Potential for Using Sunn Hemp as a Source of Biomass and Nitrogen for the Piedmont and Coastal Plain Regions of the Southeastern USA

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ABSTRACT

The tropical legume sunn hemp (*Crotalaria juncea* L.) could be a valuable green manure/cover crop for vegetable producers in the southeastern USA because of its rapid growth and large N_2 fixing ability. Planting and termination date effects on biomass and N accumulation are relatively unknown for the region, but would help producers manage sunn hemp between summer and winter cash crops. We determined sunn hemp biomass and N content at 30, 60, 90, and 120 days after planting (DAP) for four planting dates (mid-April to mid-July) at a Piedmont and a Coastal Plain location in Georgia. Maximum biomass at a given DAP was produced from May and June plantings in the Piedmont and from April and May plantings in the Coastal Plains. Maximum biomass and N ranged from 8.9 to 13.0 Mg ha^{-1} and 135 to 285 kg ha^{-1}, respectively. An equation for estimating sunn hemp biomass as a linear function of cumulative degree days (CDD) and cumulative solar radiation (CSR) was verified with independent data from Alabama, Florida, and Virginia. A similar equation for estimating N content as a quadratic function of CSR was not as accurate but still might be useful. Sunn hemp can fit well into short-rotation sustainable vegetable production systems in the Southeast, and these equations can be used by producers to make reliable estimates of sunn hemp biomass production.

Cover crops are useful for protecting soil from wind and water erosion but are also used for weed suppression, providing habitat for beneficial insects, and to help improve soil organic matter levels (Phatak et al., 2002). Legume cover crops, due to their ability to fix N_2, are especially beneficial for improving soil productivity where inorganic N inputs are limited. In the southeastern USA, the predominant cover crops are winter annuals; however, many vegetable producers may use both summer and winter cover crops as part of a rotation with cash crops. Creamer and Baldwin (2000) found that several warm-season legumes could easily be grown successfully as cover crops to provide both biomass and N during the period between summer and winter cash crop. Tropical legumes may be well suited for this role as summer cover crops since they can produce 3 to 9 Mg dry matter ha^{-1} in 50 to 60 d during the summer (Yadvinder et al., 1992).

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Sunn hemp is a tropical legume that has been used for soil improvement or green manuring in the tropics (Duke, 1981; Cook and White, 1996). Recent studies in the Southeast have focused on its use as a green manure/cover crop following corn (*Zea mays* L.) (Mansoer et al., 1997; Balkcom and Reeves, 2005; Cherr et al., 2006). Due to its rapid growth, large biomass production, and palatability to livestock, 'Tropic Sun' was introduced as a potential green manure crop to the mainland USA from Hawaii (Rotar and Joy, 1983). The crop is easily winter killed but can produce significant amounts of biomass during the fall (until frost). The biomass decomposes slowly enough to provide good cover and some supplemental N for a spring planted crop (Mansoer et al., 1997; Balkcom and Reeves, 2005; Cherr et al., 2006). When planted in Alabama as a late summer cover crop following corn, Tropic Sun produced 1.2 to 3.5 Mg ha^{-1} of biomass 42 DAP and 5.6 Mg ha^{-1} biomass and 134 kg N ha^{-1} 63 to 84 DAP (first frost) (Mansoer et al., 1997). Similar results were reported from Florida where sunn hemp produced >8 Mg ha^{-1} biomass and ≈150 kg N ha^{-1} when grown for 12 wk in the summer (Cherr et al., 2006). In addition to providing green manure and N benefits, sunn hemp has also been reported to suppress populations of plant parasitic nematodes including root-knot (*Meloidogyne* spp.), soybean cyst (*Heterodera glycines* Ichinohe), and reniform (*Rotylenchulus reniformis* Linford and Oliveira) (Wang et al., 2002).

Information about planting dates and biomass production of sunn hemp when grown at various times during the summer is limited for the Southeast (Bhardwaj et al., 2005). Work from other areas indicates that plantings that coincide with adequate soil moisture and frost-free, warm-weather conditions provide the most rapid seedling emergence and highest yields (Kundu, 1964; White and Haun, 1965). White and Haun (1965) found that a 2-wk delay in planting in Kansas reduced stalk yield 40% during 1 yr, while no influence of a delay was observed in a second year. Differences between years may have been water-stress related. Kundu (1964) reported that in India, greatest production was obtained for plantings that made optimal use of rainy season moisture. Cook et al. (1998) saw a significant decline in yield in the Lower Rio Grande Valley of Texas, USA, when planting was delayed by 4 wk or longer from late March to mid-April. Bhardwaj et al. (2005) showed significant differences in response to planting date among years for

Abbreviations: CDD, cumulative degree days; CSR, cumulative solar radiation; DAP, days after planting; EVS, E.V. Smith Research Center, Alabama; MNV, Monroeville Research Site, Alabama; UFL, Citra Research Center, University of Florida; VSU, Randolph Research Farm, Virginia.

sunn hemp grown in Virginia. Lower yields in these studies could have been due to a combination of both moisture availability and effects of daylength on physiological development (vegetative/reproductive stage triggers). Most of the cultivars of sunn hemp studied had a short-day flowering response (White and Haun 1965); therefore, the delays in planting could have shortened the growing season, resulting in lower stalk yields.

