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Development, growth, and biomass simulations of two common wetland tree species in Texas

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Abstract Monitoring the health and condition of wetlands using biological assessments can serve as an effective tool for environmental managers to better evaluate and monitor the status and trends of their wetland ecosystems. Woody species can be used as conspicuous biological assessment tools due to their direct response to environmental change, such as hydrologic alteration. The purpose of this study is to use field-measured morphological measurement indices to develop and optimize tree growth parameters and growth curves using multi-model combination approach to improve tree biomass estimations. Field morphological investigations were conducted for two common wetland tree species in Texas. A range of morphological characteristics including leaf area index, height, and biomass was measured for black willow (*Salix nigra* Marsh) and green ash (*Fraxinus pennsylvanica*) sampled from 15 sites in a wetland near Cameron, Texas. The measured morphological parameters were used to optimize tree growth and development with the ALMANAC model. The developed tree growth parameters and growth curves were subsequently used in the APEX model to simulate tree biomass at the catchment scale. Both models accurately simulated biomass of trees growing in the wetland. This accurate biomass prediction will be useful to advance science to better monitor and assess wetland health on a large scale (e.g. national or global).

Keywords Wetland · Black willow · Green ash · ALMANAC · APEX

Introduction

At the local level, wetlands often form along streams in poorly drained areas and in shallow water along the boundaries of lakes, ponds, and rivers (CCW and NRC 1995). They are usually seasonal and occur on a relatively small portion of the landscape (Cappiella and Fraley-McNeal 2007). Small seasonal wetlands are ecologically valuable sites that offer ecosystem services, such as flood control, nutrient retention, and carbon sequestration (Zedler and Kercher 2005; Daniels and Cumming 2008). When wetlands receive adequate

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rainfall, they can have high biological diversity, which provides important fish and wildlife habitat and supports hunting, fishing, and other recreational activities (Smith et al. 2015; Locke et al. 2007). As wetlands provide important ecological, economic, and social benefits to people and wildlife, the importance of efficient wetland management has often been emphasized (Ramsar Convention Secretariat 2010). Advanced science of wetland monitoring and assessment will play critical roles in wetland management decision-making (Saintilan and Imgraben 2012; Ji 2007). Vegetation has often served as a wetland biological assessment and monitoring tool useful to assess wetland health (USEPA 2002).

Woody species are a conspicuous feature of wetland ecosystems and have been recommended as one of the best indicators of wetland ecological health and condition due to their robustness, rapid growth, and responses to environment change (Mitsch and Gosselink 2015; USEPA 2002). The wetland condition can be determined by observing the wetland's structure (i.e. soil hydrology) and function (i.e. plant biomass production) (Lee et al. 2006). Previous studies have evaluated wetland health and condition by investigating woody species growth characteristics, including plant density, canopy cover, and plant volume, associated with biomass production of woody species (Sharitz and Gibbons 1989; Pendergrass et al. 1998; Doherty et al. 2000; Parkes et al. 2003; Stapanian et al. 2013). Black willow (*Salix nigra* Marsh) and green ash (*Fraxinus pennsylvanica*) are good biological wetland indicators due to their vigorous growth rates and production of massive root systems that can rapidly stabilize under anaerobic soil conditions (Grissinger and Bowie 1984; Hupp 1992; Mendelssohn 1993; van Splunder et al. 1994; Shields Jr. et al. 1995).

Black willows and green ash are flood-tolerant trees commonly found in wetlands in the Southcentral US (Hosner 1962; Smith et al. 2005; TPWD 2012). They are frequently used as restoration species that help control soil erosion while improving wildlife habitat in wetlands (Roseboom 1993; Shields Jr. et al. 1995; Watson et al. 1997; Federal Interagency Stream Restoration Working Group 1998; Gargiullo 2007). These species grow well under flooded conditions, rapidly producing adventitious roots that accelerate anaerobic respiration rate in the absence of oxygen and oxidize their rhizospheres (Hook and Brown 1973; Dionigi et al. 1985; Good and Patrick 1987; Hupp 1992; Hammerson 2004; Row and Geyer 2010). Their growth changes in response to hydrologic alteration (Reily and Johnson 1982; Li et al. 2004). Black willow and green ash have larger diameter trunks in saturated soils and develop multiple trunks resulting in increased branch surface area available for gas exchange with the atmosphere under flooded conditions (Hammerson 2004). Such changes in growth are indicators of wetland hydrologic conditions. These conditions play important roles in the structure of a wetland's ecosystem (Mitsch and Gosselink 2015). Thus process-based simulation models that accurately simulate black willow and green ash growth and development over time are valuable assessment tools. Output from such models, in coordination with environmental conditions such as climate and hydrology, is useful for improvement of wetland planning and management activities (Teck and Hilt 1991; Yahya et al. 2012).

Process-based models, also known as mechanistic or ecosystem models, are powerful tools for simulating the growth or status of trees and tree stands in different environmental conditions (Landsberg 2003). Process-based models account for physiological processes, including photosynthesis, mineral metabolism, respiration, carbon partitioning, absorption, and nutrient accumulation. These processes control trees' growth and development and trees' relationship with the environment (Pastor and Post 1985; Dixon et al. 1990; Marin et al. 2014). Such models help scientists better understand ecosystem function and give realistic prediction of productivity and nutrient, water, and carbon cycles (Landsberg 2003; Marin et al. 2014; Larocque 2016). However, process-based models are often complex and highly parameterized, requiring parameters that are difficult to obtain to describe tree and stand growth (Baker and Robinson 2010). This can discourage use of such models by increasing concerns of uncertainty around the parameter estimation (Baker and Robinson 2010). Given that process-based models cannot include all physiological processes of a tree, such models should demonstrate simplicity, with parameters that are readily obtained (Thompson et al. 1997). Two field-based process-level models, APEX and ALMANAC, have such potential in simulating tree growth in wetlands.

The Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model includes subroutines and functions related to solar interception and nutrient and water balances from EPIC (Environmental Policy Integrated Climate; Williams et al. 1984) but has more detailed simulation of plant growth (Kiniry et al. 1992). ALMANAC has a daily time step and has tree parameters based on actual field data. The Agricultural Policy Environmental eXtender (APEX) model includes the same plant growth algorithms as ALMANAC (Kiniry et al. 1992; Williams et al. 2010). APEX is a continuous model that simulates plant growth and biomass yield of tree species, with focus on soil and water quality in small-scale watersheds (Golmohammadi et al. 2014). Both APEX and ALMANAC use readily available USDA—NRCS soil data and historical daily temperature and rainfall data. They simulate processes of tree growth including light interception by leaves and dry matter production (Kiniry et al. 2008). Both models simulate tree productivity based on light interception and the species-specific radiation use efficiency (RUE). The RUE is the amount of dry biomass produced per unit of intercepted light under non-limiting conditions (Gassman et al. 2010; Kiniry et al. 2007). RUE is a conservative parameter for a plant species (Monteith 1977; Landsberg 2003). These two models have been parameterized and validated for a wide range of tree species: lodgepole pine (*Pinus controta* Douglas ex Loudon), trembling aspen (*Populus tremuloides* Michx), eastern redcedar (*Juniperus virginiana*), honey mesquite (*Prosopis glandulosa*), and *Populus* (Kiniry et al. 2008; Kiniry 1998; Guo et al. 2015).

This study was conducted in a wetland with scattered small areas dominated by black willow and green ash. The study was aimed at understanding the growth and development of these trees to determine the relationship between a range of morphological traits and their productivity as well as key morphological traits affecting their productivity. Based on field measurements, ALMANAC was used to create and to optimize both the tree growth parameters and the growth curve for a specific region and year. The resulting tree parameters and growth curves were subsequently incorporated into APEX to simulate the wetland trees at the small watershed scale. The resulting simulated trees' biomass values were compared to the measured biomass for the same location. Multiple-year productive patterns obtained by the ALMANAC and APEX models were then compared with patterns of trees' volume obtained from simple regression lines plotted based on measured volumes.

Materials and methods

Study area

The study was conducted at a small wetland (0.77 km × 2.28 km in size) near Cameron, Texas (Fig. 1). This wetland was formed by an overflowing river bank over many years. The dominant soil in the study area is a Tinn clay, 0 to 1% slope, occasionally flooded (clay, calcareous clayey alluvium) (NRCS 2017). Many flood-tolerant shrubs, grasses, and trees occur naturally in this wetland. Between July and August in 2016, several tree morphological traits and productivity were measured at 15 locations in the wetland representing distinct clusters of trees. Sampling sites occurred along ponds or flat areas within the flood plain (Figs. 1 and 2). Among the 15 sites, black willow trees were sampled at 9 sites, while green ash trees were sampled at 6 sites (Fig. 1). Each sampling site contained mixtures of different-sized trees.

Morphological trait collection

In each site, 15 trees with various sizes were randomly selected for measurement of number of trunks per a tree and trunk basal diameter. These trees were used to estimate total tree volume, maximum crown diameter, crown diameter perpendicular to the maximum crown diameter, and tree height. Among the 15 trees selected for each site, 5 trees were harvested for tree yield estimation. Total aboveground biomass of each tree and a subsample were weighted immediately following the harvest. The subsample was dried in a forced-air 66 °C oven until dry weight was stabilized. Tree height was measured from the ground to the top of the highest leaf. The heights for tall trees were measured by projecting a right triangle using a clinometer. The number of trunks per tree was counted. Each trunk's circumference was measured 100 cm above ground level. Trunk diameter was calculated by dividing the circumference by π. If the tree had multiple trunks, the trunk diameter was

