12-2007

Predicting the growth of deciduous tree species in response to water stress: FVS-BGC model parameterization, application and evaluation

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PREDICTING THE GROWTH OF DECIDUOUS TREE SPECIES IN RESPONSE TO WATER STRESS: FVS-BGC MODEL PARAMETERIZTION, APPLICATION AND EVALUATION

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Forest Resources

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by
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December 2007

Accepted by:
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ABSTRACT

A hybrid model (FVS-BGC) that couples the process-model STAND-BGC to the empirically based forest vegetation simulator (FVS) was parameterized with comprehensive ecophysiological, site, and silvicultural data collected on *Acer rubrum* L. (*A. rubrum*), *Paulownia elongata* (*P. elongata*), *Quercus nuttallii* (*Q. nuttallii*), and *Quercus phellos* (*Q. phellos*) in 2006. A series of simulations provided of estimates species-specific carbon gain, growth, and yield under well-watered and water-stressed conditions. Simulations on a species-specific basis allowed assessment of drought effects on stand production and the ability of FVS-BGC to predict on a deciduous species basis. Under well watered conditions, FVS-BGC was able to predict *P. elongata*, *Q. nuttallii* and *Q. phellos* height and caliper. Water deficit conditions were characterized by different maximum volumetric water content parameterization in the model. Under water stress, FVS-BGC accurately predicted height and caliper in *Q. nuttallii* and *Q. phellos*. For carbon sequestration, FVS-BGC predictions agreed with measured values on all study species under well watered and water stressed conditions. Thus, this study demonstrates that tree-to-tree variation and different water stress conditions can be characterized in FVS-BGC for accurate predictions of species-specific annual carbon gain, growth, and yield.

ACKNOWLEDGMENTS

We thank G. Wang for earlier reviews of this manuscript and J. Toler for statistical advice. We are grateful to Parsons Nursery Inc. for the donation of plant material. This work was funded in part by both the USDA Forest Service and the State of South Carolina Research and Experiment Station.

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INTRODUCTION

Traditionally, models of forest growth have been classified into two distinct categories: (1) empirical/statistical models are derived from observed relationships in large mensurational data sets that span management practices and site conditions; and (2) process-based models are founded on the explicit biochemical and biophysical mechanisms underlying tree growth. Each model type has its own advantages and shortcomings, a full description of which is beyond the scope of this article. Within the last decade, however, forest managers and tree physiologists have attempted to bridge the gap between the two tree growth modeling approaches (see, Valentine & Makela 2005 for a review) to create hybrid models that combine both modeling techniques (e.g., Baldwin et al. 1998; Milner et al. 2003; Valentine & Makela 2005).

Hundreds of empirical and process based models have been developed to simulate tree growth (see, e.g., Constable & Friend 2000; Le Roux et al. 2001; Kramer et al. 2002; Hanson et al. 2004 for model intercomparisons and assessment). However, a "standard model" with an accepted set of assumptions and trade-offs between practicality and detail has yet to be adopted (Valentine & Makela 2005). In this study, we have chosen to develop a hybrid model that couples the empirical model 'Forest Vegetation Simulator' (FVS) (Wykoff et al. 1982; Dixon, 2002) to a version of the process model 'FOREST-BGC' (Running & Coughlan 1988; Running & Gower 1991; White et al. 2000). 'STAND-BGC' (Milner and Coble 1995) is a derivative of the stand-level physiological model FOREST-BGC, where STAND-BGC is an individual-entity, distance-independent model. Independently, each of these models is free to download via the World Wide

Web, and extensively documented FVS – www.fs.fed.us/fmsc/fvs/; FOREST-BGC - daacsti.ornl.gov/).

Recently, Milner et al. (2003) linked FVS to STAND-BGC and named the resultant model 'FVS-BGC'. In the coupled hybrid model, STAND-BGC is initialized from standard forest inventory records and before tree information is passed from FVS to STAND-BGC, silvicultural treatments may be simulated with FVS. The linkage of the two models thus provides the user with the benefits of both model types, where the process and empirical elements are represented at the same hierarchical level – the linkage details are described in Milner et al. (2003). As a hybrid model that incorporates both mechanistic and empirical attributes, FVS-BGC can theoretically be used to assess the effects of climate change or alternative management practices on vegetation growth in forest ecosystems. In this study, we parameterize and apply FVS-BGC to estimate tree growth characteristics under well-watered and water-stressed conditions on deciduous tree species. By so doing, we expand the use of FVS-BGC to deciduous trees, for which FVS-BGC has not yet been parameterized or validated. We parameterize and develop a hybrid model responsive to water deficits in deciduous trees with the intent of predicting their species specific response to environmental stress (i.e.: drought). Specifically, the objectives of this study were to 1) parameterize and validate the hybrid model FVS-BGC on four common southeastern USA deciduous tree species: *Acer rubrum* L. (*A. rubrum*), *Paulownia elongata* (*P. elongata*), *Quercus phellos* (*Q. phellos*), and *Quercus nuttallii* (*Q. nuttallii*), and 2) to assess its prediction against independent measurements of growth under well watered and water deficit conditions.

