International Journal of Agronomy and Agricultural Research (IJAAR)
ISSN: 2223-7054 (Print) 2225-3610 (Online)
http://www.innspub.net
Vol. 16, No. 3, p. 1-11, 2020

INNSPUB

RESEARCH PAPER

OPEN ACCESS

Seasonal growth patterns of *Arundo donax* L. in the United States

Ping Huang*, David I Bransby

Department of Crop, Soil, and Environmental Sciences, Auburn University, Auburn, Alabama, USA

Article published on March 12, 2020

Key words: Giant reed, Cellulosic energy crop, Plant height and aboveground biomass yield, Growth analysis and Gompertz function, Piecewise regression analysis, SAS PROC NLIN procedure

Abstract

Giant reed (*Arundo donax* L.) has been extensively evaluated as a dedicated energy crop for biomass and biofuel production in southern Europe and the United States, with very favorable results. Current agronomic and biologic research on giant reed focuses on management practices, development of new cultivars, and determining differences among existing cultivars. Even though detailed information on the growth patterns of giant reed would assist in development of improved management practices, this information is not available in the United States. Therefore, the objective of this 2-year field study was to describe the seasonal growth patterns of giant reed in Alabama, United States. Changes in both plant height and biomass yield of giant reed with time were well described by a Gompertz function. The fastest growing period occurred at approximately 66 d after initiation of regrowth (mid-May), when the absolute maximum growth rate was of 0.045 m d^{-1} and 0.516mg ha^{-1} d^{-1}. After mid-May, the rate of growth decreased until maturation at approximately 200 d after initiation of regrowth (mid- to late September). The observed maximum average plant height and biomass yield were 5.28 m and 48.56mg ha^{-1}, respectively. Yield decreased following maturation up to 278 d after initiation (early to mid-December) of growth in spring, partly as a result of leaf loss, and was relatively stable thereafter.

* **Corresponding Author:** Ping Huang ✉ pzh0001@auburn.edu

Introduction

Giant reed (*Arundo donax* L.) is a perennial rhizomatous C3 grass native to East Asia which is grown in both grasslands and wetlands, and is especially well adapted to Mediterranean environments (Polunin and Huxley, 1987). Since giant reed is sterile, it is propagated vegetatively, either from stem cuttings or rhizome pieces, or by means of micro-propagation. Due to its easy adaptability to different environment conditions and rapid growth with little or no fertilizer and pesticide inputs, giant reed has been extensively evaluated as a dedicated cellulosic energy crop for biomass and biofuel production in southern Europe and the United States, with very favorable results (Vecchiet *et al*., 1996; Merlo *et al*., 1998; Hidalgo and Fernandez, 2000; Lewandowski *et al*., 2003; Odero *et al*., 2011; Huang *et al*., 2014; Nocentini *et al*., 2018; Monti *et al*., 2019). Most perennial grasses have poor yields during the year of establishment, but giant reed is an exception: a first-year yield of over 16mg ha^{-1} was reported by Angelini *et al*. (2005) at a planting density of 20,000 plants ha^{-1}. Biomass yields are typically 20-40mg ha^{-1} $year^{-1}$ without any fertilization after establishment (Angelini *et al*., 2005; Cosentino *et al*., 2005; Angelini *et al*., 2009). Calorific value of mature giant reed biomass is about 17 $MJkg^{-1}$ (Angelini *et al*., 2005). The average energy input is approximately 2% of the average energy output over a 12-year period (Angelini *et al*., 2009). Unlike most other grasses, giant reed possesses a lignin content of 25%, which is similar to that of wood, and a cellulose content of 42% and a hemicellulose content of 19%, making it a desirable cellulosic energy crop for both solid and liquid biofuels production (Faix *et al*., 1989; Scordia *et al*., 2012; Lemons *et al*., 2015). Giant reed can also help mitigate carbon dioxide (CO_2) emissions from fossil fuels because rhizomes sequester carbon into the soil. The reported carbon (C) sequestration by giant reed rhizomes was 40-50mg C ha^{-1} over an 11-year period (Huang, 2012), which is 6-8 times higher than that by the roots of switchgrass (*Panicum virgatum* L.) (Ma, 1999), a model cellulosic energy crop selected by the United States Department of Energy (Wright, 2007). Current agronomic and biologic research on giant reed focuses on management practices, development of new cultivars, and determining differences among existing cultivars (Nassi o Di Nasso *et al*., 2010; Nassi o Di Nasso *et al*., 2011; Nassi Nassi o Di Nasso *et al*., 2013; Dragoni *et al*., 2016). Even though detailed information on the growth patterns of giant reed would assist in development of improved management practices, this information is not available in the United States. Therefore, the objective of this study was to describe the seasonal growth patterns of giant reed in Alabama, United States.