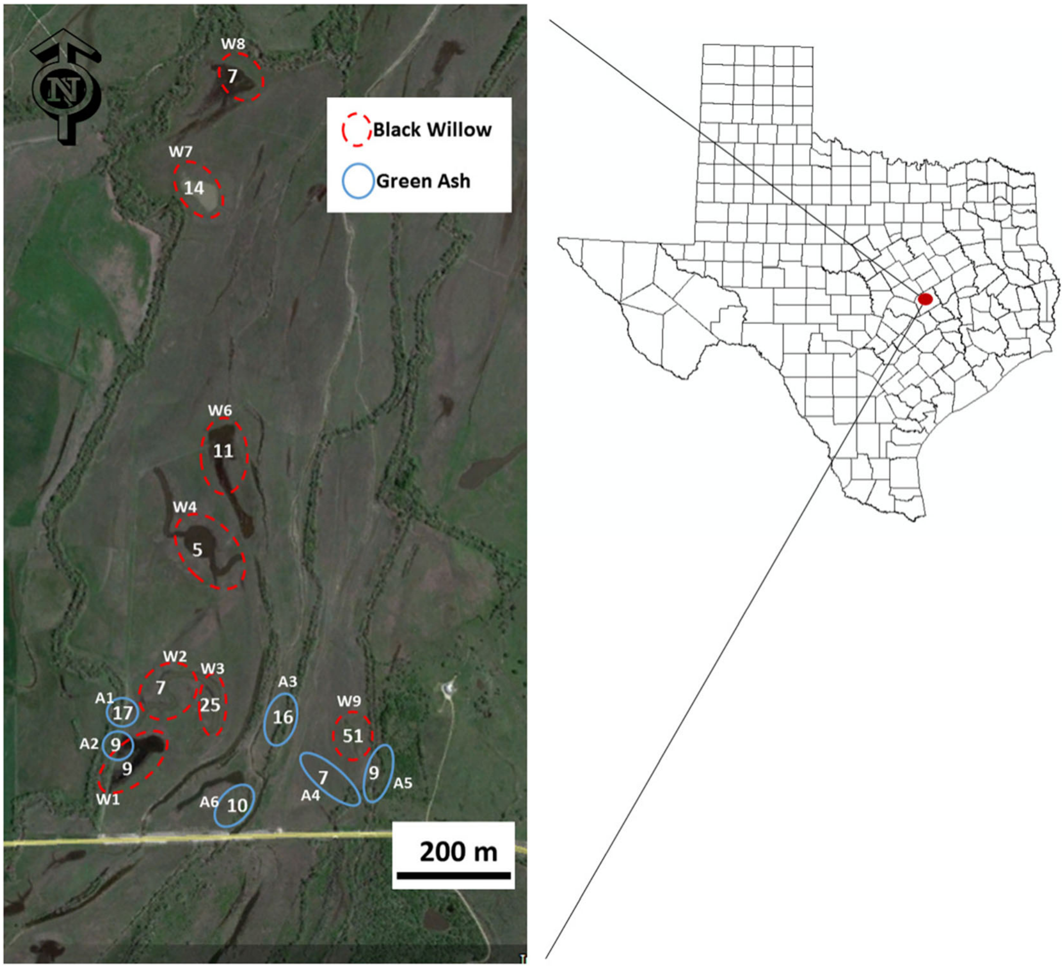


Fig. 1 Satellite imaginary of study area. The image is from 26 March 2015 and was obtained from Web Soil Survey (available in http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx). Red dotted circles indicate areas where black willow trees were sampled, while solid blue circles indicate the area where green ash trees were sampled. The numbers inside the circles indicate tree density (number of trees per 100 m^2 area)

calculated as the sum of total trunks' circumferences divided by π and then dividing the outcome by the number of trunks. Tree canopy size was calculated by multiplying two crown radii and pi (π). The tree volume was calculated by assuming that the shrub was a cone. This consisted of multiplying the canopy size by the tree height and then dividing the outcome by 3. In all locations, tree density was estimated by counting number of trees within a 300 m^2 area.

Intercepted light and leaf area measurements

In all study sites, photosynthetically active radiation (PAR) was measured below the leaf canopy using an AccuPAR LP-80 Ceptometer (Decagon Devices, Pullman, WA, USA) to enable calculation of fraction of intercepted PAR (FIPAR). Measurement of FIPAR was taken only from the five trees that were selected for harvest in each study site. Three sets of readings were made under each tree's canopy between 10:00 and 14:00. Care was taken to avoid shadows from neighboring trees. When trees were grown in standing water, measurements of PAR were taken just above the water surface. The multiple above and below readings were averaged to estimate FIPAR. FIPAR was calculated as ratio of PAR below canopy to PAR above canopy subtracted from 1.0. A subsample was harvested within each sample area for the light measurement. This subsample was brought to the laboratory for leaf area index (LAI) estimation. In

Fig. 2 Photographs of black willow (**a**,**b**) and green ash (**c**,**d**)

the laboratory, the subsample was weighed and then separated into green leaves, dark brown live woody materials (e.g. trunks and branches), and white and gray dead woody material. The leaf area was measured with a LI-3100 Area Meter (LI-COR Biosciences, Lincoln, NE, USA). LAI was calculated as leaf area of subsample (cm^2), divided by tree crown size (cm^2), and then multiplied by the ratio of total fresh weight (g) to subsample fresh weight (g). The light extinction coefficient (k) was calculated by modified Beer's law, as described by Meki et al. (2015). The value of k was calculated as the natural log of difference between 1 and FIPAR and then divided by LAI. No light measurement was taken from the 9 non-harvested samples in each study site.

Growth ring and growth rate measurements

Since black willow and green ash are deciduous trees that lose their leaves seasonally, tree age can be estimated by counting the number of annual growth rings. For measurements of growth ring count to determine growth rate and age, the largest trunk diameter which had no damage from insects and diseases was collected from all harvested tree samples from all study sites. A total of 75 trunks were used, including 45 trunks from willow trees and 30 trunks from green ash trees. To count rings, a 2–5-cm-thick cross-section was sliced from each trunk. The cut surface was sanded and polished using sandpaper of grit size 60–300. Rings were counted along the longest radius, and the length of radius was measured with ruler. The tree trunk growth rate was determined by dividing the length of the radius by the number of growth rings.

Statistical data analysis

According to the results of field measurements, similar growth patterns across different tree ages were observed in both black willow and green ash. At the youngest stage (1–6 years), black willow and green ash tended to grow slowly and to have far lower biomass than trees in stage of 6–10 years. Two groups were created for black willow and green ash based on their growth patterns. Two groups for black willow were named as BW1 (3–5 years) and BW2 (6–8 years), while groups for green ash were named as GA1 (4–6 years) and GA2 (7–10 years). All statistical analyses were performed using Statistical Analysis Software version 9.3 (SAS Institute, NC, USA). Two groups for each tree, with population means for each variable, were compared using Welch's *t* test due to unequal sample sizes (Welch 1937; Wilcox 1990). The Spearman's rank-order correlation coefficients and their significance (rho = 0) were determined for the relationships among the following traits: tree weight, number of trunks per tree, tree diameter, height, tree volume, LAI, light extinction coefficient, annual growth ring number, and growth rate using data collected from all study locations. Data collected from harvested samples were only used for calculating correlation coefficients. The absolute value of correlation coefficient (*r*) represents a very strong correlation if above 0.8, a strong correlation if between 0.60 and 0.79, a moderate correlation if between 0.4 and 0.59, a weak correlation if between 0.20 and 0.39, and a very weak correlation if below 0.19 (Evans 1996).

