell-based modeling tools could hold the key in dealing with spatial heterogeneity in natural setting.

## **Conclusion**

In this research, algorithms for addressing the 'tree effects' on understory forage growth in terms of rainfall and light interception, water and nutrient removal were developed and incorporated with the multispecies grazing simulation model (GRASIM) to form a silvopasture model (SGRASIM). Initial model evaluation showed that the new model accurately predicted the growth dynamics of three competing perennial forage species in a mixed plant community under black walnut tree canopy, and soil water content predictions did not adequately depict the observed trend due to a lack of model mechanism to account for soil water recharge due to topography and the movement of soil water table. The simple design of the model's tree-forage interface allows studies on tree-forage relation with minimal requirement of data collection and parameter estimation. Detailed analysis of various aspects of the model structure provided extensive information on the modeling of silvopastoral system. More independent model validation is needed in the future.

## Acknowledgement

This research was supported by USDA CJREES grant #97-36200-5270 in the Fund for Rural America initiative. The authors would like to extend gratitude to the Purdue University Department of

Forestry and Natural Resources staff at Martell Forest for assistance in experiment implementation. Appreciation is further extended to Mr. Gerald R. Kelly (Department of Animal Sciences of Purdue University) for providing guidance and assistance with the management of grazing animals.

## Appendix

*Appendix.* Model parameters and initial conditions for simulation of open pasture and pasture under tree canopy.

Description	Units	Open pasture	Under tree canopy				
<i>Soil property</i>							
Bulk density	g/cm <sup>3</sup>	1.60/1.59*	1.39/1.55*				
Permanent wilting point	%	0.10/0.10*	0.10/0.10*				
Field capacity	%	0.25/0.29*	0.25/0.25*				
Plant available water	%	0.15/0.19*	0.15/0.15*				
<i>Nutrient</i>							
Denitrification rate	%/day	2.7E-4	2.7E-4				
Rate coefficient of nitrification	kg/ha/day	33.6	33.6				
Mineralization rate of organic residue	/day	0.03	0.03				
Volatilization rate	%/day	2.7E-3	2.7E-3				
Mineralization rate of organic matter	%/day	7.2E-5	7.2E-5				
Soil albedo	—	0.2	0.2				
Initial ammonia N in top soil layer	kg/ha	45.6	104.28				
Initial nitrate N in top soil layer	kg/ha	26.40	43.44				
Initial nitrate N in lower soil layer	kg/ha	11.13	21.69				
Soil organic matter	kg/ha	296030	279377				
Organic residue	kg/ha	10262.0	2893.0				
C in organic residue	kg/ha	4511.18	1243.99				
N in organic residue	kg/ha	259.22	46.54				
<i>Water</i>							
Initial soil water in top layer	mm	60.0	47.47				
Initial soil water in lower layer	mm	80.5	98.83				
<i>Tree parameters</i>							
Tree specific leaf area	m <sup>2</sup> /kg C		36.0				
Tree canopy light extinction coefficient			0.46				
Diameter at breast height	m		0.367				
Exponent for leaf fall function			9.006				
Percent heartwood	%		60.0				
Maximum stomatal conductance	m s <sup>−1</sup>		0.01				
Maximum leaf area index	m <sup>2</sup> m <sup>−2</sup>		2.92				
Tree branch area index	m <sup>2</sup> m <sup>−2</sup>		0.17				
Canopy rainfall storage capacity	mm		1.0				
Canopy height	m		9.26				
Tree crown gap	m		0.99				
Forage growth parameters <sup>a</sup>	Units	Species <sup>b</sup>					
OG		BG		TF			
Canopy <sup>c</sup>	Open <sup>d</sup>	Canopy <sup>c</sup>	Open <sup>d</sup>	Canopy <sup>c</sup>	Open <sup>d</sup>		
SLA	m <sup>2</sup> /kg C	40	38	40	38	40	38
$\alpha$	kg/CO <sub>2</sub> /J	1.51E-8	1.55E-8	1.51E-8	1.60E-8	1.51E-8	1.65E-8
$K$		0.5	0.5	0.5	0.5	0.5	0.5
$M$		0.14	0.12	0.14	0.12	0.14	0.12
$\gamma$	/day	0.05	0.05	0.05	0.05	0.05	0.05
$\beta$	/day	0.002	0.002	0.002	0.002	0.002	0.002

## Appendix. Continued.

Description	Units	Open pasture	Under tree canopy				
$\phi$		0.85	0.7	0.85	0.7	0.85	0.7
$P_0$	kg CO <sub>2</sub> /m <sup>2</sup> /s	5E-6	5E-6	5E-6	5E-6	5E-6	5E-6
$P_1$	kg CO <sub>2</sub> /m <sup>2</sup> /s/c	5E-7	5E-7	5E-7	5E-7	5E-7	5E-7
$\mu_m$	/day	0.45	0.45	0.45	0.45	0.45	0.45
$Rtdpth$	Cm	70	70	70	70	70	70