MATERIALS AND METHODS

Plant material

In May of 2006, South Carolina grown *A. rubrum*, *P. elongata*, *Q. phellos* and *Q. nuttallii* were shipped to Clemson University and transferred to an outdoor gravel pad of open terrain. Upon arrival, seedlings were transplanted into 57 L plastic containers containing a Fafard 2B substrate (Fafard Inc., Anderson, SC USA) that incorporated 9 Kg m^{-3} of Osmocote Pro® 19N-5P-8K (Scotts Company, Marysville, OH USA). All pots were watered to saturation, permitted to drain for 24 h and thereafter irrigated three times daily.

Nursery experiment

Prior to experimentation, containers were covered with clear plastic sheeting to prevent precipitation recharge and the exterior of each container was wrapped with aluminum foil to reduce the radiation load. The plastic did not impede soil or root system gas exchange due to a loose seal at the stem interface and numerous air exchange openings on the side and bottom of the containers (Bauerle et al. 2002). All trees were evenly spaced on a 1.5 * 1.5 m grid and irrigated via pressure compensating micro emitters (M.L. Irrigation, Laurens, SC USA). Bulk soil volumetric water content (VWC) was recorded every 48 h at two locations in the soil profile of each container using a Theta Probe type ML2 (Delta-T Devices, Cambridge, England) at 10 cm and 20 cm below the substrate surface. Readings were taken by inserting the probe into predrilled holes at two depths, and taking the average of the readings to estimate bulk VWC for each container (Bauerle et al. 2003). In all, 40 trees of each species were randomly distributed within the plot and VWC was monitored on each individual tree. Meteorological data (air temperature, humidity, wind speed, wind direction, and direct and diffuse solar radiation) were collected at a height of 3 m using a Campbell Scientific Weather Station located on the north side immediately adjacent to the experimental plot and within 0.25 m of canopy level.

Drought treatment

After monitoring trees under well watered conditions for 45 d, a randomized drought treatment was applied. Twenty replicate trees per species were randomly assigned to a drought treatment and 20 trees to a well watered treatment. The water stress treatment trees were outfitted with 360^o micro-emitters that emit 70% less water than well-watered control emitters. Irrigation times and duration were adjusted per tree species and treatment to insure that the VWC in the drought treatment was < 0.3 $m^3 \bullet m^3$ and the well watered treatment VWC remained > 0.3 $m^3 \bullet m^3$ (a predetermined value shown to not induce water stress).

Seasonal gas exchange and growth measurements

At day zero of the experiment (Julian day 138) and at approximately three week intervals thereafter, tree height, crown width, and stem caliper (10 cm above the first lateral root) were measured on all trees in the plot. In addition, leaf transpiration measurements were randomly taken on 3 trees per species under well watered conditions. Transpiration and photosynthesis were measured on the first fully expanded leaf using a portable steady state gas-exchange system (CIRAS-I, PP System, Haverhill, MA) equipped with a light and temperature controlled cuvette (Model PLC5 (B); PP Systems). Measurements were taken on the first fully expanded and undamaged leaf form from 09:00 to 12:30 h. The leaves were tagged and measurements were taken in random order to compensate for any effects caused by time of sampling. All leaves measured were naturally south oriented and fully exposed to incoming radiation to reduce environmental interactions. Leaf temperature was controlled at 25 ^{o}C; Photosynthetic Photon Flux Density (PPFD) was maintained at 1000 umol m^{-2} s^{-1} with the cuvette light source; and vapor pressure deficit in the cuvette was kept at 1.3 ± 0.4 kPa. Measurements were recorded after reaching steady state.

Destructive harvest

Beginning at day zero and at three week intervals thereafter, all trees in the experimental plot were measured for height and caliper and six trees of each species and treatment were randomly selected and destructively harvested. The trees were separated into leaf, stem, coarse (root diameter >3 mm) and fine roots(root diameter: 0-3mm), and immediately measured for respiration on an organ basis with an SRC-1 chamber (PP System, Haverhill, MA) under temperature controlled (25 ^{o}C) laboratory conditions. Leaf samples were stored in a walk in cooler and leaf area was measured with an LI-3100 leaf area meter (Li-Cor Inc., Lincoln, NE) within four days of harvest. All tree organs were dried at 70 ^{o}C for two weeks and weighed to the nearest 0.1 g.