Multi-model simulation of development

The process-based simulation models, ALMANAC and APEX, simulate processes of tree growth and soil water balance including light interception by leaves and dry matter production. Firstly, the ALMANAC model tree parameters and growth curve were derived from field data. In the ALMANAC plant databases, one set of plant parameter was created for green ash (GA), while two sets of plant parameters were created for black willow (BW1 and BW2). According to field data, black willow increased the number of trunk per tree as it gets older. The similar growth pattern was observed in multiple-stemmed shrub, creosotebush [*Larrea tridentata* (D.C.) Cov]. The creosote bush continuously creates new stems at the center or periphery of a clone as it gets older, and two sets of plant parameters were created through the ALMANAC applications (Kim et al. 2018). In each plant database set, parameters are associated with (1) leaf area development, (2) development rate response to temperature, (3) RUE and physical description, and (4) nitrogen and phosphorus concentration in plant biomass (Kiniry et al. 1992). These values were derived from measured data, previously published research, and the ALMANAC model's database of over 100 plant species' parameters, with minimal adjustment after comparing output with measured tree biomass data. The values of potential heat units, PHU, should be close to the number of growing degree days for the area and large enough to avoid growth stoppage before normal maturity date in the simulations. The PHU values for all BW1, BW2, and GS were 3000. The heat units were accumulated annually and reset to 0 at the end of each year. The APEX model was used to simulate tree yields at small watershed scale using the plant parameters and growth properties of black willow and green ash trees transferred from the ALMANAC. The small watershed was divided into smaller spatial units called subareas (sub-watershed). All study subareas were configured with the same plant management practices used in the ALMANAC. Plant parameters for black willow and green ash are described in Table 1. The ALMANAC plant parameters and growth cycle for black willow and green ash and the APEX modeling setup were described in detail in Appendix A.

Model evaluation

To evaluate the plant parameters and validate the simulated yields, simulated tree biomass in August 1, 2016, was compared with the measured biomass that came from the field measurement. Since climate and soil characteristics were same across sampling locations, the yield simulated for a single location was used for the ALMANAC calibration and validation. Since the observed flow from the watershed of study area was not available, APEX could not be tested against the observed flow; hence, simulated yields were averaged over three subareas to compare with measured yields. The measured and ALMANAC and APEX simulated yields were statistically compared using *t* test at $\alpha = 0.05$. The *t* test was used to test for significant differences between

Table 1 Plant parameters in ALMANAC and APEX adjusted for black willow and green ash

Parameters		
ALMANAC	APEX	Description
WA	WA	Biomass–energy ratio, kg ha^{-1} per MJ m^{-2}
HI	HI	Harvest index
DMLA	DMLA	Max. leaf area index (LAI)
DLAI	DLAI	Fraction of season when LAI starts to decline
DLAP1	DLAP1	First point on optimal LAI curve
DLAP2	DLAP2	Second point on optimal LAI curve
PPL1	PPLP1	Plant population parameter (trees/100 m^2 for ALMANAC; trees/ha for APEX)
PPL2	PPLP2	Second plant population parameter (trees/100 m^2 for ALMANAC; trees/ha for APEX)
Tree1	Tree1	First point on multi-year S-curve fraction for tree LAI and height increase
Tree2	Tree2	Second point on multi-year S-curve fraction for tree LAI and height increase
CLAIYR	XMTU	No. years until maximum LAI
HMX	HMX	Max. crop height (m)
EXTINC	EXTINC	Extinction coefficient for calculating light interception
RTPRT1	RWPC1	Tree parameter, fraction of weight portioned to root for young plants.
RTPRT2	RWPC2	Tree parameter, fraction of weight portioned to root for plants near maturity.
PLANTPO	OPV5	Plant density (plants/100 m^2 for ALMANAC; plants/ha for APEX)
PHU[a]	OPV1[b]	Potential heat use

[a] Heat units are accumulated annually and reset to 0 at the end of the year in the ALMANAC model

[b] Potential heat unit in the APEX model is parameterized based on simulated LAI observed from the ALMANAC simulation

measured and simulated values using Statistical Analysis Software version 9.3 (SAS Institute, NC, USA).

Biomass prediction at different tree ages

Two linear regression lines, one for black willow and one for green ash, were created by plotting measured values for dry yield (Mg ha^{-1}) against tree volume (m^3). The tree dry yields and ages for non-destructive samples of black willow and green ash were predicted using the regression lines. The measured volume for each non-destructive sample, the *x* value, was substituted into the linear regression equations to calculate yield, *y* value. Scatter plots of estimated yield (*x* value) vs. measured volume (primary *y* value) were created for black willow and green ash. Tree ages for non-destructive samples of black willow and green ash were predicted using ALMANAC and APEX. Through these two models, tree biomasses were predicted when tree ages were 15, 20, 25, 30, and 35. Scatter plots of estimated biomass (*x* value) vs. tree ages (secondary *y* value) were created for black willow and green ash.

Results and discussion

Morphological, leaf area, and light measurements

In both black willow and green ash, different growth patterns were observed for the two growth periods. The two growth periods were 3–5 and 6–8 years for black willow, while green ash had 4–6 and 7–10 years growth periods (Fig. 3). The largest biomass increases were found between 6 and 8 years for black willow and 7–10 years for green ash (Fig. 3). Based on this growth pattern, black willow and green ash were divided into two groups: BW1 and BW2 for black willow and GA1 and GA2 for green ash (Table 2). BW2 trees had significantly larger mean values for dry weight per tree, LAI, number of trunks per tree, stem diameter, height, volume, and growth rate than BW1. GA2 trees also had significantly larger mean values for dry weight, stem diameter, height, volume, and growth rate than GA1. Although no significant difference was found for LAI between GA1 and GA2, GA2 had almost twice as large of a mean LAI as GA1 ($P = 0.0953$). For both black willow and green ash, no significant differences were observed in *k* values. The value of *k* in tree crowns is related to its shoot architecture and leaf traits (mean leaf angle and life span) (Kitajima et al. 2005). The multiple trunks of one black willow and green ash may have resulted in similar canopy pattern and density per unit area among young and older trees.