In addition to information about optimum planting dates, producers need an easy way to estimate the potential biomass and total N to expect from sunn hemp when used as a cover crop in various rotations. This would be especially useful to vegetable producers who might want to plant sunn hemp between summer and winter cash crops. Our objectives therefore were (i) to determine the influence of planting date on the accumulation of biomass and N by sunn hemp grown in two physiographic regions of the southeastern USA, and (ii) to develop equations based on climatic parameters that producers in the region could use as decision aids to estimate biomass and N production of sunn hemp.

MATERIALS AND METHODS

Evaluation of Planting Date Effects on Sunn Hemp Biomass and Nitrogen Content

Field studies were conducted in the Piedmont and Coastal Plain regions of Georgia during 2002. The Piedmont location was at the USDA Agricultural Research Service, J. Phil Campbell, Senior, Natural Resource Conservation Center near Watkinsville, GA. The climate is warm-temperate with average daily temperatures ranging from 23.9°C to 26.7°C in the summer (June–August) and from 4.4°C to 7.2°C in the winter (December–February). Mean annual temperature is 17°C. Average frost–free growing season is from 215 to 230 d. Mean annual rainfall is 1200 mm. Mean monthly rainfall ranges from 115 to 140 mm during the winter, and 77 to 86 mm in the fall. The soil at the location is a Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludults) which is a deep, well drained, moderately permeable soil developed in residuum from underlying schist, gneiss, and granite. These soils are highly weathered due to their age and are eroded due to a long period of cropping. The soil profile is generally acidic, and pH decreases with depth.

The Coastal Plain location was at the University of Georgia, Tifton Campus. The region is humid subtropical with an average rainfall of about 1200 mm per year. Average monthly temperatures at Tifton, GA, range from 11°C in January to 27°C in July and August, with a mean annual temperature of 19.2°C. Average frost–free growing season ranges from 240 to 250 d The soil at the location is a Tifton sandy loam (fine-loamy, kaolinitic, thermic Plinthic Kandiudults) which is typical of many Coastal Plain soils being sandy with low water holding capacity and a compacted subsurface layer between 45 and 60 cm that further limits water availability for crop growth.

At both locations sunn hemp was planted on or within 2 d of 15 April, 15 May, 15 June, and 15 July 2002. Seed were planted at 13 kg ha^{-1} on 76-cm-wide rows at Watkinsville and 13 kg ha^{-1} on 91-cm-wide rows in Tifton. Sunn-hemp seed was treated with a commercial cowpea [*Vigna unguiculata* (L.) Walp.] rhizobium inoculant. After each planting, ≈1.3 cm of irrigation was applied within 1 to 2 d. A small amount of starter N (16.8 kg ha^{-1}) was applied next to the row as NH_4NO_3 at each planting. Metolachlor[1] [(2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl) acetamide] (1.6 kg a.i. ha^{-1}) and pendimethalin [N-(1, ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine] (1.0 kg a.i. ha^{-1}) were applied to all areas in Tifton before planting in April. The same herbicides were applied in early May in Watkinsville to the May, June, and July planted areas. Two weeks after the April planting date at Watkinsville, glyphosate [N-phosphonomethyl) glycine] (1.1-kg ai ha^{-1}) was applied between rows due to an abundance of grassy weeds. Additional weed control for the April planting was done by hand weekly until growth of the sunn hemp began to shade out any further weed growth.

Sunn hemp biomass was collected at ≈30, 60, 90, and 120 DAP by cutting plants near the soil surface. In Watkinsville, biomass samples were collected from 0.91 m of two rows per replication (1.8 m total). In Tifton, biomass samples were collected from 1.8 m of one row. The fresh weight of biomass samples was recorded within 1 h after harvest. Subsamples consisting of 10 to 20 whole plants (depending on DAP) were randomly selected, weighed, and placed in an oven at 66°C for at least 72 h to dry. Dry weights of subsamples were recorded and used to estimate total sample dry weights. Dried subsamples were ground to pass a 1.0-mm sieve and then analyzed for C and N on a combustion-type analyzer.

The experimental design at each location was a split block in time, with planting date serving as whole plots and DAP or harvest dates serving as split plots. There were four replications of each planting date. Plots were four rows wide at each location. At Watkinsville plots were 18.3 m long, while at Tifton plots were 30.5 m long. Biomass and N data were analyzed as repeated measures using the MIXED procedure in SAS/STAT software (SAS Institute, 2003). Location, date of planting, and their interaction were considered fixed variables while DAP was treated as a continuous fixed variable. The DAP linear and quadratic effects, along with their interactions with location and date of planting, were included in the model. Replication within location was considered a random variable. Measurements of biomass and N were considered as repeatedly made on the experimental unit (the particular date of planting × replication × location). An initial evaluation for appropriate covariance structure indicated similar results for unstructured and Huynh-Feldt (HF) structures. The HF structure was selected to minimize the number of estimated covariance parameters. Due to a significant interaction among location, date of planting, and DAP linear and quadratic components, evaluations of treatment differences and fitting of regression coefficients were performed within each location. Confidence intervals for the regression coefficients were estimated based on $\alpha = 0.05$.