Model parameterization and application

A full description of FVS-BGC is provided in detail by Milner et al. (2003), where STAND-BGC functions as an extension of FVS. The STAND-BGC component of the hybrid model is a climate-driven, carbon and water balance model that operates at a daily resolution for growth processes and at an annual resolution for carbon allocation (Milner and Coble 1995). FVS, as a single entity, has been extensively tested and used in the United States on coniferous species (Dixon 2002). The FVS model is, however, coupled to STAND-BGC in our study and periodically updated by STAND-BGC calculations to mechanistically predict forest stand growth dynamics on a mechanistic basis (Milner et al. 2003). Moreover, the modeled trees in FVS-BGC were initialized by the FVS tree list at the beginning of the simulation, updated by STAND-BGC on a daily cycle, and updated by FVS at the beginning of each subsequent annual cycle. The linkage between these two models into a coupled hybrid model has been described in detail elsewhere (McMahan et al. 2002, Milner et al. 2003). We invoked FVS-BGC by a set of keywords, where three external files must be present to run the extension: a daily climate file: MTCLIM (Hungerford et al. 1989), a site file supplying information on soil depth and texture (Table 3 & Table 4), and a BETA file supplying the physiological and control parameters (Table 1 & Table 2). MTCLIM is a climate simulator which extrapolates base station weather data to other sites, thus "correcting" the base station data for the elevation, slope, and aspect of the site for which weather data are desired. The resulting climate output file yields a more realistic representation of site weather than would be represented by the base station. FVS-BGC uses the MTCLIM file format for weather data as described in McMahan et al. (2002). Since we collected our own on site weather data, we were able to directly input our meteorological data into MTCLIM, where it only functioned as a weather data input file in this study.

The parameter values in the BETA tables are all measured from gas exchange or calculated from organ dry weights. As FVS-BGC simulates tree growth, each stand and each tree in the tree list were simulated on both a daily and annual basis. It is important to note that the model calculates and predicts daily whole tree height increment and dimension increment on a per tree basis, which allowed us to directly compare against our measured values. However, as documented by McMahan et al. (2002), the FVS-BGC model will only function on trees with a minimum height of 1.37 m. Therefore, our modeling versus measured results are only presented after a species and treatment reached the threshold height, which was temporally variable among species and treatments (Figures 1-3). Although the model calculates yearly increments of carbon allocation, our comparison only included growth after the minimum height was reached.

In summary, FVS-BGC predicts growth, where specific FVS-BGC output was as introduced: (1) tabular presentation of the annual and daily predictions of stand- and tree-level carbon and water balance, and annual tree-level growth increments, (2) a mortality table showing when specific trees died, along with selected attributes, and (3) the daily site water balance for each year of the simulation. In this study, the daily growth increments and daily carbon gain were the main focus of measurement versus comparison.

Statistical analysis

A paired sample t-test for each measured tree height, caliper and carbon at each harvest time was used to test the null hypothesis that the average of the differences between measured and modeled paired observations is zero with the a=0.05.

RESULTS

FVS-BGC predicts both annual and daily tree growth and carbon gain, but we focused on the within season daily tree height growth, caliper expansion and carbon sequestration increase across both destructive and non destructive measurements throughout the seasons.

Figure 1 illustrates the prediction in height versus measured values among the four study species under both well-watered and water-stressed conditions. In general, FVS-BGC height predictions were similar to measured values (Figure 1). Under well watered conditions, we found the most significant difference between the model estimate and measured values to occur within the species *Q. phellos,* where height measurements were significantly different (P-value = 0.0024). In contrast, the other three species in this study had similar measured versus modeled values (see Figure 1). The height mean measured versus model differences for species other than *Q. phellos* ranged from 0.0295 to 0.0869 m (Table 5). Specifically, under well watered conditions, mean differences between the estimates and measured values ranged from 0.0076 cm to 0.0838 cm respectively (Table 5). Table 5 shows the model's mean predictions in comparison to measured values under well watered and water stress conditions respectively. It should be noted that the wide physiological variation in species response parameters among the four deciduous trees in this study allowed us to test the models ability to predict across a substantial difference in species intrinsic response. Under the water stressed condition, however, there was a significant difference (P-value = 0.0042) between the predicted *A*.

rubrum modeled versus measured height (Table 6). We found no significant difference for height for *Q. nattalli* and *Q. phellos*, with the mean difference between the modeled data and field measured data being as small as 0.0082 for *Q. phellos* (Table 6).

Figure 2, illustrates the caliper comparison between modeled versus measured values. Under well watered conditions, we found the most significant difference between the model estimate and measured values to occur within the species *Q. phellos,* where caliper measurements were significantly different (P-value = 0.0005). Moreover, the caliper comparison followed this same pattern, where *Q. puellos* estimates were not as accurate as those for *A. rubrum*, *P. elongata, and Q. nuttallii*. (Figure 2). And there was a significant difference for the *A. rubrum* (P-value 0.0294) and *P. elongata* (P-value 0.0189) predicted versus measured mean (Table 6). We found no significant difference for caliper for *Q. nattalli* and *Q. phellos*, with the mean difference between the modeled data and field measured data being as small as 0.0076 for *Q. nattalli* caliper (Table 6).

The carbon comparison resulted in no significant differences between measured and predicted values among all four study species and surprisingly, *Q. phellos* had the smallest divergence from model estimates (0.1818 Kg; Table 7) under well watered conditions and the second least under water stress (Table 7). For carbon assessment under the drought condition, we found no significant difference between modeled estimates and field measured data for all four species in this study (see table 7).