Associations among the traits

In both black willow and green ash trees, trunk diameter, height, volume, LAI, trunk age, and growth rate were

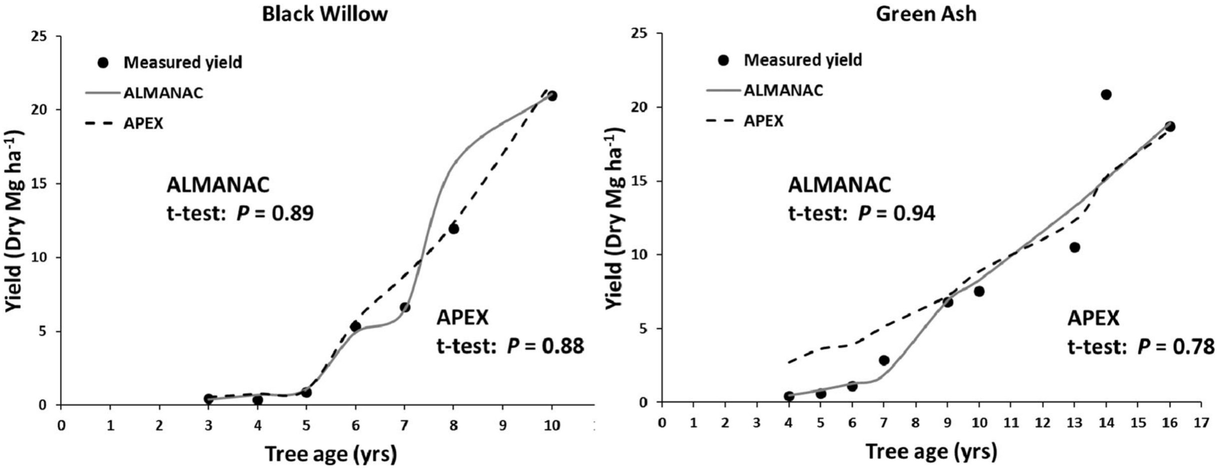


Fig. 3 Measured yields and simulated yields by ALMANAC and APEX for black willow and green ash across different ages. Measured and each of simulated yields were statistically compared using *t* test at alpha = 0.05

significantly correlated with dry weight ($P \leq 0.0001$; Tables 3 and 4). In both trees, trunk diameters were significantly associated with height, volume, trunk age, and growth rate, while the height was significantly correlated with volume, trunk age, and growth rate. Tree volume of black willow was positively correlated with trunk age and growth rate, and its tree trunk age was moderately correlated with growth rate. In multiple trunk tree species, the individual trunks are generally smaller and have less biomass than its main trunk. Matula et al. (2015) reported that multiple trunk tree biomass is largely affected by the parameters of only one or a few largest trunks. This may be why the number of trunks was not significantly correlated with black willow tree weight. However, for green ash, most of its weight was in only a few trunks. Thus, dry weight of green ash was significantly correlated with number of trunks per tree. Green ash tree volume was moderately associated with LAI, and its LAI was positively correlated with *k* and trunk age.

Aboveground biomass measurements

During growth period of 3–5 years, the black willow average biomass values were between 0.38 and 0.88 Mg ha^{-1}, while the biomass values during the growth period of 6–8 years were between 5.3 and 11.9 Mg ha^{-1}. The green ash average yields were between 0.42 and 1.1 Mg ha^{-1} during growth period of 4–6 years, while the yields during growth period of 7–

Table 2 Means of each different age group for black willow and green ash. Welch's *t* test comparison between the two age groups within each tree was performed for each variable at 0.05 significance level (Welch 1937; Wilcox 1990)

	Black willow			Green ash		
Variables Tree age range	BW1 3–5 yrs	BW2 6–8 yrs	Welch's test *P* value	GA1 4–6 yrs	GA2 7–10 yrs	Welch's test *P* value
Dry weight per tree (kg)	0.39	5.03	< 0.0001	0.62	3.75	0.0023
LAI	0.72	1.49	0.0055	0.32	0.74	0.0953
k	− 0.25	− 0.34	0.44	− 0.81	− 0.74	0.866
No. trunks tree^{-1}	3	6	0.0056	2	2	0.56
Trunk diameter (cm)	2.81	4.61	0.0019	2.67	4.5	0.0009
Height (m)	1.91	3.02	< 0.0001	2.16	3.56	< 0.0001
Volume (m^3)	0.73	6.28	< 0.0001	0.56	2.85	0.0078
Growth rate (mm yrs^{-1})	2.23	4.56	< 0.0001	2.4	3.42	0.034

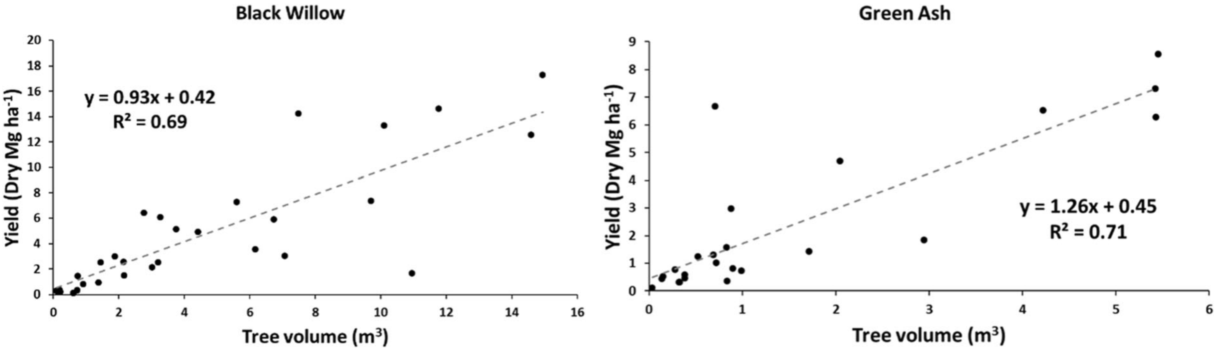


Fig. 4 Relationship between tree volume and total dry weight for black willow and green ash. The line is the fitted regression line

10 years were between 2.89 and 7.52 Mg ha^{-1}. A similar result has been reported from Bowman et al. (2012) who reported that stem basal area increment and volume increment are initially small, resulting in small biomass in younger trees. In addition, since all trees grew from seedlings, it would take longer for them to establish and to start rapid growth. Black willow may take 5 years to be established and to start rapid growth, while green ash may take 6 years to be established and to start rapid growth.