Development of Equations to Predict Sunn Hemp Growth

Climatic influences on sunn hemp biomass and N accumulation were evaluated using a similar approach as described above, where CDD, CSR, and rainfall were substituted for DAP. Degree days were estimated for each day by averaging the maximum and minimum temperatures (°C) and then subtracting 9.9°C as the base temperature (Qi et al., 1999;

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Cherr et al., 2006). Degree days, total daily solar radiation (MJ m^{-2}), and rainfall (plus irrigation) were summed from planting to a sample date. Weather data (rainfall, air temperature, and daily solar radiation) came from Georgia Automated Environmental Monitoring Network (Hoogenboom, 2007) sites within 1 km of the experimental areas. Best combinations of climatic factors for use as estimators of biomass and N content were determined using the stepwise approach in the SAS/STAT REG procedure.

Testing of Equations Against Published Data

Previously published data from two studies in Alabama, one in Florida, and one in Virginia were used to test the predictive power of our equations. Mansoer et al. (1997) determined total biomass production, N and C accumulation, and chemical composition of sunn hemp growing in dryland conditions during the period extending from corn harvest until the first killing freeze (September–November) on sandy Coastal Plain soils in south Alabama for 2 yr at the E.V. Smith Research Center (EVS) near Shorter, AL, and for 1 yr at the Monroeville Research Site (MNV) near Monroeville, AL. They measured biomass and N content at 21, 42, 63, and 84 DAP in late August or early September and determined N release from over wintered (December–March) sunn hemp residue under no-tillage and conventional tillage during the period when a subsequent summer grain crop would be grown. Balkcom and Reeves (2005) reported biomass and N content of sunn hemp under dryland conditions for two out of 3 yr from a study evaluating influences of sunn hemp on N availability to corn at EVS. Because N applications to corn (four levels) in the spring did not significantly influence sunn hemp biomass the following fall, the four N levels were considered independent values in evaluating our prediction equations (n = 8). Cherr et al. (2006) evaluated biomass and N content of sunn hemp planted as a green manure crop for sweet corn at Citra, FL, near the University of Florida (UFL). Sunn hemp was planted on 7 Aug. 2001 and 19 July 2002 and was killed with a herbicide 30 October both years. Irrigation was applied at germination and thereafter to prevent water stress. Biomass and N were determined at 2-wk intervals following emergence for 12 wk in 2001 and 14 wk in 2002. Data from Week 6 to termination were used in our model evaluations. Bhardwaj et al. (2005) reported biomass accumulation for sunn hemp grown during 1997 and 1998 at the Randolph Experimental Farm of Virginia State University (VSU) near Ettrick, VA. They evaluated the effect of four planting dates (mid-May, early- and mid- June, and early-July) and inoculated versus N fertilized treatments on sunn hemp biomass production. The study was conducted under dryland conditions and growth of sunn hemp was limited in 1997 due to below average rainfall. The data from 1998 was used in our model tests because rainfall did not appear to be limiting. The inoculated and fertilized treatments were not significantly different in 1998 and were used as two independent values for testing our equations. Biomass was determined after the first killing frost and some of the leaves had been lost from the plants. We used this data assuming that lost leaves would have contributed only 10 to 15% to the biomass (Marshall et al., 2002). Nitrogen data were not available for this location.

Temperature and rainfall data for the Alabama and Virginia locations were collected within 1.5 km of each study. Solar radiation data were not available for the years sunn hemp was grown at these locations, and was estimated with RadEst 3.0 software (Donatelli et al., 2003) using the Campbell/Donatelli (Donatelli and Campbell, 1998) radiation model component. RadEst 3.0 calculates radiation as the product of daily atmospheric solar radiation transmissivity and potential radiation outside the earth's atmosphere. Potential radiation outside the earth's atmosphere was estimated as a function of latitude and day of year. Atmospheric transmissivity is based on the daily temperature range. Estimation parameters for RadEst 3.0 were iteratively optimized for each location using 10 yr of daily solar radiation and temperature data collected from 1993 to 2003. The data for EVS came from EVS, data for MNV came from the Wiregrass Experiment Station near Headland, AL, and for VSU came from Richmond, VA. Daily solar radiation was estimated using the optimized parameters and actual temperature data from each location for the years of the sunn hemp studies. Weather data for the UFL study, including air temperature, rainfall, and incident solar radiation came from the Florida Automated Weather Network, Citra, FL, monitoring station located near the experiment site (University of Florida, 2007). Daily maximum and minimum temperatures, total rainfall, and daily solar radiation were determined from hourly data.