Note: \*soil properties for the two soil layers, top layer (0–30 cm) and bottom layer (30–100 cm)<sup>a</sup>Parameter names for the symbols are: photosynthesis fraction partitioned to shoot ( $\phi$ ), leaf photosynthetic efficiency ( $\alpha$ ), leaf extinction coefficient ( $K$ ), specific leaf area ( $SLA$ ), and maximum specific growth rate ( $\mu_m$ ). These parameters are important in determining plant standing biomass and need to be carefully estimated. Standing biomass is somewhat less sensitive to leaf transmission coefficient ( $M$ ), light saturated leaf photosynthetic rate constant ( $P_0$ ), light saturated leaf photosynthetic rate coefficient ( $P_1$ ), and recycling constant ( $\gamma$ ); and is least sensitive to senescence constant ( $\beta$ );  $Rtdpth$ , effective rooting depth; <sup>b</sup>Species group names are: OG, orchardgrass; BG, bluegrass; TF, tall fescue. <sup>c</sup>Canopy denotes parameters for simulation of forage growth under tree canopy; <sup>d</sup>Open denotes parameters for simulation of forage growth in open pasture.

## References

- Allard G., Nelson C.J. and Pallardy S.G. 1991. Shade effects on growth of tall fescue: I. Leaf anatomy and dry matter partitioning. *Crop Sci.* 31: 163–167.
- Anderson L.S., Muetzelfeldt R.I. and Sinclair F.L. 1993. An integrated research strategy for modeling and experimentation in agroforestry. *Commonwealth For. Rev.* 72: 161–174.
- Arnell A., Kelliher F.M., Bauer G., Hollinger D.Y., Byers J.N., Hunt J.E., McSeveny T.M., Ziegler W., Vygodskaya N.N., Milukova I., Sogachov A., Varlagin A. and Schulze E.-D. 1996. Environmental regulation of xylem sap flow and total conductance of *Larix gmelinii* trees in Eastern Siberia. *Tree Physiol.* 16: 247–255.
- Baltzer H., Braun W.P. and Kohler W. 1998. Cellular automata models for vegetation dynamics. *Ecol. Model.* 107: 113–125.
- Bandini S. and Pavesi G. 2004. A Model Based on Cellular Automata for the Simulation of the Dynamics of Plant Populations. In: Pahl-Wostl C., Schmidt S., Rizzoli A.E. and Jakeman A.J. (eds), *Complexity and Integrated Resources Management*, Transactions of the 2nd Biennial Meeting of the International Environmental Modelling and Software Society, iEMSs: Manno, Switzerland, 2004. Volume 1, pp. 277–282.
- Berendse F. 1979. Competition between plant populations with different rooting depths. I. Theoretical considerations. *Oecologia (Berlin)* 43: 19–26.
- Bruijnzeel L.A. 2001. Hydrology of tropical montane cloud forests: a reassessment. *Land Use Water Res. Resour.* 1: 1–18.
- Canham C.D., Denslow J.S., Platt W.J., Runkle J.R., Spies T.A. and White P.S. 1990. Light regimes beneath closed canopies and tree-fall gaps in temperate and tropical forests. *Can. J. For. Res.* 20: 620–631.
- Chazdon R.L. 1988. Sunflecks and their importance to forest understory plants. *Adv. Ecol. Res.* 18: 1–63.
- Dong S., Scagel C.F., Cheng L., Fuchigami L.H. and Rygielwicz P.T. 2001. Soil temperature and plant growth stage influence nitrogen uptake and amino acid concentration of apple during early spring growth. *Tree Physiol.* 21(8): 541–547.
- Friend A.D., Stevens A.K., Knox R.G. and Cannell M.G.R. 1997. A process-based, biogeochemical, terrestrial biosphere model of ecosystem dynamics (Hybrid v3.0). *Ecol. Model.* 95: 249–287.
- Jackson J.E. and Palmer J.W. 1981. Light distribution in discontinuous canopies: calculation of leaf areas and canopy volumes above defined ‘irradiance contours’ for use in productive modeling. *Ann. Bot.* 47: 561–565.
- Jose S. and Gillespie A.R. 1997. Leaf area-productivity relationships among mixed-species hardwood forest communities of the central hardwood region. *For. Sci.* 43(1): 56–64.
- Kang B.T., Grimme T. and Lawson T.L. 1985. Alley cropping sequentially cropped maize and cowpea with leucaena on a sandy soil in Southern Nigeria. *Plant Soil* 85: 267–277.
- Kephart K.D., Buxton D.R. and Taylor S.E. 1992. Growth of C3 and C4 perennial grasses under reduced irradiance. *Crop Sci.* 32: 1033–1038.
- Köstner B.M.M., Schulze E.-D., Kelliher F.M., Hollinger D.Y., Byers J.N., Hunt J.E., McSeveny T.M., Meserth R. and Weir P.L. 1992. Transpiration and canopy conductance in a pristine broad-leaved forest of *Nothofagus*: an analysis of xylem sap flow and eddy correlation measurements. *Oecologia* 91: 350–359.
- Kuhns M.R., Garrett H.E., Teskey R.O. and Hinckley T.M. 1985. Root growth of black walnut trees related to soil temperature, soil water potential, and leaf water potential. *For. Sci.* 31(3): 617–629.
- Lafolie F., Bruckler L. and Tardieu F. 1991. Modeling root water potential and soil-root water transport: I. Model presentation. *Soil Sci. Soc. Am. J.* 55: 1203–1212.
- Landsberg J.J. 1986. *Physiological Ecology of Forest Production*. J.J. Landsberg (ed.) Academic Press, London, pp.115–116.
- Lawson G.J., Crout N.M.J., Levy P.E., Mobbs D.C., Wallace J.S., Cannell M.G.R. and Bradley R.G. 1995. The tree-crop interface: representation by coupling of forest and crop process-models. *Agrofor. Syst.* 30: 199–221.
- Le Roux X., Grand S., Dreyer E. and Daudet F.A. 1999. Parameterization and testing of a biochemically based photosynthesis model for walnut (*Juglans regia*) trees and seedlings. *Tree Physiol.* 19: 481–492.