In summary, there were altogether no significant differences under well watered conditions for three species: *P. elongata*, *Q. nattallii* and *Q. phellos* height and caliper measured versus FVS-BGC model predictions. For water-stress condition, on the other hand, FVS-BGC accurately predicted both height and caliper in two of the four study species, namely *Q. nattallii* and *Q. phellos*. For carbon sequestration, on the other hand, FVS-BGC predictions were again not significantly different than measured values on all study species under either well watered or water stressed conditions.

DISCUSSION

The last two decades have seen a proliferation of process-based forest growth models and there are many reviews that are available (Agren, 1981; Dale et al., 1985; Ford and Bassow, 1989; Kimmins et al., 1990; Landsberg et al., 1991; Titak and van Grinsven, 1995). The prevalent perception is that process-based models are suited only to research and that silvicultural management questions are better suited to descriptive empirical models (Battaglia and Sands, 1998). That is, empirical models have been constructed from mensurational data and successfully applied to estimate tree height, diameter at breast height (DBH), and total volume for identical and/or similar conditions (Zhou et al. 2005). Process-based models, on the other hand, are not as straightforward since the data base required for model parameterization is usually not available to most forest managers and the estimates are not in straightforward bole increment growth. Therefore, they have primarily been used as a research tool to estimate carbon and water flux in response to climate change.

In the last decade several factors have lead to the coupling of process and empirical models, with tree physiologists and forest managers often working closely together to bridge the gap in an attempt to understand forest climate interactions. The cooperative affect has been spurred by changing environmental conditions that conflict with the need to maximize yield, while simultaneously minimizing the risk of long-term ecologically sustainable forest management practices (Dewar and Mcmurtrie, 1996). Moreover, predicting the influence of abiotic stress (e.g., Weinstein et al., 1991, Bauerle et al., 2007) and climate change impacts (e.g., Friend and Schugart, 1993; Kirschbaum et al., 1994) on forest growth and survivorship are two key determinants of forest sustainability that can be addresses by models that possess both empirical and mechanistic attributes.

The model we use in this study, FVS-BGC, is a hybrid of both empirical and process-based approaches. As such, it can provide a dynamic means to analyze the impact of various climate scenarios on forest growth and yield (Milner et al. 2003). To be applicable, however, model validation must be done on the species for which one expects to forecast (Bauerle et al. 2007). Even though the structure, size, and longevity of trees present a formidable challenge that can make model validation an arduous task, we were able to characterize a physiologically diverse set of deciduous tree species and effectively test the FVS-BGC models predictive abilities within uniform environmental conditions. Due to the fact that FVS-BGC has characteristics that are indicative to both forest managers and academically oriented researchers alike, we sought to decipher its limitations and potentially broaden its applicability both spatially and temporally. In so doing, we found that the integration of FVS and STAND-BGC into a linked hybrid is dynamic enough to capture the influence of environment on stand productivity.

The overall structure of forest process models consist of spatial and temporal resolution, as well as complexity and generality. An increase in model resolution is often accompanied by an increase in model complexity; however, complexity is not always associated with accuracy or the ability to generalize a response (Battaglia and Sands, 1998). So, process modelers often try to advance the highest resolution with the least complexity, while at the same time, retaining the ability to generalize across forest ecosystems. Even though agreement between predicted and observed output does not necessarily verify the conceptual structure of a particular model (Passioura, 1973), we found the FVS-BGC model capable of predicting the dynamic response of deciduous trees, further supporting the models generality via the transition from coniferous to deciduous tree species. Moreover, the input data for FVS-BGC is grounded in extensive silvicultural and ecophysiological research, so that potential users of the model are not required to establish values for most of the various coefficients (although they are user definable). The output (the carbon and water balance and dimensions and growth increment on a daily and annual time step) is useful to both researchers and forest managers alike. Therefore, the combination of relatively low model complexity, good agreement between measured and estimated values, and broad species applicability make FVS-BGC an effective forest hybrid model.

Soil water deficits are a key controller of net ecosystem productivity in deciduous trees and it has been reported that water availability controls net ecosystem productivity in 64% of all deciduous broadleaf tree growth area (Churkina and Running, 1998). While FVS-BGC has not previously been tested in response to controlled soil water deficits, we examined FVS-BGC under both well watered and water stressed conditions to get an idea of the influence of soil water stress on model estimates. With respect to carbon sequestration estimates, we observed that FVS-BGC is responsive to soil water deficits and the model worked very well on predicting the carbon accumulation in response to soil water limitation in all four study species (*A. rubrum*, P. *elongtata, Q. nuttallii, and Q.*

phellos). However, FVS-BGC estimates of the height and caliper of *A. rubrum* and caliper of *P. elongtata*, were inadequate. One possible explanation for the discrepancy could be due to the adopted stress condition classification. When we change the maximum volumetric water content in the model, we changed the maximum volumetric water content parameter in the model, a drastic response ensues. The resultant response indicates that this parameter plays a substantial role in FVS-BGC model predictions under water limiting conditions. Therefore, we recommend future studies derive a set of species-based maximum volumetric water content parameters.