Measured sunn hemp biomass and N data from Alabama, Florida, and Virginia were compared against estimates made with our developed equations using the REG procedure in SAS/STAT software. Agreement between predicted and measured data was determined with a slope test where agreement is indicated by a slope not significantly different from 1.

RESULTS AND DISCUSSION

Sunn Hemp Growth and Nitrogen Content at Tifton and Watkinsville

Temperatures and rainfall during the summer of 2002 were near long-term averages for both Tifton and Watkinsville from April through November (data not shown), with the exception of April at both locations where average temperatures were 2.3°C above normal. Relatively low average minimum temperatures were observed for the 90-to-120 DAP period following the June and July plantings at both locations, with temperatures of 12.7°C in Tifton and 8.3°C in Watkinsville. Precipitation at Tifton for April, May, and June was slightly less than long-term averages, while precipitation at Watkinsville was 55 mm below long-term averages during April and August and was close to normal or above normal for other months. Sunn hemp plots at Tifton received 13, 90, 76, 25, and 25 mm of water in April, May, June, July, and August, respectively. At Watkinsville, 0, 13, 13, 13, 50, and 13 mm of water were applied in April, May, June, July, August, and September, respectively.

Sunn hemp biomass and N content increased with DAP at both locations, but there were differences among the planting dates for both locations (Fig. 1). Biomass was significantly influenced by location, planting date, and DAP (Table 1). There were significant interactions between DAP linear and quadratic effects with location and date of planting for biomass data. Because of the significant location interaction effects, data were evaluated by location which confirmed significant linear and quadratic DAP effects found in the full data analysis (Table 2). Averaged across planting dates, biomass accumulation at 30, 60, 90, and 120 DAP was 0.5, 4.6, 8.6, and 11.6 Mg ha^{-1} at Tifton and 1.0, 5.0, 9.0, and 10.4 Mg ha^{-1} at Watkinsville. Biomass accumulation at

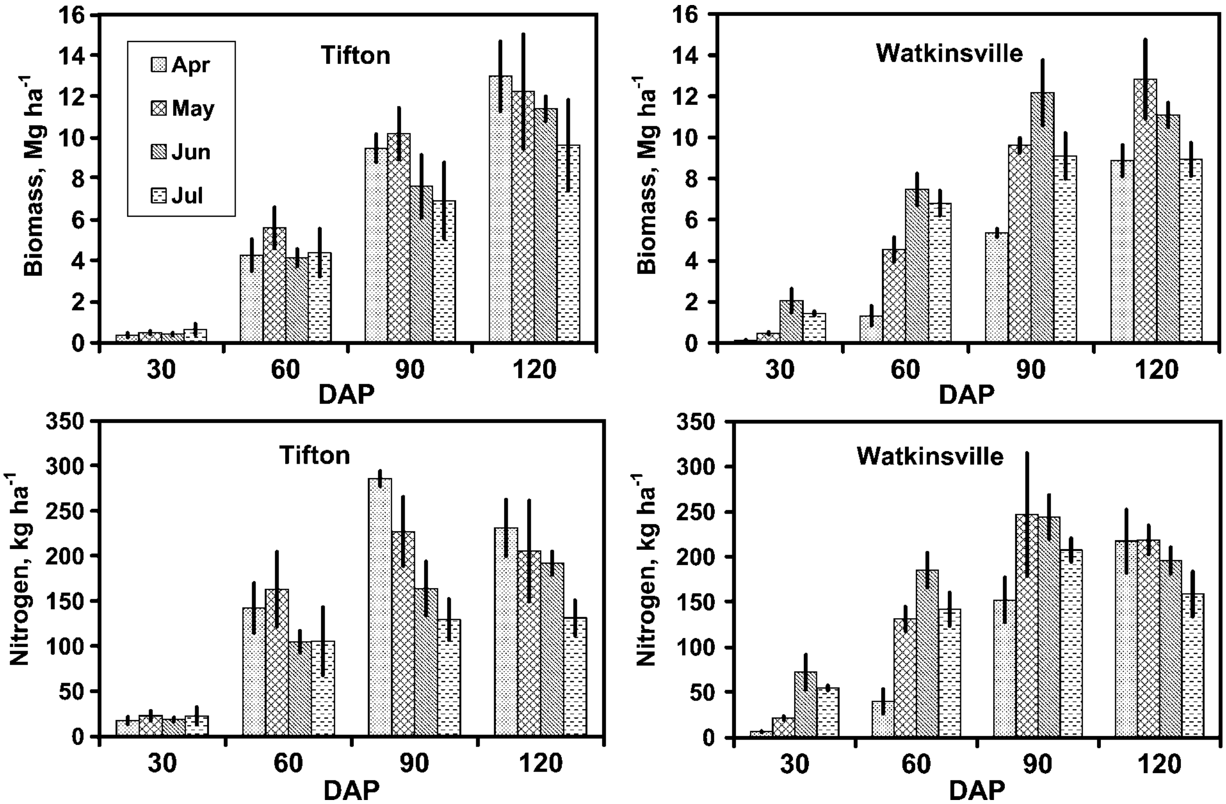

Fig. 1. Planting date effects on sunn hemp biomass production at Tifton and Watkinsville. Vertical lines on bars indicate 95% confidence interval for means.

