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Phenological responses of juvenile pecan and white oak on an upland site

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Abstract Pecan (*Carya illinoiensis*) and white oak (*Quercus alba*) produce multiple products and wildlife values, but their phenological responses to N fertilization have not been well characterized. We compared tree growth at planting and for six consecutive growing seasons during establishment (2003–2008, Test 1), and determined if phenology of budburst, leaf area index (LAI), quantum yield of photosystem II (Fv/Fm), radial growth, and total chlorophyll concentration (*a*, *b*) responded to poultry litter fertilization supplying 0, 50, and 100 kg ha^{-1} N (2010–2012, Test 2) in a mixed-species orchard on an upland site near Booneville, Arkansas. Species did not differ significantly in height in Test 1. Budburst was 9 days earlier for white oak than pecan in 2010. Budburst for both species could be predicted by accumulating chilling and forcing units throughout the dormant season. Maximum predicted radial growth was comparable for pecan (2.19 mm) and white oak (2.26 mm), and peaked 28 days earlier for white oak (3 June) than pecan (1 July). White oak LAI generally exceeded that of pecan during the growing season. Senescence began about 27 October regardless of species, and was better characterized by decreasing Fv/Fm or total chlorophyll concentration than LAI. Phenology was generally not responsive to N fertilization, perhaps because of adequate soil and foliar N. The study provides additional information on growth responses of these high-valued species to supplemental fertilization on an upland site.

Keywords Budburst · *Carya illinoiensis* · Growth · Leaf senescence · Nitrogen fertilization · *Quercus alba*

Introduction

Many areas of the central US support vigorous stands of upland hardwood species, including pecan [*Carya illinoiensis* (Wangenh.) K. Koch] and white oak (*Quercus alba* L.). Both species are common on

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alluvial and upland soils in the central US, with optimal growth occurring on well drained soils (Harlow and Harrar 1969; Peterson 1990; Rogers 1990; Sparks 2002; Turner 2006). White oak has a wider native range than pecan and grows on all but the driest upland aspects and soils (Peterson 1990; Rogers 1990). Pecan thrives on well-drained, alluvial soils and has a high water demand (Wolstenholme 1979). The phreatophytic rooting habit of pecan allows it to survive periodic dry conditions, a competitive advantage on dry sites or those with a deep water table (Wolstenholme 1979; Sparks 2005).

Pecan and white oak sawtimber stumpage is competitively valued at \$20–\$68 (US) t^{-1} in the southern US, with white oak sawtimber tending to have greater value than pecan (Timber Mart-South 2007). The species are used for hardwood agroforestry practices; pecan for nuts and sawtimber, white oak for acorns (wildlife) and sawtimber (Hodge et al. 1999; Garrett and McGraw 2000; Johnson et al. 2003). Appraised value of a pecan silvopasture used for nuts, livestock, and timber was \$2,100 (US) ha^{-1} $year^{-1}$ and annual property taxes were \$56.25 (US) ha^{-1} $year^{-1}$ with nut value the main driver of profitability (Ares et al. 2006).

Established trees in natural stands typically do not require supplemental fertilization, especially on bottomland soils, but plantation-grown tree species on upland sites may respond to fertilization or addition of organic matter, depending on the site (Francis 1984). Fertilization increases diameter growth of white and red oak (*Q. rubra* L.) in Arkansas (Graney and Pope 1978), and white oak diameter and height growth in the North Carolina Piedmont (Robison et al. 2004). Effects of fertilization on growth phenology have not been intensively studied for pecan or white oak. For our purposes, phenology describes the periodic change in growth responses commencing at budburst and ending at leaf drop. Phenological responses in tissue K and P concentrations have been reported for pecan and for foliar traits in white oak (Richardson and O'Keefe 2009; Smith 2009), but not to our knowledge in response to fertilization. Our objective was to compare tree growth at planting and for six consecutive growing seasons during establishment (2003–2008, Test 1), and determined if phenology of budburst, leaf area index (LAI), quantum yield of photosystem II (Fv/Fm), radial growth, and total chlorophyll concentration (*a* and *b*) responded to poultry litter fertilization supplying 0, 50, and 100 kg ha^{-1} N (2010–2012, Test 2) in a mixed-species orchard on an upland site near Booneville, Arkansas.

Materials and methods

Study site

The experiment was conducted at 35.06°N lat., 93.56°W long., near Booneville, Arkansas, 145 m above sea level, 2.5 % south-facing slope, on a Leadvale silt loam soil (fine-silty, siliceous, thermic Typic Fragiudult) (US Dept. Agric (USDA) 2012). The soil has a fragipan at about 60 cm depth (Burner and MacKown 2005; US Dept. Agric (USDA) 2012). The soil series is generally suited for pasture and woodland uses (US Dept Agric (USDA) 1980).

Initial establishment and growth measurements (Test 1)

The study consisted of 12 trees each of white oak and pecan transplanted at random into a mixed tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort. ex *Festuca arundinacea* Schreb.] and bermudagrass [*Cynodon dactylon* (L.) Pers.] pasture. Both grass species are allelopathic to pecan (Smith et al. 2001). Tree seedlings were non-grafted, 1-year-old from seed, and grown in 11 L pots using a root pruning technology developed to improve tree survival and initial growth (Lovelace 1998; Forrest Keeling Nursery, Elsberry, Missouri). Seed provenance was unavailable for white oak, but pecan seeds were from a southern Illinois source (Forrest Keeling Nursery, personal communication, 14 April 2009). Trees were about 1 m tall when acquired, and were transplanted in April 2003 into augered holes.

Trees of each species were initially assigned to one of four rows and transplanted at a spacing of 7.6 m within rows and 12.2 m between rows (100 trees ha^{-1}). The design emulated a mixed hardwood alley cropping agroforestry practice (Garrett and McGraw 2000) and the spacing probably resulted in minimal tree–tree competition. To reduce potential error due to row location in relation to slope, tree species were blocked by relative proximity such that most replications consisted of trees of a given species within one row of each other. There were three trees per species per replication in a randomized complete block design.

Branches of dormant trees were lightly pruned, beginning in 2005, to promote a clear trunk and a single apical meristem. This was especially important for white oak because it had a greater propensity for branching than pecan. Epicormic branches that emerged after pruning also were removed early in the growing season (prior to June).

A 1 m^2 weed mat was attached to the soil surface under each tree. Glyphosate [*N*-(phosphonomethyl) glycine] was typically applied at 1.06 kg a.i. ha^{-1} three times during the growing season (May, mid-June, and early August) to reduce competition by understory vegetation (Turner 2006). Trees were periodically irrigated to foster establishment. During 2003–2005 a 1 m^2 area around each tree received a surface application of 50 g Osmocote (ScottsMiracle-Gro, Marysville, Ohio), a commercial, slow release fertilizer having an analysis of 14-14-14 (percent N, P_2O_5, and K_2O, respectively) at budburst and mid-July (140, 108, and 117 kg ha^{-1} $year^{-1}$ per tree N, P, and K, respectively). From 2006 to 2008, a 1 m^2 area around each tree received a surface application of 40 g 34-0-0 and 100 g Osmocote at budburst, and 50 g Osmocote in mid-July (total of 346, 162, and 175 kg ha^{-1} $year^{-1}$ per tree N, P, and K, respectively). Chemical vegetation control ceased in 2008, but weed barriers remained in place. Trees were not fertilized in 2009. In July 2009, understory vegetation was suppressed with glyphosate applied in a 1.2 m radius circle. Fall webworm (*Hyphantria cunea* Drury) was a pecan pest beginning in 2009. An annual (June) application of tebufenozide [3,5-dimethylbenzoic acid 1-(1,1-dimethylethyl)-2-(4-ethylbenzoyl) hydrazide] insecticide (Dow AgroSciences, Indianapolis, Indiana) was applied at 0.40 mL L^{-1} a.i. to canopies of both species with an air-blast sprayer. Height was measured with a fiberglass pole at planting (April 2003) and in October for six subsequent growing seasons (2003–2008).