Materials and methods

Treatments and experimental design

A small plot experiment was conducted at the E.V. Smith Research Center, Plant Breeding Unit of the Alabama Agricultural Experiment Station near Tallassee, Alabama, United States. The soil test was performed by Auburn University Soil Testing Laboratory (Auburn, Alabama). The soil was a Wickham sandy loam (fine-loam, mixed, semiactive, thermic Typic Hapludult), containing 30$mgkg^{-1}$ P, 67.5$mgkg^{-1}$ K, 300.5$mgkg^{-1}$ Ca, 65$mgkg^{-1}$mg, and pH 6.5. The experimental site was fallow prior to the planting of giant reed. In the spring of 1999, 1-m stem segments of a giant reed accession from California were hand-placed end-to-end in furrows 75cm apart and covered with 5-7.5cm of soil in prepared plots that were 3m wide and 9m long. Plots were fertilized with ammonium nitrate at a rate of 112kg N ha^{-1} in May 2000, but received no fertilizer in subsequent years. Biomass was harvested annually each winter before this study began, and rhizomes had completely filled in the spaces between rows to form a solid stand.

Data collection

Giant reed emerged in mid- and early March in 2010 and 2011, respectively. Biomass was harvested by hand from a 1-m^2 quadrat within each of four plots at approximate 30 d intervals from April 2010 to February 2012, with all material from plots being harvested in late February of each year. Cutting height was 5cm above ground. More harvest date information is presented in Table 2.

In the second growing season, each harvest was conducted on a different area within each plot from the quadrats that had been harvested in the previous season, to avoid any impact of cutting date in the previous season on second season results. All harvested plant material was weighed immediately after harvesting to determine fresh weight in the field by using a hanging scale. Five randomly identified plants from each plot were used for determination of plant height, which was measured from the base of the stem to the collar of the highest leaf. Subsamples taken from the harvested material from each plot at each harvest date were dried at 60°C for 72 h for dry matter determination.

Statistical analysis

Analysis of variance for biomass yield data was performed using SAS v9.2 PROC GLIMMIX procedure (SAS Institute, 2009, Cary, NC). This analysis was conducted by year since harvest dates were slightly different between years. Diagnostic plots were obtained by using the option PLOTS= STUDENTPANEL and were used to evaluate the model assumptions. Harvest date was tested as a fixed effect. The critical *P*-value of 0.05 was used as cutoff for testing the fixed effect, and determination of differences in least-squares means was based on adjusted *P*-value obtained by using the option ADJUST=SIMULATE in the LSMEANS statement.

Scatter diagrams of plant height and biomass yield against time were drawn for each year to help determine the most appropriate function to describe the data. Generalized logistic (Eq. 1), Gompertz (Eq. 2) and logistic functions (Eq. 3) (Sit and Poulin-Costello, 1994) were tested for describing changes in plant height and biomass yield with time in the first part of the year starting in March, because the scatter diagrams suggested a sigmoid-shaped curve during this phase of growth. In the latter part of the year biomass yield decreased steadily with time, so this suggested use of a linear function (Eq. 4).

The Generalized logistic function employed in the analyses was:

$$Y_{ij} = \frac{A}{D+e^{(B-C*X_i)}} + e_{ij} \quad (1)$$

where Y_{ij} is plant height or aboveground biomass yield of *j* th experimental unit in the *i* th recording time, *A* is the product of predicted maximum plant height or biomass yield and *D*, *B* is the product of relative growth rate and time when absolute growth rate is maximum, *C* is the relative growth rate, *D* is near which asymptote maximum growth occurs ($D>1$ near bottom, $D<1$ near top, $D=1$ normal), X_i is the *i* th recording time, day after emergence, and e_{ij} is the residual term for *j* th experimental unit at *i* th recording time.

The Gompertz function employed in the analyses was:

$$Y_{ij} = Ae^{-e^{(B-C*X_i)}} + e_{ij} \quad (2)$$

where Y_{ij}, X_i, *B*, and e_{ij} are as in Eq. 1, *A* is the predicted maximum plant height or biomass yield, and *C* is the relative growth rate at time when absolute growth rate is maximum, and at which growth has reached $e^{-1}*A$.

The logistic function employed in the analyses was:

$$Y_{ij} = \frac{A}{1+e^{(B-C*X_i)}} + e_{ij} \quad (3)$$

where Y_{ij}, X_i, *A*, and e_{ij} are as in Eq. 1, *B* is the product of twice the relative growth rate and time when absolute growth rate is maximum, and *C* is twice the relative growth rate at time when absolute growth rate is maximum.

The linear function employed in the analyses was:

$$Y_{ij} = A_1 + B_1X_i + e_{ij} \quad (4)$$

where Y_{ij}, X_i, and e_{ij} are as in Eq. 1, A_1 is the intercept or constant, and B_1 is the slope of the regression line.

Initial starting parameter estimation and model fitting of generalized logistic, Gompertz, and logistic functions were performed using SAS v9.2 PROC NLIN procedure, and linear function using SAS PROC REG procedure. For biomass yield data, the starting parameters were then used to fit the piecewise regression model with the PROC NLIN procedure in SAS. Specifically, the IF syntax was included to determine when using different model to fit the biomass yield data, and determination of the breakpoint was based on the lease square values in the iteration history (See SAS codes in Supplementary Fig. S1).

Selection of the best fitting function was done based on the mean square error (MSE) rather than the residual sum of squares (RSS), since the MSE also takes into account the number of parameters in the models.