Multi-model evaluation

The growth and biomass of two multiple trunk tree species were simulated using a multi-model combination approach, combining the application of the ALMANAC field-scale model and the APEX watershed-scale model. The ALMANAC model was used to develop plant parameters and growth curves of black willow and green ash (Table 2). The plant parameters and growth curves were optimized based on field morphological measurements and a literature review (Table 5). Leaf area index is a valuable index of plant growth and is related to the accumulation of dry matter, plant metabolism, and yield (Ishak and Awal 2007). Realistic values of LAI for both species are critical for accurate simulation of light interception (Debaeke et al. 1997). In ALMANAC, three parameters are used to simulate the maximum LAI of each species at different population density. First is the DMLA, the potential maximum leaf area index at high density without limiting factor. DMLA values for both species were obtained from the measured data in this study. Black willow DMLA was greater than green ash DMLA. Black willow DMLA value was 3.2, while green ash DMLA value was 1.0. Since black willow has more trunks per tree and

Table 3 Phenotypic correlation coefficients among morphological and growth characteristics evaluated for black willow including two different age groups: BW1 (age range in 3–5 years) and BW2 (age range in 6–8 years). According to significance test of Spearman's correlation (rho = 0), *** significant at $P \leq 0.0001$, ** significant at $P \leq 0.01$, and * significant at $P \leq 0.05$. The absolute value of correlation coefficient (*r*) represents a very strong correlation if above 0.8, a strong correlation if between 0.60 and 0.79, a moderate correlation if between 0.40 and 0.59, a weak correlation if between 0.20 and 0.39, and a very weak correlation if below 0.19 (Evans 1996)

Variables	Dry weight	No. of trunks	Trunk diameter	Height	Volume	LAI	*k*	Trunk age
No. of trunks	0.34							
Trunk diameter	0.68***	−0.20						
Height	0.85***	0.28	0.61***					
Volume	0.87***	0.34	0.67***	0.86***				
LAI	0.64***	0.10	0.36	0.55*	0.36			
k	−0.08	−0.22	−0.03	0.08	−0.27	0.46*		
Trunk age	0.78***	0.29	0.51*	0.71***	0.74***	0.63**	0.07	
Growth rate	0.84***	0.25	0.71***	0.76***	0.80***	0.43*	−0.12	0.58**

Table 4 Phenotypic correlation coefficients among morphological and growth characteristics evaluated for green ash including two different age groups: GA1 (age range in 4–6 years) and GA2 (age range in 7–10 years). According to significance test of Spearman's correlation (rho = 0), *** significant at $P \leq 0.0001$, ** significant at $P \leq 0.01$, and * significant at $P \leq 0.05$. The absolute value of correlation coefficient (r) represents a very strong correlation if above 0.8, a strong correlation if between 0.60 and 0.79, a moderate correlation if between 0.40 and 0.59, a weak correlation if between 0.20 and 0.39, and a very weak correlation if below 0.19 (Evans 1996)

Variables	Dry weight	No. of trunks	Trunk diameter	Height	Volume	LAI	*k*	Trunk age
No. of trunks	0.42*							
Trunk diameter	0.74***	− 0.04						
Height	0.81****	0.11	0.69**					
Volume	0.79***	0.11	0.77***	0.78***				
LAI	0.67**	0.40	0.57**	0.38	0.53**			
k	0.12	0.16	0.09	0.01	0.12	0.60**		
Trunk age	0.80***	0.28	0.63**	0.84***	0.78	0.50*	0.13	
Growth rate	0.54**	0.19	0.49*	0.46*	0.37	0.25	− 0.1	0.28

branches, black willow may have higher DMLA than green ash (Tables 1 and 5). This result is supported by Broeckx et al. (2012) who reported that tree crown architecture is an important determinant of maximum leaf area index. Light extinction coefficient, EXTINC, is also closely related to tree crown architecture. Thus, EXTINC is related to the leaf inclination angle, leaf arrangement, which is correlated to the LAI, and provides indication of the plant's efficiency on intercepting solar radiation (Rodríguez et al. 2015). Value of

Table 5 Derived plant parameter values of black willow (BW1 and BW2) and green ash (GS1 and GS2) used to calibrate the ALMANAC and APEX models

Parameters	ALMANAC		APEX	
	Black willow	Green ash	Black willow	Green ash
WA	30	30	30	30
HI	0.01	0.01	0.01	0.01
DMLA	3.17	1	3.17	1
DLAI	0.99	0.99	0.99	0.99
DLAP1	30.15	30.15	30.15	30.15
DLAP2	54.84	54.84	54.84	54.84
COSD (tree 1)	30.31	40.35	30.31	40.35
PRY (tree 2)	70.5	80.6	70.5	80.6
CLAIYR	9	10	9	10
HMX	3.74	4.01	3.74	4.01
EXTINC	0.31	0.84	0.31	0.84
RTPRT1	0.7	0.7	0.7	0.7
RTPRT2	0.3	0.3	0.3	0.3
PLANTPO	12	11	1200	1100
PHU/OPV1	3000	3000	[a]	[a]
If tree ages are	*BW1 (< 5 yrs)*	*GA (All)*	*BW1 (< 5 yrs)*	*GA (All)*
PPL1	10.13	10.23	1500.35	1500.83
PPL2	15.35	15.83	1000.13	1000.23
If tree ages are	*BW2 (> 6 yrs)*	–	*BW2 (> 6 yrs)*	–
PPL1	10.23	–	1500.85	–
PPL2	15.85	–	1000.23	–

[a] PHU in APEX was parameterized based on simulated LAI observed from the ALMANAC model

EXTINC for black willow was 0.31, which is close to the value in the literature (Williams et al. 2017). Black willow had more leaves per unit area than green ash, resulting in higher canopy layers in black willow and lower values in EXTINC (Table 5).