The objective of this study was to investigate the potential to estimate growth and yield of deciduous trees by parameterizing the process model STAND-BGC and allowing it to modify growth and yield predictions in FVS. To our knowledge, FVS-BGC has never been validated on deciduous tree species. In fact, prior to this study FVS-BGC was used on only eleven species, all of which are conifers. In addition, validation has only occurred in eight western USA FVS variants. We parameterized, applied, and evaluated FVS-BGC's ability to operate on four common deciduous tree species in the southeastern USA. In so doing, our findings show that the hybrid model FVS-BGC can be used to predict height, diameter and carbon increment on the species of *Q. nuttallii* both under well-watered and drought stress conditions. While under the well watered conditions, FVS-BGC can also predict height and diameters for the species *A. rubrum*, *P. elongata* and *Q. phellos*. Under water stressed condition, FVS-BGC was able to predict the diameter, height and carbon increment for *Q. nuttallii* and *Q. phellos*.

CONCLUSION

This study parameterized, applied, and evaluated a hybrid model, FVS-BGC, on southeastern USA deciduous tree species under both well watered and water stressed conditions. The model predicted height and caliper under well water conditions for *A. rubrum, P. elongate* and *Q. nuttallii*. In response to water stress, the model was also capable of predicting both caliper and height of *Q. nuttallii* and *P. elongata*. Accuracy, however, varied on a species-specific basis. For instance, *A. rubrum* predictions were only good under well-watered conditions and FVS-BGC performed poorly on *Q. phellos*. Our results indicate that the model is useful beyond conifers and further model calibration and opportunities for improving deciduous tree prediction accuracy are warranted.

TABLES

Table 1. The physiological parameter values of the four species under well-watered conditions. Values are means developed from field based measurements

Species	*A. rubrum*	*P.elongata*	*Q. phellos*	*Q. nuttallii*
Max. Leaf conductance	0.0040	0.0076	0.0031	0.0033
Stem respiration (μmol m^{-2} s^{-1})	0.0005	0.0015	0.0007	0.0017
Fine root respiration (μmol m^{-2} s^{-1})	0.0008	0.0010	0.0009	0.0042
Max. Photosynthesis rate (μmol m^{-2} s^{-1})	37.0	46.0	44.9	40.7
Optimum photosynthesis temperature (^{o}C)	30.0	30.0	30.0	30.0
LAI	4.0	4.0	1.4	2.0
Max. Ratio of leaf C/ (leaf + fine root) C	0.73	0.40	0.81	0.86
Specific leaf area (m^2/Kg)	13.0	36.0	11.5	11.3

Table 2. The physiological parameter values of the four species under water stress conditions. Values are means developed from field based measurements

Species	A. *rubrum*	*P.elongata*	*Q. phellos*	*Q. nuttalli*
Max. Leaf conductance	0.0040	0.0076	0.0031	0.0033
Stem respiration (μmol m^{-2} s^{-1})	0.0002	0.0004	0.0003	0.0002
Fine root respiration (μmol m^{-2} s^{-1})	0.0003	0.0003	0.0004	0.0009
Max. Photosynthesis rate (μmol m^{-2} s^{-1})	37.0	46.0	44.9	40.7
Optimum photosynthesis temperature (^{o}C)	30.0	30.0	30.0	30.0
LAI	3.4	2.2	1.4	1.5
Max. Ratio of leaf C/ (leaf + fine root) C	0.73	0.40	0.66	0.70
Specific leaf area (m^2/Kg)	14.82	15.92	10.48	13.63

Table 3. Summary of site file parameter values under the well-watered conditions.

Initial soil water content (m^3/ha)	1692.0
Soil depth (m)	0.36
Max volumetric water content (m^3/m^3)	0.0
Initial snowpack (m^3 of H_2O/ha)	0.0
Percent sand (%)	40.0
Percent silt (%)	40.0
Percent clay (%)	20.0

Table 4. Summary of the site file parameter values under water stressed conditions.

Initial soil water content (m^3/ha)	1692.0
Soil depth (m)	0.36
Max volumetric water content (m^3/m^3)	0.14
Initial snowpack (m^3 of H_2Oha)	0.0
Percent sand (%)	40.0
Percent silt (%)	40.0
Percent clay (%)	20.0

Table 5: A paired sample t-test comparison of field measured data versus FVS-BGC model estimates for height (m) and caliper (cm) under well watered conditions (n=20 for the first harvest time, and 17 for the second harvest time, 14 for the third harvest time, etc.)