Following determination of the best fitting function, the full model, which has different parameters set for each year, was compared with the reduced model, which has common parameters for both years, via a sum of square reduction *F* test (Eq. 5) (Draper and Smith, 1966) (See SAS codes in Supplementary Fig. S2), in order to determine whether the growth pattern of plant height or biomass yield in the two years can be expressed via a single set of parameters or not. The *t* test was also conducted to compare the estimated coefficients of the best-fitting full models for plant height and biomass yield data between the two years (See SAS codes in Supplementary Fig. S3).

The sum of square reduction *F* test employed in the analyses was:

$$F = \frac{(RSS_R - RSS_F)/D}{MSE_F} \sim F_{\alpha\,(D, RdfF)} \quad (5)$$

where RSS_R is the residual sum of square for reduced model, RSS_F is the residual sum of square for full model, D is the difference in residual degrees of freedom between reduced (R_{dfR}) and full (R_{dfF}) models, MSE_F is the mean square error for full model, and $F_{\alpha\ (D,\ RdfF)}$ is the tabulated value of the F distribution with D and R_{dfF} degrees of freedom for the selected α.

Results and discussion

Precipitation and temperature data are presented in Table 1 and Fig. 1, respectively. Growing season rainfall (March to October) in both years was slightly below the average growing season rainfall from 1990 to 2009. Mean minimum air temperature in mid-winter was -8.8℃ and mean maximum air temperature in mid-summer was 37.5℃.

Table 1. Monthly and growing season (March to October) precipitation 2009-2011.

Year	Precipitation (mm)												
	Month												Growing
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	season
2009											154	276	
2010	152	76	124	32	176	56	128	122	46	31	52	59	716
2011	57	100	139	49	56	57	204	16	124	25			670
Average (1990-2009)	119	120	169	106	85	109	126	103	91	85	115	146	875

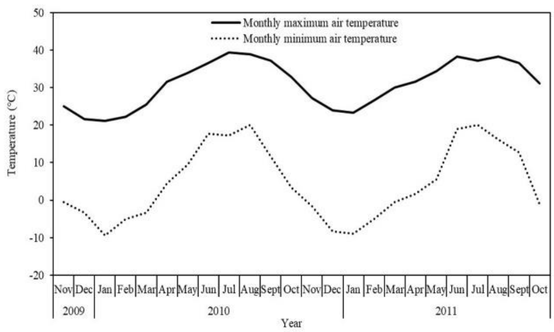

Fig. 1. Monthly maximum and minimum air temperatures from November 2009 to October 2011.

Recognizing that experimental plots received no fertilizer and that giant reed is a C3 species, growth rates and yields recorded for giant reed in this study were remarkably high: maximum yield was 47.11mg ha^{-1} and 48.56mg ha^{-1} in September of 2010 and 2011, respectively. In contrast, yields of unfertilized 'Alamo' switch grass during the same period and at the same location were 11.55 and 6.80mg ha^{-1} in 2010 and 2011, respectively (Huang *et al.*, 2014). Biomass yield for consecutive harvests differed in the first three months of each year, but this difference was reduced or eliminated as maturity was reached and as yield declined in the latter part of the year (Table 2).

A Gompertz function provided the best fit for changes in plant height with time in the two years, probably because the data were distinctly asymmetrical. No difference was detected for the estimated coefficients of the fitted Gompertz function between the two years (Table 3). Result from the sum of square reduction test also suggests that the growth curve of plant height in the two years can be expressed via a single set of parameters (Table 3) (Fig. 2). Therefore, plant height data from the two years were pooled for model fit. The fitted model is as follows:

$y = 5.0918 * e^{-e^{(1.4675-0.0238*x)}}$ $0 < x \leq 202\ d;\ R^2{}_{adj} = 0.9762$ ***

* $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$, model fit.

Table 2. Aboveground biomass yield of giant reed at different harvest times in 2010 and 2011 growing seasons.

Harvest date	Day after emergence	Biomass yield (Mg ha^{-1})	Harvest date	Day after emergence	Biomass yield (Mg ha^{-1})
04/15/2010	36	3.81 ± 1.71^{d}	04/15/2011	44	4.09 ± 0.99^{e}
05/14/2010	65	21.10 ± 1.71^{c}	05/19/2011	78	24.98 ± 0.99^{d}
06/14/2010	96	31.07 ± 1.71^{b}	06/15/2011	105	32.01 ± 0.99^{c}
07/15/2010	127	40.78 ± 3.44^{ab}	07/18/2011	138	41.94 ± 0.99^{b}
08/16/2010	159	44.25 ± 5.94^{ab}	08/15/2011	166	46.80 ± 2.93^{ab}
09/15/2010	189	47.11 ± 5.94^{ab}	09/20/2011	202	48.56 ± 0.99^{a}
10/20/2010	224	42.48 ± 5.84^{ab}	10/21/2011	233	43.62 ± 4.41^{abc}
11/15/2010	250	41.95 ± 1.71^{a}	12/14/2011	287	38.62 ± 2.93^{abc}
12/03/2010	268	38.19 ± 3.44^{ab}	01/25/2012	329	32.74 ± 2.93^{bcd}
01/21/2011	317	34.60 ± 3.44^{ab}			
02/18/2011	345	32.10 ± 3.44^{ab}			

^{abcde} means within each column with different superscripts differ significantly ($p<0.05$).