Tifton was linearly related to DAP with no significant quadratic effect (Table 2 and Table 3). There were differences in biomass accumulation among the four planting dates as indicated by the significant DAP × date of planting interaction. Based on the slopes, plants in the April planting grew faster than those in the July planting (Table 3). At Watkinsville, maximum biomass accumulation occurred before the final sampling, resulting in a nonlinear response for three of the planting dates but not for the May planting date (Fig. 1). A significant quadratic effect was present for the April, June, and July planting dates. Growth of plants from the April planting was delayed during the first 30 d, which could have been the result of limited water availability. After the first 30 d, these plants grew at a rate similar to those planted in May. The June and July plantings have similar linear and quadratic coefficients. These two planting dates had a greater nonlinear response probably due to slowing of sunn hemp growth with decreasing fall temperatures.

For the mid-July planting, biomass accumulation 60, 90, and 120 DAP at Tifton (4.4, 6.9, and 9.6 Mg ha^{-1}) and at Watkinsville (6.8, 9.1, and 9.0 Mg ha^{-1}) was not greatly different from that reported in Florida by Cherr et al. (2006) (4.5, 9.4, and 10.8 Mg ha^{-1} for 60, 90, and 105 d, respectively). Mansoer et al. (1997) reported a range of biomass from 4.6 to 6 Mg ha^{-1} at 63 DAP and 4.8 to 7.3 Mg ha^{-1} at 84 DAP for plantings in late August and early September in Alabama. Bhardwaj et al. (2005) reported biomass accumulation of 8.8 Mg ha^{-1} after 108 DAP for an early July planting in Virginia.

Table 1. Results of the mixed model analysis for evaluating location (LOC), date of planting (MTH), and days after planting (DAP) effects on sunn hemp biomass and total N content.

		Biomass			Nitrogen		
Effect	Num DF	Den DF	*F* value	*P* > *F*	Den DF	*F* value	*P* > *F*
LOC	1	5.9	1.8	0.2243	27.1	2.5	0.1241
MTH	3	18.0	9.2	0.0007	35.8	5.0	0.0053
MTH × LOC	3	18.0	16.6	<0.0001	35.8	16.1	<0.0001
DAP†	1	31.8	1715.9	<0.0001	80.0	648.2	<0.0001
DAP × LOC	1	31.8	8.9	0.0054	80.0	0.1	0.7179
DAP × MTH	3	31.8	12.0	<0.0001	80.0	15.3	<0.0001
DAP × MTH × LOC	3	31.8	3.4	0.0297	80.0	1.3	0.2646
DAP × DAP†	1	78.8	25.07	<0.0001	80.0	120.6	<0.0001
DAP × DAP × LOC	1	78.8	4.21	0.0436	80.0	0.9	0.3359
DAP × DAP × MTH	3	78.8	7.10	0.0003	80.0	2.4	0.0748
DAP × DAP × MTH × LOC	3	78.8	9.87	<0.0001	80.0	11.8	<0.0001

† DAP was treated as a continuous variable and DAP × DAP represents the quadratic effect of DAP.

Table 2. Results of the mixed model analyses by location for evaluating date of planting (MTH), and days after planting (DAP) effects on sunn hemp biomass and total N content.

		Biomass			Nitrogen		
Effect	**Num DF**	**Den DF**	***F* value**	***P* > *F***	**Den DF**	***F* value**	***P* > *F***
Tifton quadratic							
MTH	3	11.1	3.1	0.0725	26.9	12.5	<0.0001
DAP†	1	42.2	518.6	<0.0001	40.0	378.3	<0.0001
DAP × MTH	3	42.2	2.8	0.0498	40.0	8.9	0.0001
DAP × DAP†	1	39.3	3.5	0.0692	40.0	81.0	<0.0001
DAP × DAP × MTH	3	39.3	1.4	0.2680	40.0	5.0	0.0051
Tifton linear							
MTH	3	11.9	2.8	0.0873			
DAP	1	43.3	491.9	<0.0001			
DAP × MTH	3	43.3	2.7	0.0570			
Watkinsville quadratic							
MTH	3	15.6	69.9	<0.0001	7.6	22.4	0.0004
DAP	1	32.1	988.0	<0.0001	40.0	281.5	<0.0001
DAP × MTH	3	32.1	12.6	<0.0001	40.0	7.8	0.0003
DAP × DAP	1	48.4	30.0	<0.0001	40.0	44.8	<0.0001
DAP × DAP × MTH	3	48.4	18.4	<0.0001	40.0	8.7	0.0001

† DAP was treated as a continuous variable with DAP × DAP representing the quadratic effect.