- Malkin S. and Fork D.C. 1981. Photosynthetic units of sun and shade plants. *Plant Physiol.* 67: 580–58.
- McNaughton K.G. and Jarvis P.G. 1983. Predicting effects of vegetation changes on transpiration and evaporation. In: Kozlowski T.T. (ed.), *Water Deficits and Plant Growth VII, Additional Woody Crop Plants*. Academic Press, New York, pp. 2–42.
- Mobbs D.C., Cannell M.G.R., Crout N.M.J., Lawson G.J., Friend A.D. and Arah J. 1998. Complementarity of light and water use in tropical agroforests I. Theoretical model outline, performance and sensitivity. *For. Ecol. Manage.* 102: 259–274.
- Mobbs D.C., Lawson G.J. and Brown T.A.W. 1999. HyPAR – Model for Agroforestry Systems. Technical Manual. The British Department for International Development (DFID) Forestry Research Programme, pp. 40–41
- Mohtar R.H., Buckmaster D.R. and Fales S.L. 1997a. A grazing simulation model: GRASIM A: model development. *Trans. ASAE* 40(5): 1483–1493.
- Mohtar R.H., Jabro J.D. and Buckmaster D.R. 1997b. A grazing simulation model: GRASIM B: field testing. *Trans. ASAE* 40(5): 1495–1500.
- Mohtar R.H., Zhai T. and Chen X.W. 2000. A world wide web-based grazing simulation model (GRASIM). *Computers and Electronics in Agriculture* 29: 243–250.
- Neitsch S.L., Arnold J.G., Kiniry J.R. and Williams J.R. 2001. Soil and Water Assessment Tool (SWAT) Technical Manual. Version 2000. Grassland, Soil and Water Research Laboratory, Agricultural Research Service and Blackland Research Center, Texas Agricultural Experiment Station.
- Noordwijk M.V. and Lusiana B. 1999. WaNuLCAS, a model of water, nutrient and light capture in agroforestry systems. *Agrofor. Syst.* 43: 217–242.
- Ong C.K. 1991. Interactions of light, water, and nutrients in agroforestry systems. In: Avery M.E., Cannell M.G.R. and Ong C.K. (eds), *Biophysical Research for Asian Agroforestry*. Winrock International, USA and Oxford & IBH Publishing Co. PVT. LTD.
- Ozier-Lafontaine H., Vercambre G. and Tournebize R. 1997. Radiation and transpiration partitioning in a maize-sorghum intercrop: Test and evaluation of two models. *Field Crops Res.* 49: 127–145.
- Parsch L.D. and Loewer O.J. 1995. GRAZE beef-forage simulation model: user guide. Parsch L.D. and Loewer O.J. (eds), Fayetteville, Ark, University of Arkansas.
- Pearce A.J., Rowe L.K. and Stewart J.B. 1980. Night-time, wet canopy evaporation rates and the water balance of an evergreen mixed forest. *Water Resour. Res.* 16: 955–959.
- Pearson H.A. 1990. Silvopasture: forest grazing and agroforestry in the southern coastal plain. Presented at the Practical Agroforestry in the Mid-South Conference, West Memphis, AR, pp. 27–30, November, 1990.
- Pearson J.A., Fahey T.J. and Knight D.H. 1984. Biomass and leaf area in contrasting lodgepole pine forests. *Can. J. For. Res.* 14: 259–265.
- Peri P.L., Moot D.J. and McNeil D.L. 2005. Modelling photosynthetic efficiency ( $\alpha$ ) for the light-response curve of cocksfoot leaves grown under temperate field conditions. *Eur. J. Agron.* 22(3): 277–292.
- Phelps J.E. and Chen P.Y.S. 1989. Lumber and wood properties of plantation-grown and naturally grown black walnut. *For. Prod. J.* 39(2): 58–60.
- Polanin N., Maletta M., Cowgill W.P. and Kamara S. 1999. How to Fertilize Shade Trees (FS031). Rutgers Cooperative Extension New Jersey Agricultural Experiment Station. 4 pages.