± numbers after means represent standard errors.

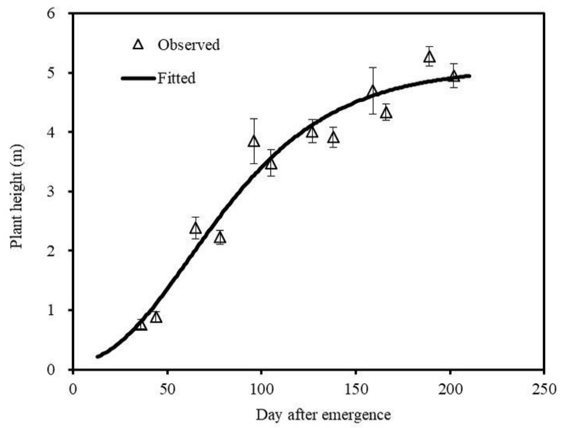

Fig. 2. Changes in plant height of giant reed with time fitted with a Gompertz function in 2010 and 2011 (pooled). Vertical bars represent standard errors.

According to this model, an absolute maximum growth rate of 0.045m d^{-1} or 0.315m week^{-1} occurred 62 d after initiation of growth (mid-May) and at a plant height of 1.89m (Fig. 3). The rate of growth then started to decrease over time until maturity approximately 200d after emergence (mid- to late September).

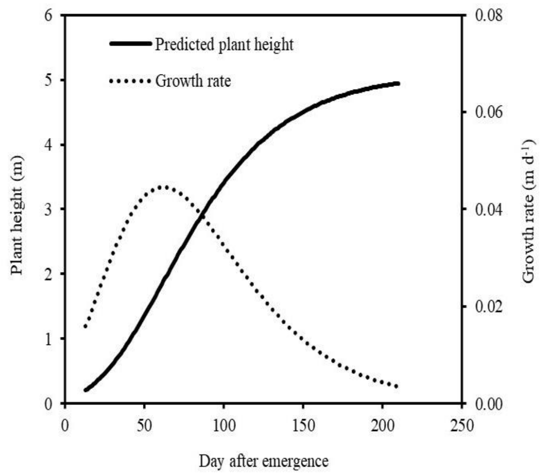

Fig. 3. Predicted plant height and growth rate of giant reed with time in 2010 and 2011 (pooled).

Table 3. Estimated coefficients and standard errors for plant height response to day after emergence fitted with a Gompertz function for giant reed in 2010 and 2011 in Alabama, USA.

Model	Year	Estimated coefficients			p-value for model fit	p-value for sum square reduction F test
		A	B	C		
Full	2010	5.1536 ± 0.1817^{a}	1.5166 ± 0.1761^{a}	0.0266 ± 0.0033^{a}	<0.001	0.1238
	2011	5.0338 ± 0.2202^{a}	1.5032 ± 0.1826^{a}	0.0222 ± 0.0030^{a}		
Reduced	2010 & 2011	5.0918 ± 0.1830	1.4675 ± 0.1571	0.0238 ± 0.0028	<0.001	

Estimated coefficients within each column between the two years with different superscripts differ significantly ($p<0.05$).

± numbers after estimated coefficients represent standard errors.

Other studies have shown that growth of many annuals, such as corn and wheat are better described by a logistical curve than by a Gompertz curve (Katsadonis *et al.*, 1997; Karadavt *et al.*, 2008), indicating that the data were distinctly symmetrical. Unlike these annual crops, but in agreement with the findings of another study on giant reed and miscanthus conducted in central Italy (Nassi o Di Nasso *et al.*, 2011), a Gompertz function provided the best description of changes in biomass yield of giant reed with time until maturity in this study, and thereafter a linear function was used to describe the subsequent decline in yield. Again, no difference was detected for the estimated coefficients of the fitted Gompertz function between the two years (Table 4). Result from the sum of square reduction test also suggests that the growth pattern of biomass yield in the two years can be expressed via a single set of parameters (Table 4) (Fig. 4). Therefore, aboveground biomass yield data from the two years were pooled for model fit. The fitted model is as follows:

$$y = \begin{cases} 47.8698 * e^{-e^{(1.9240-0.0293*x)}} & 0 < x \leq 200\ d; \\ 68.3698 - 0.1069 * x & 200 < x \leq 350\ d. \end{cases} \quad R^2{}_{adj} = 0.9731^{***}$$

* $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$, model fit.

Table 4. Estimated coefficients and standard errors for aboveground biomass yield response to day after emergence fitted with a Gompertz function (pre-maturity) and a linear function (post-maturity) for giant reed in 2010 and 2011 in Alabama, USA.

Model	Year	Estimated coefficients					*p*-value for model fit	*p*-value for sum square reduction *F* test
		Gompertz function			Linear function			
		A	*B*	*C*	A_1	B_1		
Full	2010	47.4623±3.3666[a]	1.8156±0.4162[a]	0.0291±0.0071[a]	63.1714±8.9462[a]	-0.0901±0.0315[a]	<0.001	0.8741
	2011	48.2687±4.8814[a]	2.0833±0.5394[a]	0.0300±0.0087[a]	72.2847±8.5066[a]	-0.1195±0.0318[a]		
Reduced	2010 & 2011	47.8698±2.7425	1.9240±0.3201	0.0293±0.0053	68.3698±5.9512	-0.1069±0.0215	<0.001	

Estimated coefficients within each column between the two years with different superscripts differ significantly (p<0.05).
± numbers after estimated coefficients represent standard errors.