From these results it appears that producers can expect sunn hemp to produce 4.5 to 9 Mg ha^{-1} of biomass in 90 d for most locations in the south. Larger amounts would be expected where water availability is not limited as in the study of Cherr et al. (2006). Bruce et al. (1995) demonstrated that soil productivity increases with adoption of conservation tillage practices only when accompanied by crop culture that produces at least 12 Mg ha^{-1} yr^{-1} residues. After 4 yr of intensive biomass inputs in their system, soil C levels in the surface 15 mm and water-stable aggregate levels in the surface 80 mm were sufficiently elevated to significantly increase rainfall infiltration and crop-available soil water. Repeated use of sunn hemp as a cover crop in conservation tillage systems could be expected to improve soils in the region due to the large amount of residue produced in a short growing period.

Analysis of N content data showed a similar response as for biomass with significant location, date of planting, and DAP effects (Table 1). Again DAP significantly

Table 3. Regression coefficients for equations† describing changes in biomass and total N over the growing season at Tifton and Watkinsville for each planting date (MTH).

		Biomass			Nitrogen		
Location and effect	**MTH**	**Coefficient**	**Confidence interval (±)**	***P* > |*t*|**	**Coefficient**	**Confidence interval (±)**	***P* > |*t*|**
Tifton							
Intercept	4	−3876.7	1876.3	0.0002	−235.31	58.05	<0.0001
Intercept	5	−2909.8	1876.3	0.0034	−200.24	58.05	<0.0001
Intercept	6	−3222.0	1876.3	0.0014	−97.58	58.05	0.0016
Intercept	7	−2074.2	1876.3	0.0313	−93.94	58.05	0.0023
Intercept	*Overall*	*−3040.6*	*924.0*	*<0.0001*			
Linear	4	141.9	22.5	<0.0001	10.10	2.29	<0.0001
Linear	5	131.7	22.5	<0.0001	8.80	2.29	<0.0001
Linear	6	121.8	22.5	<0.0001	4.37	2.29	0.0004
Linear	7	99.0	22.5	<0.0001	4.54	2.29	0.0003
Linear	*Overall*	*123.5*	*12.3*	*<0.0001*			
Quadratic	4	NA‡	NA	NA	−0.050	0.015	<0.0001
Quadratic	5	NA	NA	NA	−0.045	0.015	<0.0001
Quadratic	6	NA	NA	NA	−0.016	0.015	0.0346
Quadratic	7	NA	NA	NA	−0.023	0.015	0.0043
Watkinsville							
Intercept§	4	−751.2	2671.9	0.5747	−78.99	42.705	0.0009
Intercept¶	5	−3707.5	1750.1	0.0002	−193.91	75.27	<0.0001
Intercept	6	−7897.2	2671.9	<0.0001	−133.84	75.27	0.0009
Intercept	7	−6509.3	2671.9	<0.0001	−123.22	75.27	0.0021
Linear§	4	3.9	81.6	0.9232	2.49	0.72	0.0000
Linear¶	5	141.2	21.9	<0.0001	8.10	2.58	<0.0001
Linear	6	376.6	81.6	<0.0001	8.14	2.58	<0.0001
Linear	7	312.5	81.6	<0.0001	6.93	2.58	<0.0001
Quadratic	4	0.6	0.5	0.0188	ns	ns	ns
Quadratic	5	ns	ns	ns	−0.038	0.017	<0.0001
Quadratic	6	−1.8	0.5	<0.0001	−0.045	0.017	<0.0001
Quadratic	7	−1.5	0.5	<0.0001	−0.038	0.017	0.0001

† Equations are constructed using the intercept, linear, and quadratic coefficients for a location and month.
‡ NA, not applicable.
§ Nitrogen regression coefficients for Month 4 at Watkinsville were estimated for a linear fit of the data because the quadratic component was not significant (ns).
¶ Biomass regression coefficients for Month 5 at Watkinsville were estimated for a linear fit of the data because the quadratic component was not significant (ns).

influenced N content of sunn hemp, having a predominantly nonlinear response across the four planting dates at both locations (Fig. 1). Analysis of the data by location confirmed a consistent nonlinear response of N content to DAP (Table 2). Averaged across planting dates, N contents at 30, 60, 90, and 120 DAP were 20, 130, 201, and 190 kg ha^{-1} at Tifton and 39, 125, 212, and 198 kg ha^{-1} at Watkinsville. At Tifton, N content increased similarly for the April and May planting dates and for the June and July planting dates as indicated by regression coefficients (Table 3). At Watkinsville, N content of sunn hemp in the April planting followed a linear response while the responses for May, June, and July planting dates were nonlinear. Regression coefficients indicate similar rates of N accumulation for the last three planting dates (Table 3). The June and July plantings at Watkinsville experienced lower temperatures during the period from 90 to 120 DAP than for the April and May planting in Watkinsville and for all four plantings at Tifton. Although lower temperatures most likely slowed growth and N accumulation, the effects were not large enough to differentiate the response to DAP compared with the May planting in Watkinsville.