Phenology study (Test 2)

Growing conditions and management

The experiment was conducted on the same 12 trees of each species from Test 1 in a randomized complete block design. Tree spacing was the same as in Test 1, and canopies did not touch or overlap during the test. Glyphosate was typically applied in mid-June at 1.06 kg a.i. ha^{-1} as needed throughout the growing season to maintain a comparatively vegetation-free understory of 2.0 and 2.5 m radius for white oak and pecan, respectively (Brauer et al. 2004; Turner 2006). Glyphosate was subsequently reapplied as needed for vegetation control. Since the vegetation-free zone was based on mean canopy diameter, some tree canopies exceeded the diameter of the vegetation-free zone. One tree was randomly assigned a fertilization treatment (0, 50, and 100 kg ha^{-1} N) within each of the four replications per species.

Poultry litter fertilizer was split applied to the soil surface in an annular band likely to contain feeder roots, i.e., 0.8 m radius distal to the stem to the mean drip line radius (2.0 and 2.5 m for white oak and pecan, respectively), at budburst and 30 days later (Turner 2006) in 2010 and 2011. The fertilizer was Microstart60 (Perdue AgriRecycle, Seaford, Delaware), an organic, pasteurized, pelletized form of poultry litter (poultry species unknown) with an elemental N–P–K nutrient composition of 40, 20, and 30 g kg^{-1}, respectively (Burner et al. 2010; Perdue AgriRecycle 2012). Fertilization treatments based on 2.6 Mg ha^{-1} of PPL were designed to supply equivalent N–P–K (100 kg ha^{-1} of N, 50 kg ha^{-1} of P, and 80 kg ha^{-1} of K, respectively).

Environmental monitoring

Air and soil temperature and rainfall were measured on-site to characterize climatic conditions. Data were recorded continuously at 0.5 h intervals from 1 January 2010 to 31 March 2012 using a WatchDog logger (Spectrum Technologies Inc., Plainfield, Illinois) located within the study area. Air and soil temperatures were measured with thermocouples located 1.5 m above ground or 15 cm below grass sod, respectively. Rainfall was recorded at 1.5 m above ground with a self-tipping gauge. Data were summarized as daily minimum, maximum, and mean air temperature, mean soil temperature, and total rainfall. Air temperature and rainfall were compared to long-term (1971–2000) data from a weather station located 1.5 km east of the experimental site (NOAA 2002).

Penman–Monteith reference evapotranspiration (PM ETo) was calculated (Allen et al. 1998; Snyder and Eching 2007) from air temperature, relative humidity, solar radiation ($\lambda = 300$–1, 100 nm), and wind speed measured at 0.5 h intervals with a Model 900ET electronic weather station (Spectrum Technologies, Inc, Plainfield, Illinois) located 5.6 km southwest of the study site from 1 June 2010 to 31 October 2011. Daily values were summed to calculate PM ETo in mm mo^{-1}.

Water deficit was possible at this site during summer (Brauer et al. 2004), so irrigation water was applied every 2–3 days from June to October 2010 and 2011 to reduce the effect of water stress on tree growth (Walker and Oswald 2000). Irrigation water came from a well and passed from the main line into each of three 1.9 cm diameter lateral lines fitted with a water timer, meter (Model DLJ, Watermeters.com, Hackensack, New Jersey), and a 240 kPa pressure regulator. One drip emitter was mounted at the soil surface about 1 m from the tree stem. Flow through lateral lines was adjusted so trees received similar quantities of irrigation water. Meter readings taken at each irrigation event were used to estimate the quantity of water applied to each tree, and converted to rainfall equivalent (mm ha^{-1} mo^{-1}).

Volumetric soil water was measured using time domain reflectrometry (TDR, MESA Systems Co., Medfield, Massachusetts) calibrated for mineral soil. Access tubes 1 m long were permanently installed about 1.5 m from the irrigation emitter under four random trees per species. Soil water was measured weekly at 35 and 70 cm depths from April to October 2010 and 2011.

Foliage and soil analyses

Tree foliage was sampled for N, P, and K in early July 2010 and 2011. Fifty leaves or leaflets were collected around the periphery of the tree canopy, dried at 60 °C, ground to pass a 1 mm screen, and stored at −20 °C prior to laboratory analysis.

Topsoil (0–15 cm depth) was sampled from the fertilized area under each tree in March 2010, prior to fertilization, and in July 2010, 2011, and March 2012 using a truck-mounted soil sampler with a soil tube 5.7 cm diameter (Giddings Machine Co., Windsor, CO). Topsoil samples were air-dried and ground in a mortar to pass a 1.4 mm screen.

Analysis of total C (topsoil) and N (foliage and topsoil) was by combustion using an Elementar Variomax (Elementar Analysensysteme GmbH, Hanau, Germany). Water soluble and exchangeable topsoil ($NO_3 + NO_2$)-N was extracted in a 1:10 (topsoil:water) paste for 2 h (Self-Davis et al. 2000), filtered (0.45 µm), and analyzed colorimetrically by Cd-reduction (Method 418-F, APHA 1992). Topsoil NH_4-N was extracted for 2 h in 1:10 (topsoil:1 *N* KCl) paste, filtered (0.45 µm), and analyzed colorimetrically by the salicylate-nitroprusside method on acidified samples (Method 351.2, US Environ Prot Agency (US EPA) 1979. Foliar P and K were determined using inductively coupled plasma spectrometry (ICP) (Varian VistaPro, Santa Clara, California) following HNO_3 digestion (Havlin and Soltanpour 1980). Topsoil P and K were extracted in Mehlich 1984 III and analyzed using ICP. Topsoil P and K were not determined for the March 2012 sampling.

Growth measurements

Dormant (fall or winter 2009–2011) trees were measured annually for height with a fiberglass pole, and diameter at 1.4 m above soil surface (dbh) was measured with a diameter tape. A hand-crafted band dendrometer (Keeland and Young 2012), was installed on each tree at about 1 m above soil surface in February 2010. Bands were replaced, as needed, when trees were dormant. Radial growth (mm diameter) was recorded at 2 weeks intervals from March to October 2010 and 2011.