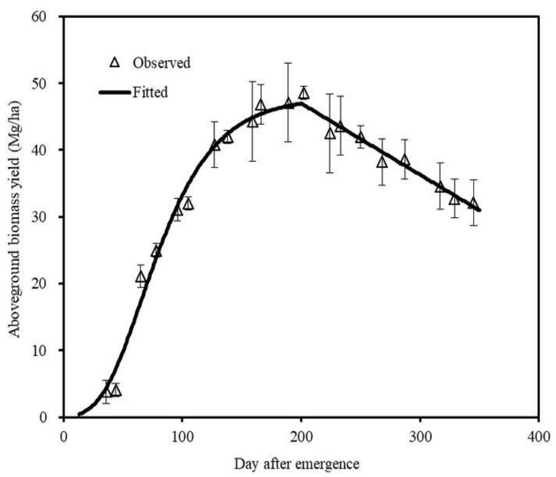

Fig. 4. Changes in aboveground biomass yield of giant reed with time fitted with a Gompertz function (pre-maturity) and a linear function (post-maturity) in 2010 and 2011 (pooled). Vertical bars represent standard errors.

According to this model, inflection point was predicted on day 66 (mid-May) after initiation of growth, when biomass yield was 17.78mg ha^{-1} (Fig. 5). At this inflection point, relative growth rate for biomass yield was 0.0293mg ha^{-1} d^{-1}, which is very close to the findings by Nassi o Di Nasso *et al.* (2011) in central Italy, and absolute maximum growth rate was 0.516mg ha^{-1} d^{-1} or 3.61mg week^{-1}. The rate of growth subsequently decreased over time until maturation at approximately 200 d after emergence (mid- to late September) when a maximum yield of 46.94mg ha^{-1} was reached. After this point yield decreased steadily at a rate of 0.1069mg ha^{-1} d^{-1}, or 0.75mg ha^{-1}week^{-1}, probably due mainly to leaf loss (Fig. 6) and possibly translocation of nutrients from shoots to rhizomes.

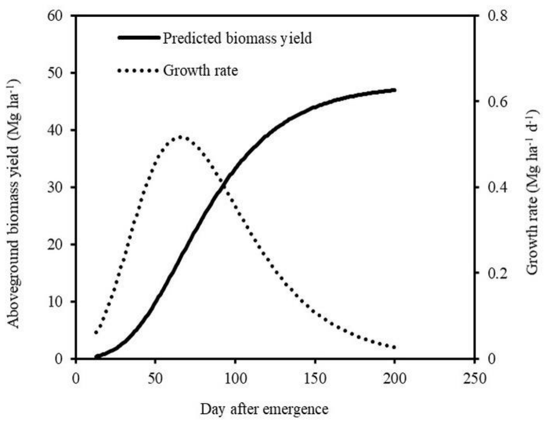

Fig. 5. Predicted aboveground biomass yield and growth rate of giant reed with time in 2010 and 2011 (pooled).

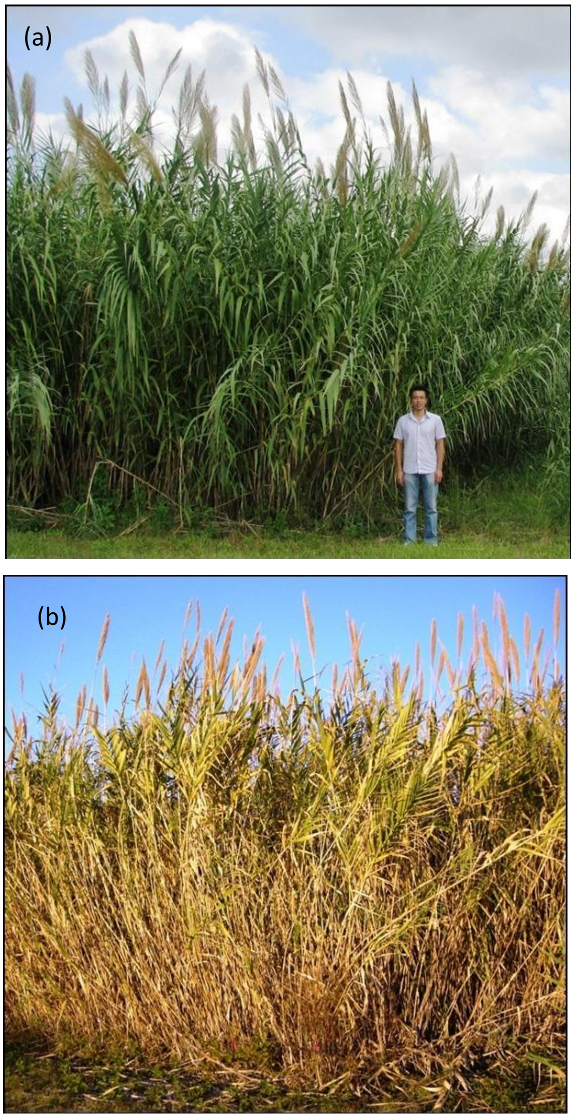

Fig. 6. Pictures of giant reed showing leaf loss in late season: (a) taken on October 8th, 2010; and (b) taken on November 18th, 2010.