Height comparison				Caliper comparison			
Species	P-value	Mean Difference	Standard Error	Species	P-value	Mean Difference	Standard Error
A .rubrum	0.0927	0.0295	0.0713	*A .rubrum*	0.4325	0.0152	0.1918
P. elongate	0.1926	0.0869	0.6366	*P. elongata*	0.2714	0.0838	0.2669
Q. nuttallii	0.2792	0.0332	0.5976	*Q. nuttallii*	0.4727	0.0076	0.1582
Q. phellos	0.0024	0.1106	0.5249	*Q. phellos*	0.0005	0.3860	0.2334

Table 6: A paired sample t-test comparison of field measured data versus FVS-BGC model estimates for height (m) and caliper (cm) under water stress conditions (n=20 for the first harvest time, and 17 for the second harvest time, 14 for the third harvest time, etc.)

Height comparison				Caliper comparison			
Species	P-value	Mean Difference	Standard Error	Species	P-value	Mean Difference	Standard Error
A .rubrum	0.0042	0.1139	0.3784	*A .rubrum*	0.0294	0.2565	0.1478
P.elongata	0.4073	0.0070	0.2529	*P.elongata*	0.0189	0.0838	0.2318
Q. nuttallii	0.0940	0.0457	0.4766	*Q.nuttallii*	0.0784	0.0076	0.1942
Q. phellos	0.2958	0.0082	0.1929	*Q. phellos*	0.1636	0.0838	0.1271

Table 7. A paired sample t-test comparison of field measured data versus FVS-BGC model estimates for carbon sequestration under both well watered and water stress conditions (n=3).

Well-watered				Water-stressed			
Species	P-value	Mean Difference	Standard Error	Species	P-value	Mean Difference	Standard Error
A.rubrum	0.1009	0.3210	0.3942	*A.rubrum*	0.2976	0.1100	0.2871
P.elongata	0.1499	0.2157	0.2693	*P.elongata*	0.1252	0.0923	0.0998
Q.nuttallii	0.4018	0.5210	0.3420	*Q.nuttallii*	0.2226	0.1200	0.0547
Q.phellos	0.1654	0.1818	0.2425	*Q.phellos*	0.1026	0.1020	0.0951

FIGURES

Figure 1. Comparison between predicted versus measured height (m) for *A. rubrum, P. elongata, Q. nuttallii,* and *Q. phellos* under well watered and water stressed conditions. The solid line represents field measured data and the dashed line depicts model estimates. Under well watered conditions, solid squares (■) depict measured data, whereas solid circles (●) illustrate model estimates. Under water stress conditions, open squares (□) depict measured data, whereas open circles (○) illustrate model estimates. Error bars represent standard errors.