Budburst (Polgar and Primack 2011) was the date at which green tissue was first visible between scales of the swelling buds (Foss and Rieske 2003). Date of budburst was monitored at 2 d intervals in spring 2010, 2011, and 2012. Budburst is predicted to occur only when some combination of chilling and accumulated warming (forcing) has been achieved (Richardson and O'Keefe 2009). In this study, chilling and forcing units were determined from 1 November to the date of 50 % budburst for each species in 2010–2012 (usually March–April) using functions described by Harrington et al. (2010). Air temperatures below −4 °C do not count toward chilling in that model. The relationship of chilling and forcing units for each species was compared to the budburst possibility line developed for Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco], $Y = 357 + 5123 * \exp(-0.0016X)$, where Y is forcing unit and X is chilling unit (Harrington et al. 2010).

At 2 weeks intervals from July to October 2011, leaf area index (LAI) of each tree canopy was measured at two positions, roughly 180° apart, at 1.2 m above soil surface and 40 cm from the tree stem, with a plant canopy digital imager (CI-110, software version 3.0.2.0, CID, Inc., Camas, Washington). At 2 week intervals from July to November 2010 and 2011, maximum photosynthetic quantum yield of photosystem II (Fv/Fm) was measured by leaf fluorescence (OS1–FL modulated chlorophyll fluorometer, Opti-Sciences, Hudson, New Hampshire) on two random leaves per tree. Measurements were conducted at pre-dawn on healthy, dark-adapted leaves oriented on the outside of the tree canopy. A leaf disc measuring 6.3 mm diameter each was collected at mid-day from the lamina of each of three fully illuminated leaves per tree at 2 weeks intervals from July to October 2011. Samples were immediately placed in an amber glass vial containing 5 mL of 100 % EtOH. After 7 days incubation at 5 °C, absorbance of the extract was read at 649 and 665 nm (Spectronic 20, ThermoFisher Scientific Inc., Pittsburgh, Pennsylvania), and converted to total chlorophyll (*a* and *b*) concentration in μg cm^{-2} (Knudson et al. 1977; Dillenburg et al. 1995).

Statistical analyses

Tests 1 and 2 were randomized complete block designs with individual tree as the experimental unit. For Test 1, analysis of variance (ANOVA) of tree height was conducted with a mixed linear model procedure, Proc Mixed (Littell et al. 1996; SAS Inst. 2002), with species ($n = 2$), measurement date ($n = 7$), and the interaction as fixed effects; replication ($n = 4$) was the random effect. Tree-within-species was the repeated measure with a first-order autoregressive covariance structure and restricted maximum likelihood estimation method (Littell et al. 1996; SAS Institute 2002). Least squares means were compared at $P \leq 0.05$ using the Tukey honest significant difference (HSD) when main effects or interactions differed at $P \leq 0.05$. Regression effects on height were analyzed by Proc Reg (SAS Institute 2002).

For Test 2, analysis of variance (ANOVA) was conducted with a mixed linear model procedure, Proc Mixed (Littell et al. 1996; SAS Institute 2002), with year (or day-of-year), species, N-rate, and interactions as fixed effects, and replication as the random effect. Soil analyses were compared across dates using data from March 2010 as a covariate in ANOVA. Depending on the variable, tree or day-of-year was the repeated measure with a first-order autoregressive covariance structure and restricted maximum likelihood estimation method (Littell et al. 1996; SAS Institute 2002). Soil water had eight replications in a completely randomized design. Chilling and forcing units were examined by ANOVA for effects of year, species, and the year by species interaction, with date as the repeated measure. LAI data for day 186 were excluded from regression analysis to allow a quadratic fit. Least squares means were compared at $P \leq 0.05$ using Tukey honest significant difference (HSD) when main effects or interactions differed at $P \leq 0.05$. Where appropriate, the Proc Reg procedure (SAS Institute 2002) also was used to examine temporal responses. Pairs of regression coefficients were compared for significant differences at $P \leq 0.10$ using confidence intervals calculated according to Freund and Littell (2000). Use of the term "significant" implies a $P \leq 0.05$ except as noted otherwise.

Results

Test 1 (2003–2008)

There was a significant year by species interaction for tree height, with both species increasing significantly across growing seasons (Fig. 1). Species did not differ significantly in height within a growing season

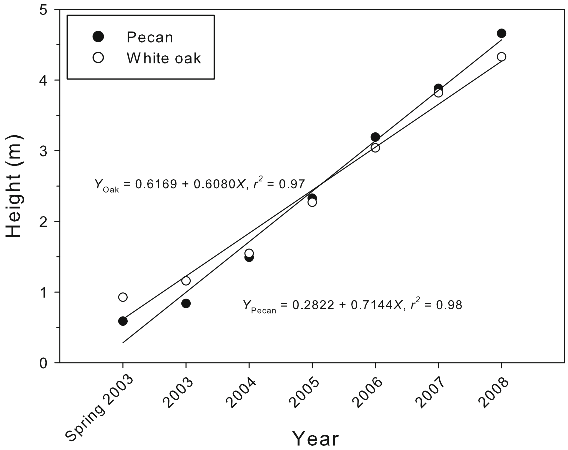

Fig. 1 Height of pecan and white oak seedlings at planting (spring 2003) and in October 2003–2008 near Booneville, Arkansas (Test 1). Regression equations describe linear response of height (Y) of pecan and white oak (oak) with year (X, range 1–7)

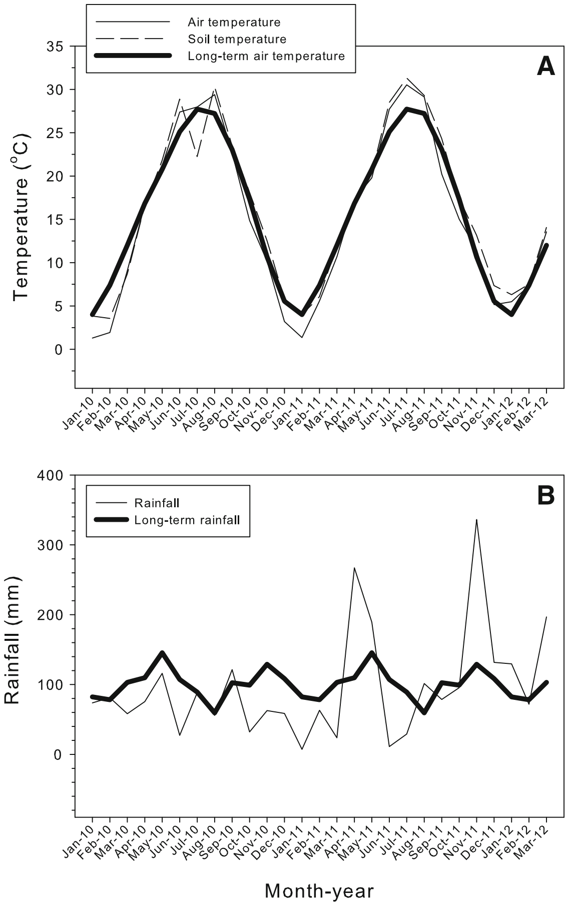

Fig. 2 **a** Mean monthly ambient air and soil (15 cm depth) temperatures in 2010–2012 and long-term (1971–2000) air temperature (National Oceanic and Atmospheric Administration (NOAA) 2002), and **b** total versus long term rainfall (National Oceanic and Atmospheric Administration (NOAA) 2002), near Booneville, Arkansas

($P \geq 0.12$), although there was tendency ($P = 0.12$) for white oak trees (0.93 m) to be taller than pecan (0.59 m) at planting. Height increased linearly for each species ($P < 0.001$), but linear coefficients of pecan (0.7 m y^{-1}) and white oak (0.6 m y^{-1}) were not significantly different.