The asymmetrical nature of the growth curve of giant reed reflects extremely rapid growth following emergence, and attainment of the maximum growth rate within a third (66 d) of the time it takes to reach maximum yield (200 d). This pattern is probably due to existence of an extensive permanent root system, and stored energy and nutrients in the very large rhizomes of giant reed, which facilitate rapid growth in the early part of the season. Therefore, while results from this study indicate that maximum yield is attained in mid- to late September, annual harvesting at this time might reduce long-term yields. Results from other studies support this view by demonstrating that yield of giant reed is sensitive to time of harvest (Huang, 2012; Nassi o Di Nasso *et al.*, 2010; Dragoni *et al.*, 2016). Consequently, unless additional research indicates otherwise, harvesting giant reed after it reaches dormancy (November or December) will likely ensure the highest sustainable yields, even though this will result in approximately 6 to 9% reduction in short-term yield when compared to harvesting in mid- to late September.

Conclusions

The overall objective of this 2-year field study was to describe the seasonal growth patterns of giant reed in the United States, with the hope to provide information that would assist in development of improved field management practices for giant reed. Results demonstrated that the growth pattern of giant reed in Alabama, United States is distinctly asymmetrical, and a Gompertz function provided the best fit for changes in plant height and aboveground biomass yield with time till maturation in the two years. Maximum growth rate is achieved approximately 60 d after emergence (mid-May), and maximum yield is attained approximately 200 d after emergence (mid- to late September). Yield decreased linearly following maturation up to 278 d after initiation (early to mid-December) of growth in spring, partly as a result of leaf loss, and was relatively stable thereafter. Harvesting giant reed after initiation of dormancy in November or December will probably be the best strategy to ensure sustainable long-term yields, even though this will result in a 6-9% reduction in short term yield compared to harvesting in mid- to late September.

Acknowledgments

The authors express their appreciation to Ms. Suan Sladden and the team at the E.V. Smith Plant Breeding Unit of Auburn University for their help with field work. The authors would also like to thank the reviewers for the insightful comments that helped to improve the paper.

Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this article.

References

Angelini LG, Ceccarini L, Bonari E. 2005. Biomass yield and energy balance of giant reeed (*Arundo donax* L.) cropped in central Italy as related to different management practices. Eur. J. Agron **22,** 375-389.

Angelini LG, Ceccarini L, Nassi o Di Nasso N, Bonari E. 2009. Comparison of *Arundo donax* L. and *Miscanthus×giganteus* in a long-term field experiment in Central Italy: Analysis of productive characteristics and energy balance. Biomass Bioenergy **33,** 635-643.

Cosentino SL, Copani V, D'Agosta GM, Sanzone E, Mantineo M. 2005. First results on evaluation of *Arundo donax* L. clones collected in Southern Italy. Ind. Crops Prod **23(2),** 212-222.

Dragoni F, Nassi o Di Nasso N, Tozzini C, Bonari E, Ragaglini G. 2016. Nutrient concentrations and uptakes in giant reed (*Arundo donax* L.) as affected by harvest time and frequency. Bioenergy Res **9(2),** 671-681.

Drapper NR, Smith H. 1966. Applied Regression Analysis. John Wiley and Sons, New York.

Faix O, Meier D, Beinhof O. 1989. Analysis of lignocellulose and lignines from *Arundo donax* L. and *Miscanthus sinensis* Andress, and hydroliquefaction of Miscanthus. Biomass **18,** 109-126.

Hidalgo M, Fernandez J. 2000. Biomass production of ten populations of giant reed (*Arundo donax* L.) under the environmental conditions of Madrid (Spain). In: Kyritsis S, Beenackers AACM, Helm P, Grassi A, Chiaramonti D. (ed), Biomass for Energy and Industry. Proceeding of the First World Conference, Sevilla, Spain, 5-9 June. James and James, Science Publisher Ltd, London pp 1181-1184.

Huang P, Bransby DI, van Santen E, Sladden S. 2014. Long-term biomass yields of giant reed, mimosa and switchgrass in Alabama. Biofuel Bioprod. Biorefin **8(1),** 59-66.

Huang P. 2012. Evaluation of selected cellulosic energy crops for the Southeastern United States. Dissertation, Auburn University.

Karadavt U, Kayi SA, Palta C, Okur O. 2008. A growth curve application to compare plant heights and dry weights of some wheat varieties. Am Eurasian J. Agric. Environ. Sci **3(6),** 888-892.

Katsadonis N, Evangelidis G, Bladenopoulou S, Simonis A. 1997. Nutrition of corn plant: I. Uptake and distribution of N, P, K in plant part of three corn hybrids. Geot. Sci **3,** 17-24.

Lemons e Silva CF, Schirmer MA, Maeda RN, Barcelos CA, Pereira N. 2015. Potential of giant reed (*Arundo donax* L.) for second generation ethanol production. Electron. J. Biotechnol **18,** 10-15.