Other studies in the south have shown that sunn hemp can accumulate from 75 to 120 kg N ha^{-1} in 60 d and 120 to 150 kg N ha^{-1} in 90 d when planted in mid to late summer (July–September) (Mansoer et al., 1997; Balkcom and Reeves, 2005; Cherr et al., 2006). Variability in N content can be related to growing conditions and soil N availability. Much of the N accumulated by

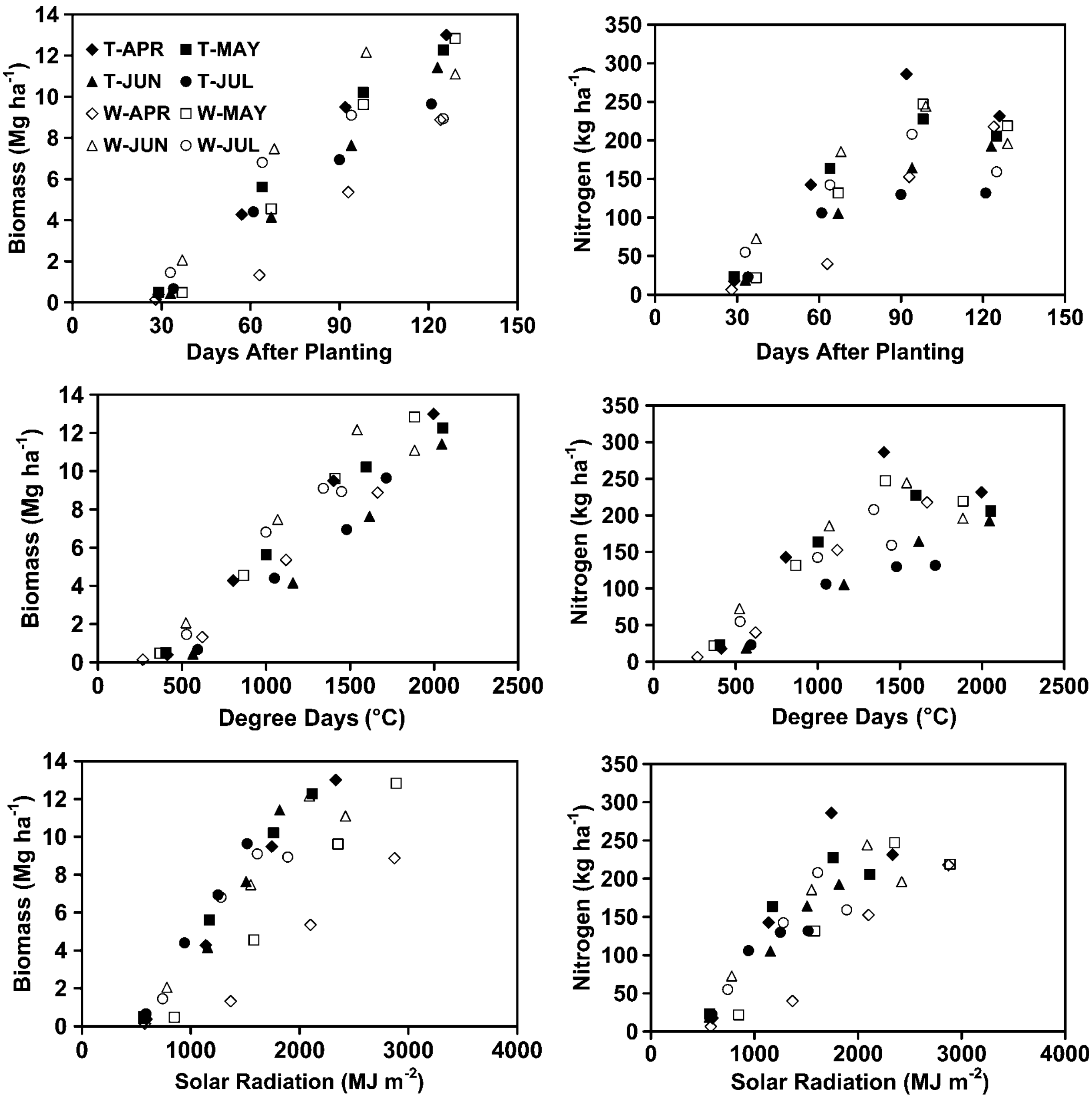

Fig. 2. Biomass and N content of sunn hemp at Tifton (T) and Watkinsville (W) as functions of days after planting, degree days, and solar radiation.

Table 4. Regression analysis of variance for evaluating days after planting (DAP), cumulative degree days (CDD), and cumulative solar radiation (CSR) as predictors of sunn hemp biomass.