- Ritchie J.T. 1972. A model for predicting evaporation from a row crop with incomplete cover. *Water Resour. Res.* 8(5): 1204–1213.
- Rowe L.K. 1983. Rainfall interception by an evergreen beech forest, Nelson, New Zealand. *J. Hydrol.* 66: 143–158.
- Rotz C.A., Black J.A., Mertens D.R. and Buckmaster D.R. 1989. DAFOSYM: A model of the dairy forage system. *J. Prod. Agr.* 2: 83–91.
- Shiflet T.N. 1980. What is the resource?. In: Dennis Child R. and Evert K. Byington (eds), *Southern Forest Range and Pasture Resources*. Winrock International, Morrilton, AR, pp. 17–28.
- Shuttleworth W. and Wallace J.S. 1985. Evaporation from sparse crops – an energy combination theory. *Quart. J. R. Met. Soc.* 111: 839–855.
- Stannard D.I. 1993. Comparison of Penman-Monteith, Shuttleworth-Wallace, and modified Priestley-Taylor evapotranspiration models for wildland vegetation in semiarid rangeland. *Water Resour. Res.* 29(5): 1379–1392.
- Teklehaimanot Z. and Jarvis P.G. 1991a. Modelling of rainfall interception loss in agroforestry systems. *Agrofor. Syst.* 14: 65–80.
- Teklehaimanot Z. and Jarvis P.G. 1991b. Direct measurement of evaporation of intercepted water from forest canopies. *J. Appl. Ecol.* 28: 603–618.
- Teklehaimanot Z., Jarvis P.G. and Ledger D.C. 1991. Rainfall interception and boundary layer conductance in relation to tree spacing. *J. Hydrol.* 123: 261–278.
- Thompson B. 1976. Black walnut for profit: [a guide to risks and rewards] Bruce Thompson (ed.), Forest Grove, Timber Press, Ore.
- Thornley J.H.M. 1991. A transport-resistance model of forest growth and partitioning. *Ann. Bot.* 68: 211–226.
- Thornley J.H.M. and Johnson I.R. 1990. Plant and crop modeling A mathematical approach to plant and crop physiology. J.H.M. Thornley and I.R. Johnson (ed.), Clarendon Press, Oxford 1990.
- Wallach D., Loisel P., Goffinet B. and Habib R. 1990. Modeling the time dependence of nitrogen uptake in young trees. *Agron. J.* 82(6): 1135–1140.
- Watson V.H., Hagedorn C., Knight W.E. and Pearson H.A. 1984. Shade tolerance of grass and legume germplasm for use in the southern forest range. *J. Range Manag.* 37: 229–232.
- Weinbaum S. and Van Kessel C. 1998. Quantitative estimates of uptake and internal cycling of  $^{14}\text{N}$ -labeled fertilizer in mature walnut trees. *Tree Physiol.* 18: 795–801.
- Whitehead D. and Kelliher F.M. 1991. A canopy water balance model for a *Pinus radiata* stand before and after thinning. *Agric. For. Meteorol.* 55: 109–126.
- Wilson J.R. 1996. Shade-stimulated growth and nitrogen uptake by pasture grasses in a subtropical environment. *Aust. J. Agric. Res.* 47: 1075–1093.
- Young H.E., Ribe J.H. and Wainwright K. 1980. Weight Tables for Tree and Shrub Species in Maine, Life Sciences and Agricultural Experiment Station. University of Maine at Orono. Miscellaneous Report 230.

Zhai T., Mohtar R.H., Karsten H. and Carlassare M. 2004. Modeling growth and competition of multi-species pasture system. *Trans. ASAE* 47(2): 617–627.

Zinke P.J. 1967. Forest interception studies in the United States. In: Sopper W.E. and Lull H.W. (eds), *International Symposium on Forest Hydrology*. Oxford, Pergamon, pp. 137–161.