Lewandowski I, Scurlock JMO, Lindvall E, Christou M. 2003. The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. Biomass Bioenergy **25,** 335-361.

Ma ZQ. 1999. Carbon sequestration by switchgrass. Dissertation, Auburn University.

Merlo L, Morgana B, Sardo V, La Loggia F. 1998. Experiences with giant reed and perennial C4 grasses in Sicily. In: Kopetz H, Weber T, Pals W, Chartier P, Ferrero GL. (ed), Proceedings of the International Conference on Biomass for Energy and Industry. Würzburg, Germany, 8-11 June. CARMEN, Rimpar Germany pp1006-1008.

Monti A, Zegada-Lizarazu W, Zanetti F, Casler M, Sparks DL. 2019. Nitrogen fertilization management of switchgrass, miscanthus and giant reed: a review. Adv. Agron **153,** 87-119.

Nassi o Di Nasso N, Angelini LG, Bonari E. 2010. Influence of fertilisation and harvest time on fuel quality of giant reed (*Arundo donax* L.) in central Italy. Eur. J. Agron **32(3),** 219-227.

Nassi o Di Nasso N, Roncucci N, Bonari E. 2013. Seasonal dynamics of aboveground and belowground biomass and nutrient accumulation and remobilization in giant reed (*Arundo donax* L.): a three-year study on marginal land. Bioenergy Res **6(2),** 725-736.

Nassi o Di Nasso N, Roncucci N, Triana F, Tozzini C, Bonari E. 2011. Productivity of giant reed (*Arundo donax* L.) and miscanthus (*Miscanthus x giganteus* Greef et Deuter) as energy crops: growth analysis. Ital. J. Agron **6 (e22),** 141-147.

Nocentini A, Field J, Monti A, Paustian K. 2018. Biofuel production and soil GHG emissions after land-use change to switchgrass and giant reed in the U.S. Southeast. Food Energy Secur **7(1),** 1-18. https://doi.org/10.1002/fes3.125

Odero D, Gilbert R, Ferrell J, Helsel Z. 2011. Production of giant reed for biofuel. University of Florida, IFAS Extension, SS-AGR-318.

Polunin O, Huxley A. 1987. Flowers of the Mediterranean. Hogarth Press, London.

Scordia D, Cosentino SL, Lee JW, Jeffries TW. 2012. Bioconversion of giant reed (*Arundo donax* L.) hemicellulose hydrolysate to ethanol by Scheffersomyces stipites CBS6054. Biomass Bioenergy **39,** 296-305.

Sit V, Poulin-Costello M. 1994. Catalogue of curves for curve fitting. Biometrics information handbook series. Handb 4. Victoria, BC, Canada.

Vecchiet M, Jodice R, Schenone G. 1996. Agronomic research on giant reed (*Arundo donax* L.) management system and cultivation of two different provenances. In: Proceedings of the Ninth European Bioenergy Conference, Copenhagen, 24-27 June pp 644-648.

Wright L. 2007. Historical perspective on how and why switchgrass was selected as a 'model' high-potential energy crop. Oak Ridge National Laboratory, ORNL/TM2007/109.

```
ods trace on;
proc nlin data=filename  maxiter=100 method=newton;
    parms a1=47.2752 b1=1.8215 c1=0.0293 bp=189 a2=63.3518 b2=-0.0907
          aa1=48.9310 bb1=2.0033 cc1=0.0291 bp1=202 aa2=71.3984 bb2=-0.1166; /*a1, b1,
          c1, bp (breakpoint), a2, and b2 are pre-estimated parameters for year 1, and aa1, bb1,
          cc1, aa2, and bb2 are pre-estimated parameters for year 2. */;
          e=exp(b1-c1*day1); ee=exp(bb1-cc1*day1);
          e1=exp(-e); ee1=exp(-ee);
          e2=e*e1*a1; ee2=ee*ee1*aa1;
          xpart=e1*a1*(year=2010)+ee1*aa1*(year=2011);
    if (day>bp) or (day>bp1) then do;
          xpart=(a1*exp(-exp(b1-c1*bp))-b2*bp+b2*day)*(year=2010)+(aa1*exp(-exp(bb1-
          cc1*bp))-bb2*bp1+bb2*day1)*(year=2011);
           *(a2+b2*day1)*(year=2010)+(aa2+bb2*day1)*(year=2011);
    end;
    model y=xpart; /* y is aboveground biomass yield. */;
    output out=piecefit  r=residual  p=predicted stdi=stderr student=student;
    ods output  ParameterEstimates=parms ANOVA=anova
run;
ods trace off;
quit;
```