Test 2 (2010–2012)

Environmental conditions

As expected, mean monthly air and soil temperatures corresponded fairly closely throughout the growing season, with the greatest divergence occurring in July and December to February (Fig. 2a). The decrease in soil temperature in July 2010 was evidently due to sensor malfunction because no such decrease occurred in other field studies conducted at the same time (data not shown). Monthly rainfall was variable (Fig. 2b). Mean monthly irrigation was 730 mm ha^{-1} (range 662–778 mm ha^{-1}) in 2010 (Fig. 3a), and irrigation increased 27 %–928 mm ha^{-1} (range 616–1,161 mm ha^{-1} $month^{-1}$) in 2011. Irrigation rate was equivalent to 1700 and 2,200 L $month^{-1}$ per tree in 2010 and 2011, respectively, and little runoff of irrigation water was observed. Irrigation exceeded mean PM ETO by 6.5 and 7.2 times in 2010 and 2011, respectively.

Soil water had significant year, depth, and day-of-year main effects, but the year by depth and depth by day-of-year interactions were not significant ($P \geq 0.13$). At any given date within 2010 and 2011, there usually was significantly less soil water at 35 cm depth than at 70 cm depth (Fig. 3). Despite irrigation, soil water at 35 cm decreased from a maximum of 306 g kg^{-1} in May 2010 to a minimum of 202 g kg^{-1} in August. Depletion was more profound in 2011, when soil water at 35 cm decreased from a maximum of 375 g kg^{-1} in May to 158 g kg^{-1} in August. Across depths and day-of-year, mean soil water was significantly lower in 2011 (248 g kg^{-1}) than 2010 (272 g kg^{-1}) despite increased irrigation.

Height and diameter growth

Tree height had significant year, species, and N-rate effects, while dbh had a significant year effect (data not shown). The year by species interaction was not significant ($P = 0.07$). Mean height of species did not differ significantly ($P = 0.27$) in 2010 (5.7 and 5.4 m for pecan and white oak, respectively), but pecan was significantly taller than white oak in 2011 (6.5 and 5.9 m, respectively). Pecan and white oak increased significantly in height across years regardless of N-rate. There was no consistent change in tree height with N-rate (5.9, 5.7, and 6.0 m for 0, 50, and 100 kg ha^{-1} N, respectively).

Similarly, annual stem dbh in 2011 (12.3 cm) was significantly greater than in 2010 (11.0 cm), and dbh growth rate for pecan and white oak was 1.4 and 1.3 cm y^{-1}, respectively (data not shown). There was a significant species by day-of-year interaction for radial growth, but N fertilization and its interactions with main effects were not significant ($P \geq 0.18$). Pecan and white oak had quadratic ($R^2 = 0.32$) and

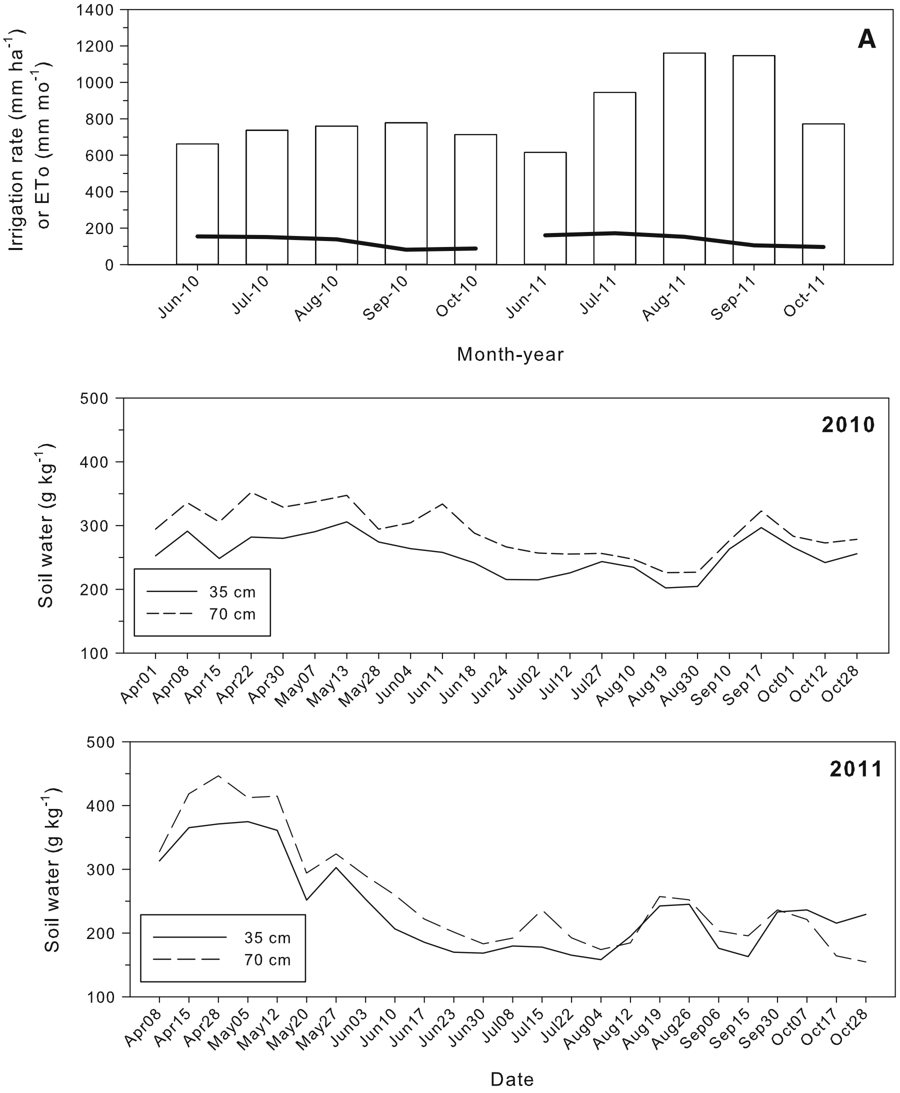

Fig. 3 Total monthly irrigation in rainfall equivalent (*bars*, mm ha^{-1}) and Penman–Monteith evapotranspiration (ETo, *solid lines*, mm mo^{-1}) (**a**), and weekly change in volumetric soil water at 35 and 70 cm depths under irrigated pecan and white oak trees near Booneville, Arkansas in 2010 and 2011

cubic ($R^2 = 0.50$) temporal responses, respectively, in radial growth (Fig. 4). Maximum predicted radial growth was roughly comparable for pecan (2.19 mm) and white oak (2.26 mm), but mean predicted growth peaked 28 days earlier for white oak (day 154) than pecan (day 182).

Budburst

Budburst had significant year, species, and year by species effects, and was not significantly affected by N-rate or other interactions ($P \geq 0.35$). In 2010, budburst occurred significantly (9 days) earlier for white oak than pecan (Fig. 5). Species did not differ significantly ($P \geq 0.16$) in budburst within other years, although white oak tended to be earlier than pecan by 5 and days in 2011 and 2012, respectively.