The other two parameters that were used to simulate LAI in black willow and green ash over growing seasons are PPL1 and PPL2. These two parameters were used to fit a sigmoid curve function for a zero-to-one factor which reduces DMLA at different population densities (Debaeke et al. 1997). Two parameters, DLAP1 (first point in optimal leaf area development curve) and DLAP2 (second point in optimal leaf area development curve), describe the development of LAI prior to flowering, under non-stress conditions (Table 2). Both black willow and green ash are fast-growing hardwood species and share similar seasonal growth curve. They resume growth each spring, with growth slowing down in May or June and ceasing in late July or August. The two points on the yearly LAI curve for black willow and green ash are 30.15 and 54.84. The detailed descriptions of other plant parameter settings were provided in Appendix A.

The developed plant parameters and growth cycles developed using ALMANAC were then transferred to APEX (Table 2). Unlike ALMANAC, APEX predicts tree biomass in each delineated subarea, so the tree biomass was simulated in a larger area than actual measured area. Plant growth simulation in APEX is regulated by available resources and environmental variables, such as soil moisture, solar radiation, soil/air temperature, and soil nutrient content. APEX was not directly validated against measured streamflow rates due to the lack of such data. An alternative way to calibrate the model is to compare APEX outputs in adjacent watersheds where data are available. However, the small-scale wetland catchments are rarely monitored in the region and no data were available. Nevertheless, the successful calibration of plant growth and biomass yield by ALMANAC/APEX indicates that the partitioning of rainfall between runoff, infiltration, evapotranspiration, and lateral flow in APEX was reasonably simulated. For example, an excess runoff discharge or a fast vertical/lateral drainage of soil water in APEX would result in low soil moisture, which in turn provides insufficient soil water for willow trees to achieve daily potential growth rate with water stress. Literature indicates that even uncalibrated APEX reasonably predicts flow, sediment, nutrient, and herbicide loss in a forested watershed (Wang et al. 2007).

Hydrologic behavior of the watershed was assessed based on how APEX-simulated surface runoff correlated with measured rainfall during a 10-year period (2007–2016). Appendix B provides monthly simulated water flow along with the monthly rainfall. Simulated surface runoff from subarea 2 was in reasonable agreement with observed precipitation. In particular, the highest flow simulated by APEX occurred in 2007 in response to intensive precipitation events observed from January to August. In 2011 which was a dry year, very few runoff events were simulated in response to low precipitation (Appendix B).

In this study, the simulated biomass values for black willow and green ash from both calibrated ALMANAC and APEX were compared with average measured biomass at different tree ages (Fig. 3). Both ALMANAC- and APEX-simulated biomasses of black willow and green ash agreed well with the measured biomass. According to the *t* test, no significant differences between simulated and measured biomass for black willow and green ash were observed (all $P > 0.7$, Fig. 3).

Biomass prediction at different tree ages

Tree biomass had moderately positively linear correlation with tree volume ($R^2 > 0.69$ for both black willow and green ash, Fig. 4). Bowman et al. (2012) reported that tree volume is correlated with tree biomass because both strongly affect the tree growth, defined as an increase in dimensions of a tree through time. Tree volume was measured for non-destructive samples for both black willow and green ash (Fig. 5). The tree volume of non-destructive black willow samples varied between 0.01 and 85 m^3, while green ash tree volume varied between 0.02 and 32 m^3 (Fig.5). The tree biomass of non-destructive samples was calculated using linear equations obtained from linear relationship between measured tree biomass and measured tree volume (Figs. 4 and 6). Through the ALMANAC and APEX model applications, tree ages of those non-destructive samples were estimated (Fig. 6). Most of the non-destructive samples of black willow and green ash were under 15 years old and had biomass values less than 36 and 16 Mg ha^{-1}, respectively. The biggest trees for both black willow and green ash were over 30 years old, and they had the highest biomass. This result is supported by McKnight (1965) who reported biomass of black