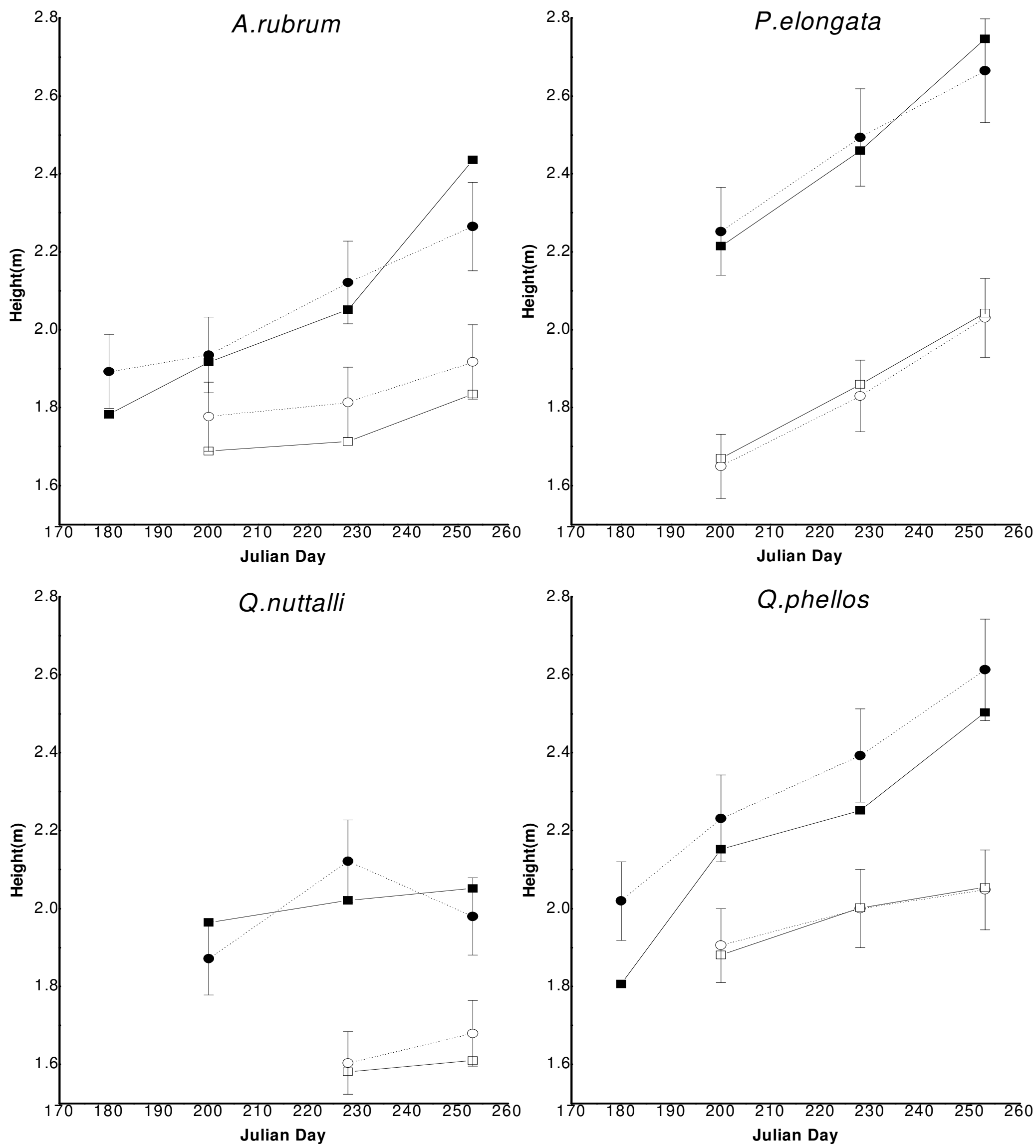


Figure 2. Comparison between predicted versus measured caliper (cm) for *A. rubrum*, *P. elongata*, *Q. nuttallii*, and *Q. phellos* under well watered and water stressed conditions. The solid line represents field measured data and the dashed line depicts model estimates. Under well watered conditions, solid squares (■) depict measured data, whereas solid circles (●) illustrate model estimates. Under water stress conditions, open squares (□) depict measured data, whereas open circles (○) illustrate model estimates. Error bars represent error.