Chilling and forcing units differed significantly among years, but species and the year by species interactions were not significant ($P \geq 0.28$). Significantly more chilling units accumulated in 2010 (928) than in following years (749 and 801 units for 2011

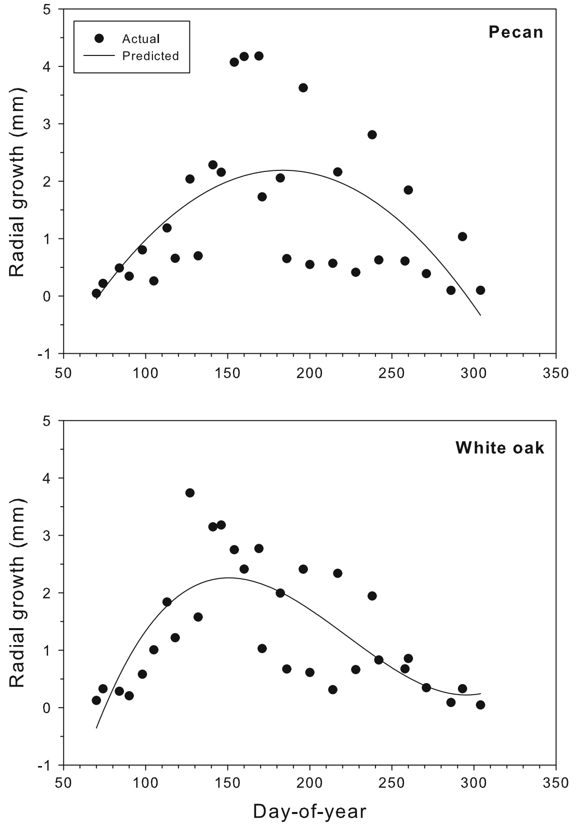

Fig. 4 Phenology of radial growth for irrigated pecan and white oak trees in 2010 and 2011 near Booneville, Arkansas. Leaf senescence began about day 300 but white oak retained leaves into the fall and winter

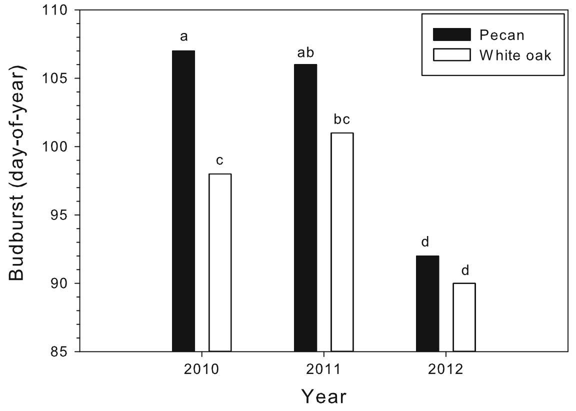

Fig. 5 Effect of the year by species interaction on budburst of pecan and white oak near Booneville, Arkansas. Means followed by a *common letter* do not differ ($P > 0.05$)

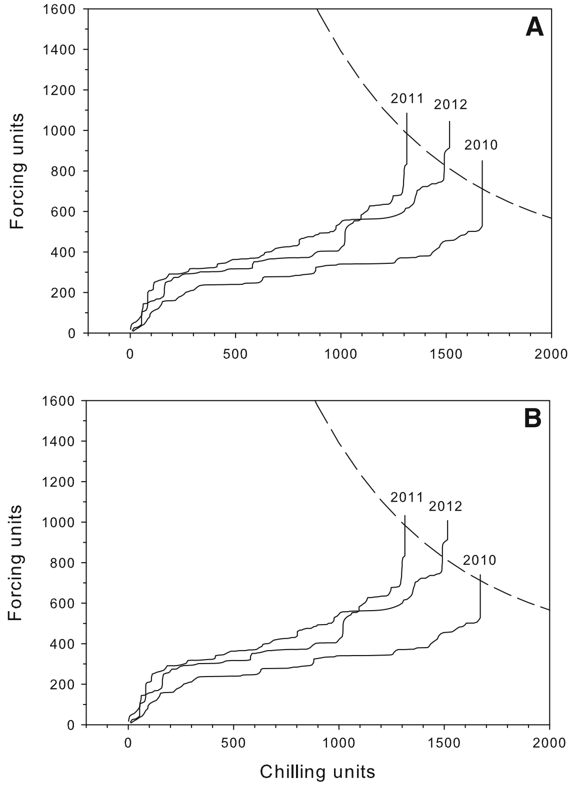

Fig. 6 Accumulation of chilling and forcing units for pecan and white oak near Booneville, Arkansas in 2010–2012. The budburst possibility line for Douglas fir (Harrington et al. 2010) is shown as a *dashed line*. *Solid lines* become vertical on 21 March when the budburst model assumes chilling is no longer being accumulated, and terminate at 50 % budburst

and 2012, respectively). Conversely, significantly fewer forcing units accumulated in 2010 (335) than 2011 and 2012 (448 and 476 units, respectively). Date of budburst was similar in 2010 and 2011 even though yearly patterns of accumulation of chilling and forcing units tended to differ (Fig. 6).

Foliar responses

Foliar N concentration was significantly greater in 2010 ($25.7 \mathrm{gkg}^{-1}$) than 2011 ($23.2 \mathrm{gkg}^{-1}$), and pecan foliage had a higher concentration of N ($26.3 \mathrm{gkg}^{-1}$) than white oak ($22.7 \mathrm{gkg}^{-1}$). The year by N-rate interaction approached significance ($P = 0.10$), although trends were inconsistent, with foliage in 2010 tending to have more N at the 0 and 50 kg ha^{-1} N-rates (≥ 26.0 g kg^{-1}) than in 2011 (≤ 22.9 g kg^{-1}). The effect of N-rate approached significance ($P = 0.09$) for K, with the 0 kg ha^{-1} N-rate tending to have greater foliar K than the 50 kg ha^{-1} N-rate (8.1 and 7.2 g kg^{-1}, respectively). The year by species interaction tended toward significance ($P = 0.06$) for

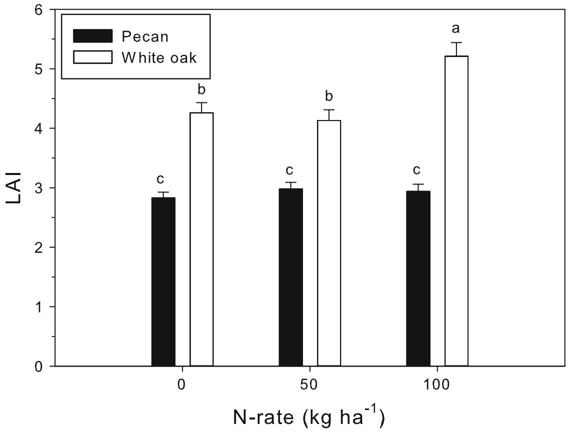

Fig. 7 Effect of the species by N-rate interaction on leaf area index (LAI) of pecan and white oak near Booneville, Arkansas in 2011. *Bars* indicate standard errors ($n = 80$). Means followed by a *common letter* do not differ ($P > 0.05$)