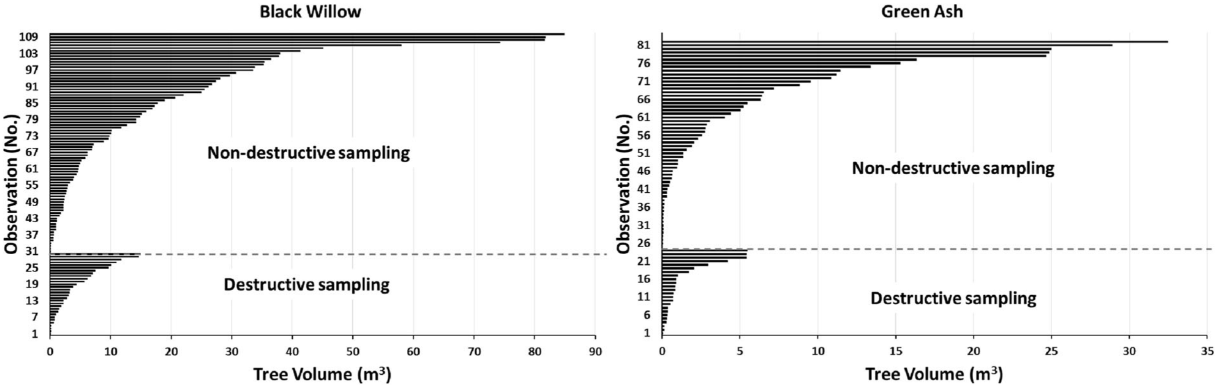


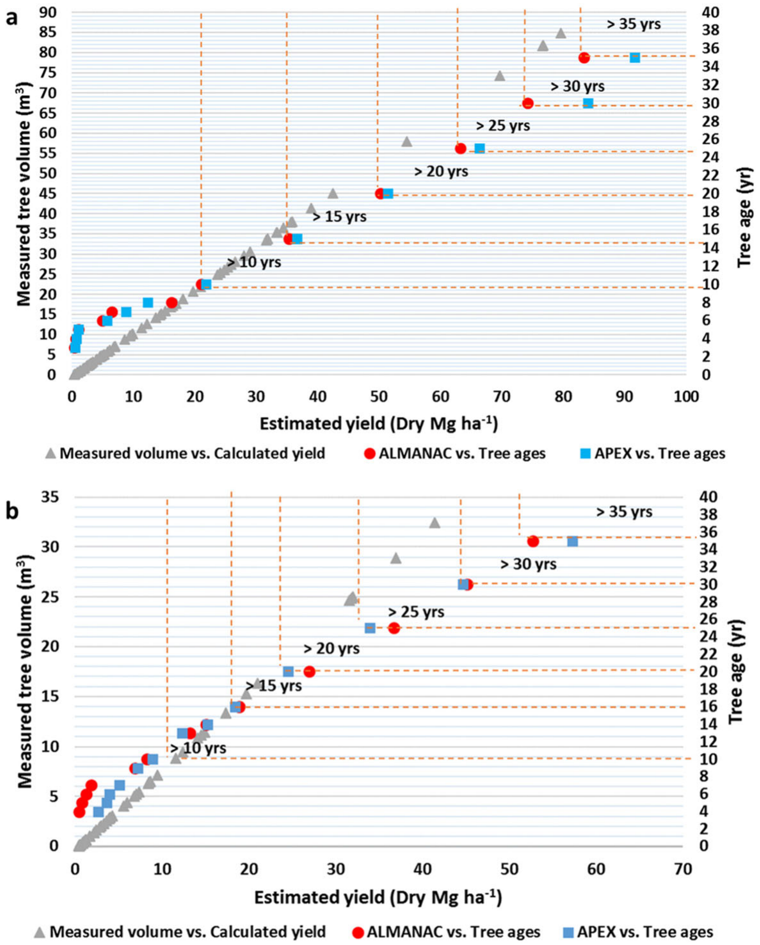
Fig. 5 Bar graphs of tree volumes of black willow and green ash. Bars under the dashed line indicate destructive samples, while bars above the dashed line indicate non-destructive samples

willow trees in the southern US continuously increased up to 50 years old. Moreover, Mecuccini et al. (2005) and Bond et al. (2007) reported that tree age and tree size increased together in natural conditions, which strongly affects tree growth.

Assumptions and limitation

Since plant growth model in the APEX is largely built from the ALMANAC model (Williams et al. 1989), we assumed that plant parameters and plant

Fig. 6 Relationship between calculated biomass using simple linear equation and measured tree volumes (gray triangle), relationship between ALMANAC simulated biomass and trunk age (red circle), and relationship between APEX simulated biomass and trunk age (blue rectangle) for (**a**) black willow and (**b**) green ash. The simple linear equation is derived from Fig. 4 showing relationship between measured tree volumes and measured dry biomass of black willow and green ash. The orange dot lines indicate threshold lines for tree ages estimated based on simulated biomass from both ALMANAC and APEX



growth properties derived from the ALMANAC model application could be transferrable to the APEX model without losing simulation accuracy. The sampling sites were distributed throughout the upper portion of the wetland which receives standing water in the spring season and the water dries out by mid-summer as evapotranspiration exceeds rainfall amounts. It is common in central Texas that evapotranspiration exceeds rainfall during summer seasons (Swanson and Fipps 2013). An implicit assumption was made with APEX that calibrating plant growth and biomass yield provides reasonably accurate estimation of evapotranspiration. As evapotranspiration dominates the overall water balance, we assume that the APEX hydrologic processes are indirectly calibrated. Nonetheless, the absence of a direct calibration against observed flow may lead to an uncertainty in hydrologic outputs. This can be overcome by extending model application to other watersheds where hydrological data are available.

Conclusion

In both black willow and green ash, two growth patterns were observed between two age groups. Tree growth rate increased slowly under 5 or 6 years and became exponential after 6 or 7 years. Since black willow and green ash are multi-stemmed woody species, their trunks may develop at different times, which can delay tree growth and delay large biomass increases. In this study, a hybrid and multiscale modeling approach with two process-based models, ALMANAC and APEX, was developed to simulate tree yield production. Through the ALMANAC application, plant parameters and growth cycles for black willow and green ash were characterized based on the measured field data and a literature review. Both black willow and green ash are fast-growing hard wood species and share similar parameters, except for parameters related to leaf area. This may be due to different tree crown architectures observed between the two tree species. To evaluate the plant parameters and test ALMANAC's ability to accurately simulate tree dry yield, simulated tree biomass values at different tree ages were compared with the measured biomass values from field measurements. The simulated dry yield production agreed well with measured yields of both black willow and green ash. After parameters were successfully created using ALMANAC at small plot scale, the developed parameters were transferred into APEX to simulate tree yield production at the watershed scale. APEX results on plant growth simulation and biomass yield compared well with measured values and to the ALMANAC results. Although APEX could not be tested against the observed flow, the trend in simulated monthly flow followed the trend in observed rainfall. This indicates that APEX can be used to simulate tree yield response to different climate conditions. However, in future studies, an extended data collection for measured data, such as flow and soil nutrient, from the study area is needed to quantify errors in simulated values (e.g. biomass, runoff) in APEX. The calibrated APEX model can be used for further studies on tree growth–climate interactions and land use and wetland management for larger region. According to our modeling results, APEX reasonably estimates biomass accumulation of black willow and green ash biomass in a wetland environment.

In this study, plant parameters for black willow and green ash were created based on detailed morphological investigations, and the parameter accuracy was validated by using two models at different scales. Since there are few publications on developing simulation models for black willow and green ash, some main parameters, such as leaf area index, extinction coefficient, and growth curve, developed in this study can be used as reference values in other modeling studies. The accurate plant parameters are essential components for yield prediction through plant growth models. The accurate biomass prediction of wetland trees under various hydro-climatologic conditions can be critical information for wetland mangers to monitor wetland health conditions. Moreover, the well-developed modeling system can provide improved monitoring of changes in wetland conditions (e.g. changes in hydrologic and biological conditions) associated with future climate change.

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