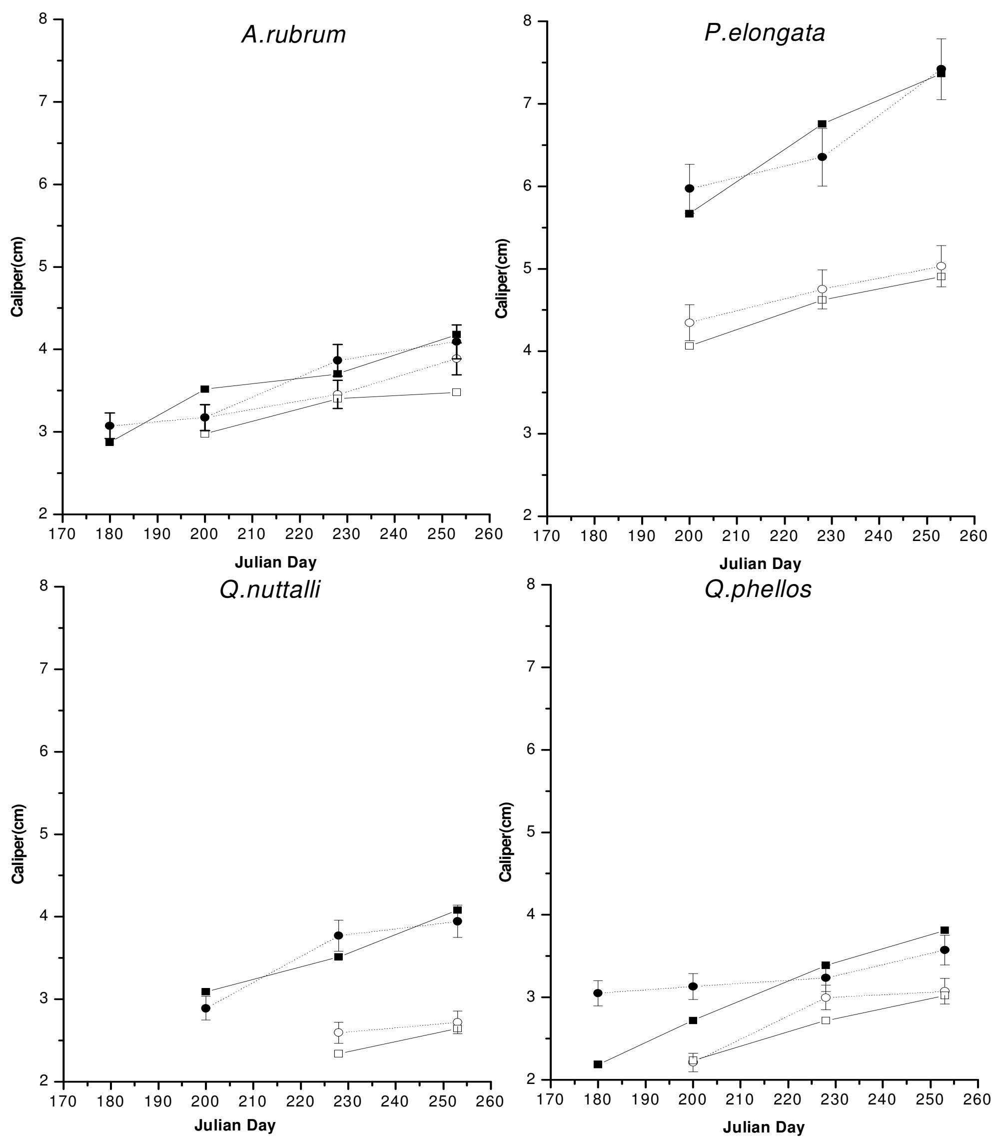
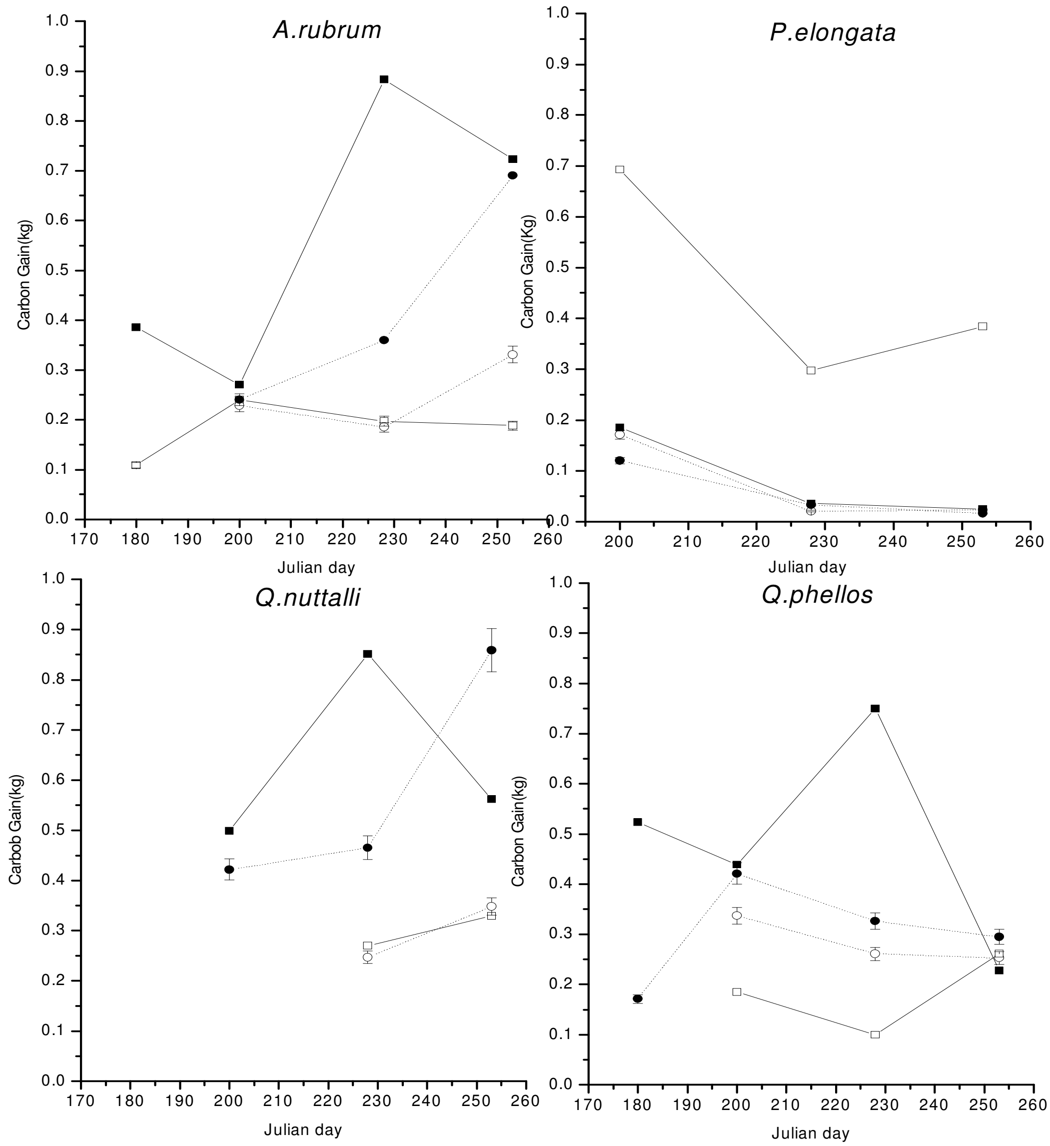


Figure 3. Comparison between predicted versus measured carbon (kg) for *A. rubrum, P. elongata, Q. nuttallii, and Q. phellos* under well watered and water stressed conditions. The solid line represents field measured data and the dashed line depicts model estimates. Under well watered conditions, solid squares (■) depict measured data, whereas solid circles (●) illustrate model estimates. Under water stress conditions, open squares (□) depict measured data, whereas open circles (○) illustrate model estimates. Error bars represent error.



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