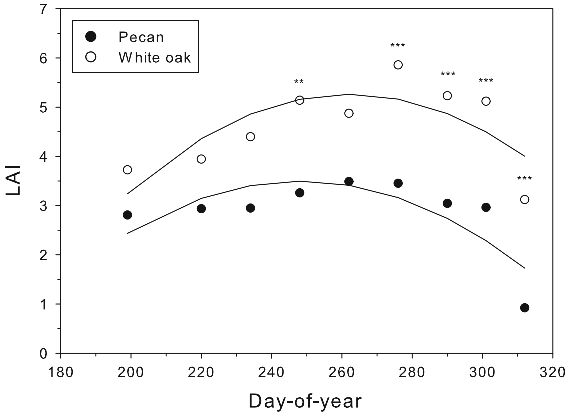

Fig. 8 Phenology of leaf area index (LAI) of irrigated pecan and white oak near Booneville, Arkansas in 2011. *Asterisks* (** and ***) indicate dates when species means differed ($P \leq 0.01$ and 0.001 levels, respectively). Leaf senescence began about day 300

K, with pecan (8.9 g kg^{-1}) tending toward greater K than white oak (6.6 g kg^{-1}) in 2010, but not in 2011 (7.9 and 7.3 g kg^{-1} for pecan and white oak, respectively). Averaged across treatments, pecan foliage had significantly greater concentrations of P (1.4 g kg^{-1}) and K (8.4 g kg^{-1}) than white oak (1.2 and 6.9 g kg^{-1}, respectively).

There was a significant species by N-rate interaction for LAI, caused by white oak having greater LAI at 100 kg ha^{-1} N (LAI 5.2) than other species by N-rate combinations (Fig. 7). Other white oak by N-rate combinations had significantly greater LAI (4.1–4.2) than pecan (LAI 2.8–2.9), which did not differ significantly at any N-rate. There also was a significant species by day-of-year interaction for LAI. White oak and pecan had quadratic day-of-year responses for LAI ($R^2 = 0.51$ and 0.44 for pecan and white oak, respectively, Fig. 8). White oak LAI often significantly exceeded that of pecan on any given day-of-year. White oak had a maximum predicted LAI of 5.26 on day 262, while the maximum for pecan, 3.49, occurred 14 days earlier (day 248). At the final measurement of 2011 (day 312), pecan LAI was significantly less than white oak, but this might have occurred because pecan was fully deciduous while senesced white oak foliage persisted on the tree. We did not otherwise monitor brown, senesced white oak leaves, but they usually persisted until just before budburst the following spring.

The species by day-of-year interaction for Fv/Fm showed that species means differed significantly during senescence, rather than earlier in the year (Fig. 9a). Prior to senescence, regression lines for the two species were nearly identical, although white oak maintained quantum yield about 10 days longer than pecan before decreasing (Fig. 9b). Similarly, rate of decrease in Fv/Fm was similar for the two species, although the decrease for pecan began on day 301 (0.69) while that for white oak began on day 313 (0.63). The decrease of Fv/Fm to about 0 occurred during 10 days (white oak) and 15 days (pecan).

There was a significant species by N-rate interaction for total chlorophyll, but total chlorophyll was not consistently related to either species or N-rate (Fig. 10). Pecan at 0 kg ha^{-1} N and white oak at 100 kg ha^{-1} N generally had significantly more chlorophyll than most other treatment combinations ($\leq$38.5 μg cm^{-2}). There also was a significant species by day-of-year interaction for total chlorophyll. Pecan and white oak both had significant quadratic temporal responses ($R^2 = 0.75$ and 0.46, respectively, Fig. 11). There were species differences in total chlorophyll concentration at day 202 and during senescence (days 301 and 307).

Topsoil responses

Sampling date was significant for the topsoil nutrients NO_3-N, NH_4-N, C, N, and P. Concentrations of all

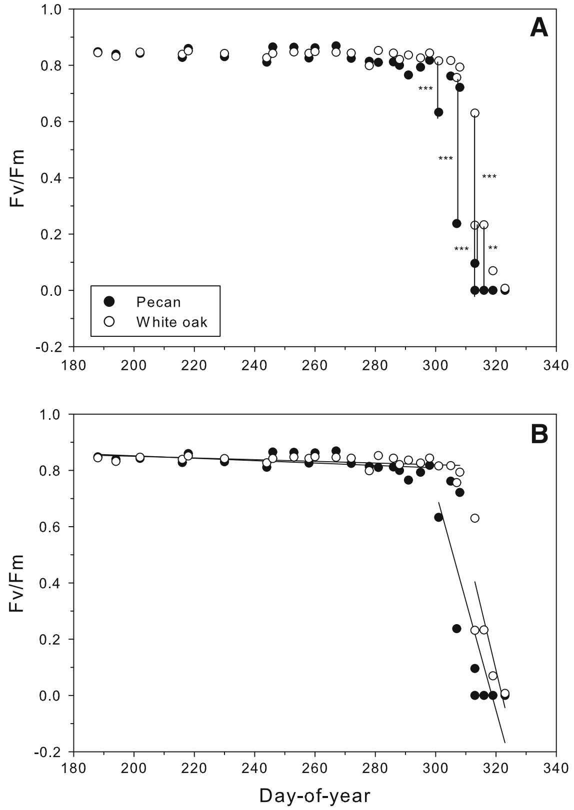

Fig. 9 Phenology of Fv/Fm for irrigated pecan and white oak near Booneville, Arkansas. *Vertical lines* between pairs of means **a** show days when species means differed significantly (** and *** indicate $P \leq 0.01$ and 0.001 levels, respectively). The same data **b** show regression lines separating early (day-of-year <300) and late season (day-of-year >300) responses

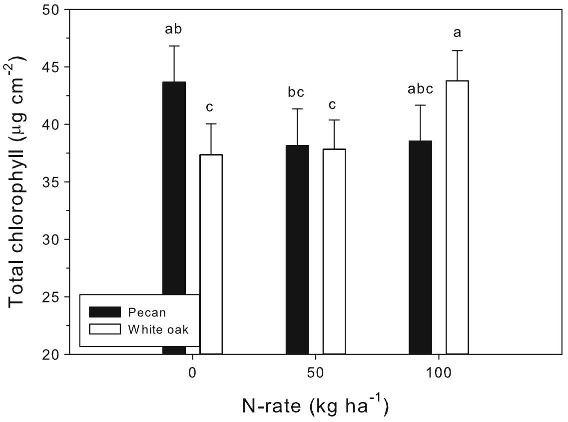

Fig. 10 Effect of the species by N-rate interaction on total leaf chlorophyll (*a* and *b*) concentration of pecan and white oak near Booneville, Arkansas in 2011. *Bars* indicate standard errors ($n = 40$). Means followed by a *common letter* do not differ ($P > 0.05$)