Supplementary Fig. S1. SAS codes for piecewise regression analysis.

```
ods trace on;
proc nlin data=filename  maxiter=100 method=newton;
    parms a1=47.4623 b1=1.8156 c1=0.0291 bp=189 a2=63.1714 b2=-0.0901
        aa1=48.2687 bb1=2.0833 cc1=0.0300 bp1=212 aa2=72.2847 bb2=-0.1195; /*a1, b1, c1, bp
        (breakpoint), a2, and b2 are estimated parameters for year 1, and aa1, bb1, cc1, aa2, and bb2
        are pre-estimated parameters for year 2. */;
        e=exp(b1-c1*day1); ee=exp(bb1-cc1*day1);
        e1=exp(-e); ee1=exp(-ee);
        e2=e*e1*a1; ee2=ee*ee1*aa1;
        xpart=e1*a1*(year=2010)+ee1*aa1*(year=2011);
    if (day>bp) or (day>bp1) then do;
        xpart=(a2+b2*day1)*(year=2010)+(aa2+bb2*day1)*(year=2011);
    end;
    model y=xpart; /* y is aboveground biomass yield. */;
    output out=piecefit  r=residual  p=predicted stdi=stderr student=student;
    ods output  ParameterEstimates=parms ANOVA=anova_full;
run;
ods trace off;
quit;
ods trace on;
proc nlin data=filename  maxiter=100 method=newton;
    parms a1=47.4623 b1=1.8156 c1=0.0291 bp=189 a2=63.1714 b2=-0.0901;
        aa1=a1; bb1=b1; cc1=c1; bp1=bp; aa2=a2 bb2=b2; /*a1, b1, c1, bp (breakpoint), a2, and b2
        are pre-estimated parameters for year 1, and aa1, bb1, cc1, aa2, and bb2 are pre-estimated
        parameters for year 2. */;
        e=exp(b1-c1*day1); ee=exp(bb1-cc1*day1);
        e1=exp(-e); ee1=exp(-ee);
        e2=e*e1*a1; ee2=ee*ee1*aa1;
        xpart=e1*a1*(year=2010)+ee1*aa1*(year=2011);
    if (day>bp) or (day>bp1) then do;
        xpart=(a2+b2*day1)*(year=2010)+(aa2+bb2*day1)*(year=2011);
    end;
    model y=xpart; /* y is aboveground biomass yield. */;
    output out=piecefit  r=residual  p=predicted stdi=stderr student=student;
    ods output  ParameterEstimates=parms ANOVA=anova_reduced;
run;
ods trace off;
quit;
data anova1; set anova_full; ss_full=ss; ms_full=ms; df_full=df;
    drop ss ms df FValue     ProbF;
run;
data anova2; set anova_reduced; ss_reduced=ss; ms_reduced=ms; df_reduced=df;
    drop df ss ms FValue     ProbF;
run;
proc sort data=anova1; by source; run;
proc sort data=anova2; by source; run;
data f_test; merge anova1 anova2; by source;
    if source="Error"; df_numerator=df_reduced-df_full; df_denominator=df_full;
    F=(ss_reduced-ss_full)/df_numerator/ms_full;
    call symput('F', F);
run;
data P_value; prob=1-probf(0.3600, 5, 70); run;
```

Supplementary Fig. S2. SAS codes for sum of square reduction test.

```
ods trace on;
proc nlin data=filename  maxiter=100 method=newton outest=cov;
     parms a1=47.4623 b1=1.8156 c1=0.0291 bp=189 a2=63.1714 b2=-0.0901
           aa1=48.2687 bb1=2.0833 cc1=0.0300 bp1=212 aa2=72.2847 bb2=-0.1195; /*a1, b1, c1, bp
           (breakpoint), a2, and b2 are estimated parameters for year 1, and aa1, bb1, cc1, aa2, and bb2
           are pre-estimated parameters for year 2. */;
           e=exp(b1-c1*day1); ee=exp(bb1-cc1*day1);
           e1=exp(-e); ee1=exp(-ee);
           e2=e*e1*a1; ee2=ee*ee1*aa1;
           xpart=e1*a1*(year=2010)+ee1*aa1*(year=2011);
     if (day>bp) or (day>bp1) then do;
           xpart=(a2+b2*day1)*(year=2010)+(aa2+bb2*day1)*(year=2011);
     end;
     model y=xpart; /* y is aboveground biomass yield. */;
     ods output  ParameterEstimates=p_estimate;
run;
ods trace off;
quit;
data cov1; set cov (where=(_type_='COVB'));
      col1=a1;col2=b1;col3=c1; col4=a2;col5=b2;col6=aa1;col7=bb1;col8=cc1;col9=aa2;col10=bb2;
      row=_n_; parm=1;keep parm row col1 col2 col3 col4 col5 col6 col7 col8 col9 col10;
run;
ods trace on;
proc glimmix data=p_estimate order=data;
     class parameter;
     model estimate=parameter/ noint df=70 s;
     random _residual_ / type=lin(1) ldata=cov1 v;
     parms (1) / noiter pdata=p_estimate;
     lsmeans parameter /cl;
     lsmestimate parameter
         'a1 vs aa1' 1 0 0 0 0 -1 0 0 0 0,
         'b1 vs bb1' 0 1 0 0 0 0 -1 0 0 0,
         'c1 vs cc1' 0 0 1 0 0 0 0 -1 0 0,
         'a2 vs aa2' 0 0 0 1 0 0 0 0 -1 0,
         'b2 vs bb2' 0 0 0 0 1 0 0 0 0 -1/
         adjust=bon stepdown ftest (label='Homogeneity');
    ods output  LSMeans=lsmeans LSMEstimates=lsestimate LSMFTest=HomoFtest;
run;
ods trace off;
quit;
```

Supplementary Fig. S3. SAS codes for estimated coefficients of the full model between the two years.