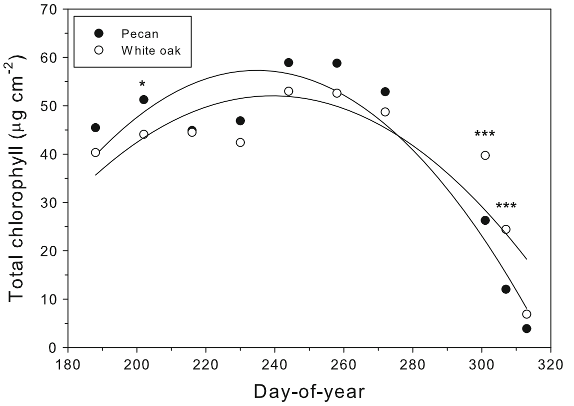

Fig. 11 Phenology of total leaf chlorophyll (*a* and *b*) concentration for irrigated pecan and white oak near Booneville, Arkansas in 2011. *Asterisks* (* and ***) indicate dates when species means differed significantly at $P \leq 0.05$ and 0.001 levels, respectively. Leaf senescence began about day 300

Table 1 Effect of sampling date on concentrations of topsoil nutrients (exchangeable NO_3-N and NH_4-N, total N, total C, and available P and K) for irrigated pecan and white oak near Booneville, Arkansas

Sampling date	NO_3-N mg kg^{-1}	NH_4-N	N g kg^{-1}	C	P mg kg^{-1}	K
July 2010	8.5 a	3.7 b	1.5 b	14.2 a	29 b	36 a
July 2011	6.5 a	9.3 a	1.8 a	16.1 1	40 a	41 a
March 2012	0.37 b	6.1 b	1.2 c	10.3 b	nd	nd

Means within columns followed by a common letter do not differ ($P > 0.05$)

nd not determined

topsoil nutrients, except K, usually were greater in July 2011 than at other sampling dates (Table 1). Concentrations of NO_3-N, N, and C were significantly lower in March 2012 than at earlier dates, suggesting that similar sites might need annual applications of poultry litter to maintain topsoil nutrient concentrations. Topsoil P increased significantly from July 2010–2011; concentrations of K did not differ significantly but were shown for information.

Discussion

Environmental conditions

Summer (June–August) temperatures (Test 2) tended to be warmer, and winter (December 2010–February

2011) temperatures tended to be cooler than the long-term mean (NOAA 2002). Monthly rainfall (Fig. 2b) was variable relative to long-term monthly means (NOAA 2002). There was a rainfall deficit of 363 mm in 2010, and surplus of 120 mm in 2011 relative to the long-term mean of 1,214 mm (National Oceanic and Atmospheric Administration (NOAA) 2002). Irrigation was expected to reduce soil water deficits, if any, caused by low rainfall. Since rainfall equaled or exceeded the normal amount required for species survival (Peterson 1990; Rogers 1990), supplemental irrigation might have been unnecessary. But a water supply adequate for survival is not the same as that adequate for high productivity, because pecan has a high water demand and responds to irrigation (Wolstenholme 1979; Harrison 2012). Regardless, irrigation greatly exceeded PM ETo, suggesting that drought stress was unlikely.

Concentration of soil water and the seasonal trend of soil water depletion were similar to that of Brauer et al. (2004), who measured soil water about 1 m from stems of 15-year-old, non-irrigated pecan on a nearby Leadvale soil. We applied about 1,700 (2010) and 2,200 L mo^{-1} per tree (2011), while Harrison (2012) recommended rates of 34,000 L mo^{-1} per tree in the Georgia Piedmont. While irrigation might have been of insufficient quantity (Harrison 2012) or poorly distributed in a spatial sense, we did not have a non-irrigated treatment for comparison. However, we did not observe symptoms of drought stress (leaf curling, chlorosis, or premature senescence) in either 2010 or 2011. Fragipans can perch water and make it available to deep roots for longer in the season than would be true in soils without that layer. Based on rainfall and irrigation rate in relation to ETo, trees should have had adequate soil water even if it was perched.

Height and radial growth

Growth rate (Test 1, Fig. 1) differed little for white oak and pecan seedlings (0.6 and 0.7 m y^{-1}, respectively), although previous reports indicated that growth rate of transplanted white oak seedlings, 0.6 m y^{-1} under ideal conditions, is generally slower than that of pecan seedlings, 0.9 m y^{-1} (Peterson 1990; Rogers 1990). In Test 2, height growth rate, 0.5 m y^{-1} (white oak) and 0.8 m y^{-1} (pecan) was similar to previous reports (Peterson 1990; Rogers 1990). Pecan height growth exceeded that of white oak in 2011, regardless of fertilization, but it was expected that pecan growth would have been challenged on this upland site with sub-optimal internal soil drainage due to a fragipan (Brauer et al. 2004; Burner and MacKown 2005; US Dept. Agric (USDA) 2012).

Annual dbh growth rates of 1.4 and 1.3 cm y^{-1} for pecan and white oak, respectively (Test 2), was at least twice (0.5 and 0.3 cm y^{-1} for white oak and pecan, respectively) that of unmanaged trees of comparable age-size class (Peterson 1990; Rogers 1990). Annual growth rate also corresponded to the 1.0 cm dbh y^{-1} for 15-year-old non-irrigated pecan at a nearby upland site (Brauer et al. 2004).

Radial growth typically exhibits a cubic temporal response resulting from tissue dehydration associated with decreased soil water availability (Monk 1959), and we observed this trend for white oak (Fig. 4). Tissue dehydration after mid-summer is a normal physiological process associated with development of frost hardiness (Monk 1959). Our results for pecan and white oak support the finding that radial growth of hardwood species generally begins at or about budburst, or soon after full leaf expansion (Walker and Oswald 2000; Gould et al. 2011a). However, relative timing of radial growth and budburst differs in other *Quercus* L. species, as about 25–30 and 43 % of the total annual radial increment of *Q. pubescens* (Switzerland) and *Q. petraea* (France), respectively, occurs by date of budburst (Bréda and Granier 1996; Zweifel et al. 2006).

Total seasonal diameter growth differed significantly according to measurement method (dbh by diameter tape vs. total radial growth by band dendrometry), supporting previous literature (Zimmermann and Brown 1971; Day and Monk 1977). There was a significant year by method effect, exemplified by a large difference between methods in 2010 (26.2 mm total radial growth >17.2 mm dbh). There was no significant difference between methods in 2011 (13.9 and 13.2 mm for total radial growth and dbh, respectively). The physiological basis for this discrepancy is attributed to disparity between the relative rates of stem hydration-dehydration in spring and fall versus cambial growth (Monk 1959). This suggested greater relative stem rehydration to cambial growth for both species in 2010 than 2011. Experimental error in radial measurements per se, or measuring dbh and radial growth at different positions on the tree stem, also could contribute to the discrepancy, although data from 2011 suggested this was not a major factor. Failure of newly installed bands to be properly seated on the stem also can cause measurement error, but this source of error was unlikely because a loose band causes radial growth to be underestimated (Keeland and Young 2012). Regardless, the discrepancy does not negate the value of periodic radial growth measurements for interspecific comparisons unless comparing growth rates with and without cell division (Monk 1959).

Budburst

Budburst of the two species in this study occurred within the generally reported time frame of March–May (Peterson 1990; Rogers 1990). Climatic gradients, especially latitude and elevation, can affect budburst phenology of tree species via species-specific environmental cues like chilling and forcing (Richardson and O'Keefe 2009). In Massachusetts, for example, white oak budburst occurs about day-of-year 127, much later than in the present study (Richardson and O'Keefe 2009).

Trees with an obligate chilling requirement need a period of exposure to cold temperatures before they break dormancy and burst bud (Polgar and Primack 2011). This chilling requirement prevents budburst during mid-winter periods of warm weather (Harrington et al. 2010). Within a species, timing of budburst is influenced by long-term accumulation of forcing and chilling units (Harrington et al. 2010; Richardson and O'Keefe 2009). Winters which result in many chilling units require fewer forcing units for budburst. Budburst is greatly influenced by temperature, supposedly occurring earlier in warmer than cooler years (Polgar and Primack 2011), but warm spring temperatures alone will not promote rapid budburst if adequate chilling has not previously occurred. The tradeoff between chilling and forcing units results in a very wide range of temperature conditions that cause spring budburst. Budburst of *Q. petraea* (France) occurred across a 25 days range during a 5 year study period (Bréda and Granier 1996). Our results indicated that timing of budburst was influenced by air temperature and differed somewhat by species (Fig. 5), but not by fertilization.

Pecan and white oak crossed the budburst possibility line developed for Douglas fir (Fig. 6) (Harrington et al. 2010). Budburst of white oak occurred, or tended to occur, sooner than pecan (Fig. 5), suggesting that white oak had a lower chilling requirement than pecan or that the species differ in their forcing requirements (Gould et al. 2011b). The differences in chilling, forcing, and budburst across years demonstrate the plasticity of plant response to temperatures experienced during winter and spring (Amasino 2004). In the absence of additional species-specific data, it appeared that the model developed for Douglas fir (Harrington et al. 2010) could be used to predict the approximate timing of budburst for pecan and white oak. Species can be genetically variable for budburst (St Clair et al. 2005), but our sample of genotypes was very limited. The general relationship between budburst and previous accumulation of chilling and forcing units suggested a conservation of responses among diverse woody species, although further research is needed to determine the model's applicability and the exact shape of the effectiveness functions between species (Harrington et al. 2010).

Foliar and soil responses

Foliar N and P concentrations were comparable to those of many hardwood species (Lee et al. 2003). Standard sufficiency ranges for pecan are 25–30 g kg^{-1} N, 1.2–3.0 g kg^{-1} P, and 7.5–25.0 g kg^{-1} K (Plank and Mitchell 2000), and those for *Quercus* are 19–30 g kg^{-1} N, 1.3 to 2.8 g kg^{-1} P, and 5–8 g kg^{-1} K (Leaf 1973). Leaf N concentration of 22.2 g kg^{-1} is the minimum for adequate growth of white oak (Mitchell and Chandler 1939). Thus, trees in this study had nominal foliar concentrations of macronutrients for adequate growth.

As much as 25 % of total pecan tree N is contained in the foliage (Acuña-Maldonado et al. 2003). Nuts rarely occurred on the pecan trees, and fruit set is not expected for native pecan trees of this age (Peterson 1990). Most of the white oak trees produced acorns in 2010, but not in 2011, but fruiting is not expected for 8-year-old white oak (Rogers 1990). Thus, the sink effect, if any, of nuts on foliar nutrients (Acuña-Maldonado et al. 2003; Smith 2009) was differentially expressed in species and years.

We found significant species by N-rate (Fig. 7) and species by day-of-year (Fig. 8) interactions interaction for LAI. Canopy imaging detected only presence and absence of leaves, not if they were live or senesced. We observed little or no leaf drop for white oak until just before budburst, while leaf drop of white oak occurred about day-of-year 282 in Massachusetts (Richardson and O'Keefe 2009). Thus, LAI was not a sensitive indicator of leaf senescence in this study because pecan was fully deciduous while senesced foliage of white oak persisted on the trees. Conversely, onset of senescence was better characterized by the decrease in photosynthetic capacity, such as Fv/Fm (Fig. 9) or chlorophyll concentration (Figs. 10 and 11) (Wingler et al. 2006), than LAI. Similar Fv/Fm values and chlorophyll concentrations have been reported for mature and senescent leaves of many hardwood species (Lee et al. 2003).

Annual applications of poultry litter benefited tree growth, and fertilization significantly increased topsoil P. However, topsoil P concentration was medium to high for production of row and forage crops (Espinoza et al. 2007) so additional topsoil P might not have benefited tree growth on this site. On the other hand, topsoil K concentration was considered very low for row and forage crops (Espinoza et al. 2007) despite annual applications of poultry litter. Thus, trees might have responded to additional K fertilization.

At a nearby site with the same soil type, growth of 15-year-old non-irrigated pecan trees was not differentially affected by bermudagrass or tall fescue understory (Brauer et al. 2004), even though both species are allelopathic to pecan (Smith et al. 2001). Competition control is recommended for at least the first year post-planting during establishment of hardwood seedlings (Krinard et al. 1997; Moree et al. 2010). Further, we maintained a vegetation-free understory with weed barrier and glyphosate as standard agroforestry practice (Garrett and McGraw 2000; Brauer et al. 2004; Smith et al. 2005). It would be interesting to determine if similar results occurred in the presence of allelopathic and non-allelopathic herbage species (Smith et al. 2001). Tree establishment and growth also benefited from use of containerized planting stock (Dey et al. 2004), auger planting, and irrigation.

Conclusions

Phenological responses of pecan and white oak to N fertilization have not been well characterized in an agroforestry practice. We compared tree growth at planting and for six consecutive growing seasons during establishment (2003–2008, Test 1), and determined if phenology of budburst, leaf area index (LAI), quantum yield of photosystem II (Fv/Fm), radial growth, and total chlorophyll concentration (*a*, *b*) responded to poultry litter fertilization supplying 0, 50, and 100 kg ha^{-1} N (2010–2012, Test 2) when intercropped on an upland site near Booneville, Arkansas. In general, pecan and white oak growth and phenology showed little response to poultry litter fertilization at rates up to 100 kg ha^{-1} N. While date of budburst differed significantly in 2012 compared to 2010 and 2011, species responses to budburst tended to be highly conserved despite exposure to varied environmental conditions, i.e., the chilling: forcing ratio, during the dormant season. Maximum predicted radial growth was roughly comparable for pecan (2.19 mm) and white oak (2.26 mm), but mean maximum growth peaked 28 days earlier for white oak (day 154) than pecan (day 182). White oak LAI tended to exceed that of pecan on any given date during the growing season. Foliar Fv/Fm and total chlorophyll concentration indicated that leaf senescence began about day 300, but there were few temporal responses prior to senescence. Site constraints or management factors that might have affected tree growth included, (1) poor internal soil drainage due to a shallow fragipan (not easily corrected in long-term), (2) inadequate rate and distribution of irrigation water, (3) N fertilization too low and effects measured for only 2 years, and 4 low concentration of topsoil K. Both species grew well on this upland site, 1.4 and 1.3 cm y^{-1} for pecan and white oak, respectively. Phenological responses tended to be insensitive to N fertilization probably because the trees had adequate soil and foliar N. The study provides additional information on growth responses of these two species to supplemental fertilization.

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