			DAP		CDD		CSR	
Effect†	Effect DF	Error DF	*F* value	*P* > *F*	*F* value	*P* > *F*	*F* value	*P* > *F*
LOC	1	8	1.88	0.2072	1.30	0.2874	1.25	0.2959
MTH	3	8	2.45	0.1384	0.75	0.5524	1.43	0.3032
LOC × MTH	3	8	4.18	0.0470	2.64	0.1207	2.63	0.1215
Linear	1	8	115.10	0.0000	57.04	0.0001	29.94	0.0006
Linear × LOC	1	8	2.70	0.1390	3.81	0.0866	0.95	0.3579
Linear × MTH	3	8	4.67	0.0361	0.70	0.5795	1.81	0.2231
Linear × LOC × MTH	3	8	9.09	0.0059	5.78	0.0212	4.10	0.0491
Quadratic	1	8	18.56	0.0026	3.86	0.0850	6.62	0.0330
Quadratic × LOC	1	8	3.83	0.0859	3.24	0.1098	1.60	0.2412
Quadratic × MTH	3	8	5.32	0.0262	4.16	0.0475	4.71	0.0355
Quadratic × LOC × MTH	3	8	8.74	0.0066	5.54	0.0236	3.62	0.0646

† LOC is location; MTH is date of planting; linear is the linear effect of DAP, CDD, or CSR; and quadratic is the quadratic effect of DAP, CDD, or CSR.

sunn hemp in these published studies and from our work would be expected to come from N_2 fixation since most soils in the region are low in organic matter and have low N mineralization potentials. About half of the N in the sunn hemp residue should be available to a subsequent crop depending on how soon the next crop is grown. Balkcom and Reeves (2005) reported that sunn hemp contributed the equivalent of 58 kg ha^{-1} of N fertilizer for corn planted the following spring. Cherr et al. (2006) found similar contributions but also found that N losses (most likely due to leaching) during the winter greatly reduced availability of N from sunn hemp residues to sweet corn on a sandy soil in Florida. Long-term use of sunn hemp as a green manure in combination with a cover crop like rye (*Secale cereale* L.) that is known to scavenge residual N could eventually lead to improved N use efficiency in systems where organic matter and mineralizable N are increased (Dabney et al., 2001). Kuo et al. (1997) showed that increases in soil N and longer-term retention of N as soil organic N is dependent on biomass C inputs, which would be large with sunn hemp.

Estimating Biomass and Nitrogen Content

Our second objective was to develop simple equations for predicting biomass and N content of sunn hemp grown in the southeastern USA. Producers interested in using sunn hemp as a green manure or N source could use these equations to determine how much biomass or N might be produced between cash crops and planting dates. Our approach was to evaluate various climatic descriptors individually and in combinations to derive the best predictors of biomass and N content across locations and planting dates. The responses of biomass and N as functions of DAP, CDD, and CSR are illustrated in Fig. 2. The response to rainfall for biomass and N was similar to that shown for CSR but was more variable (data not shown). For all of the climatic factors evaluated individually, significant linear and/or quadratic interactions with either location or date of planting were present for biomass estimations (Table 4). This indicated that combining climatic factors might be more useful than using a single factor for predicting biomass. For estimating N, CSR and CDD resulted in significant linear relationships that did not interact with locations and planting dates, although some of the interactions had P values near 0.05 (Table 5). The overall analysis indicated that equations could be developed with these factors alone for estimating N content of sunn hemp.

Further development of equations for estimating sunn hemp biomass and N accumulation relied on use of stepwise regression for selection of the best combination of climatic factors across locations and planting dates. A linear equation that combined CDD and CSR was determined to be best for estimating biomass. The equation is

$$\text{sunn hemp biomass (Mg ha}^{-1}) = -2.77 + 0.0060\ \text{CDD} + 0.0014\ \text{CSR}$$

Coefficients were significant at $P < 0.02$ and the equation had a root mean square error of 1.17, adjusted R^2 of 0.92, F value of 189.9, and was significant at $P <$

Table 5. Regression analysis of variance for evaluating days after planting (DAP), cumulative degree days (CDD), and cumulative radiation (CSR) as predictors of sunn hemp N content.

			DAP		CDD		CSR	
Effect†	Effect DF	Error DF	*F* value	*P* > *F*	*F* value	*P* > *F*	*F* value	*P* > *F*
LOC	1	8	0.02	0.9034	0.32	0.5898	0.05	0.8293
MTH	3	8	0.61	0.6290	0.05	0.9849	0.41	0.7489
LOC × MTH	3	8	2.66	0.1198	1.65	0.2533	1.62	0.2609
Linear	1	8	89.04	0.0000	58.28	0.0001	34.05	0.0004
Linear × LOC	1	8	0.13	0.7272	0.01	0.9171	0.57	0.4701
Linear × MTH	3	8	0.77	0.5444	0.12	0.9477	0.59	0.6399
Linear × LOC × MTH	3	8	5.51	0.0239	3.82	0.0576	2.38	0.1452
Quadratic	1	8	45.72	0.0001	1.81	0.2151	3.10	0.1165
Quadratic × LOC	1	8	0.29	0.6079	0.12	0.7374	0.02	0.9052
Quadratic × MTH	3	8	0.84	0.5084	1.75	0.2341	2.91	0.1010
Quadratic × LOC × MTH	3	8	5.59	0.0230	3.82	0.0575	1.78	0.2294

† LOC is location; MTH is date of planting; linear is the linear effect of DAP, CDD, or CSR; and quadratic is the quadratic effect of DAP, CDD, or CSR.

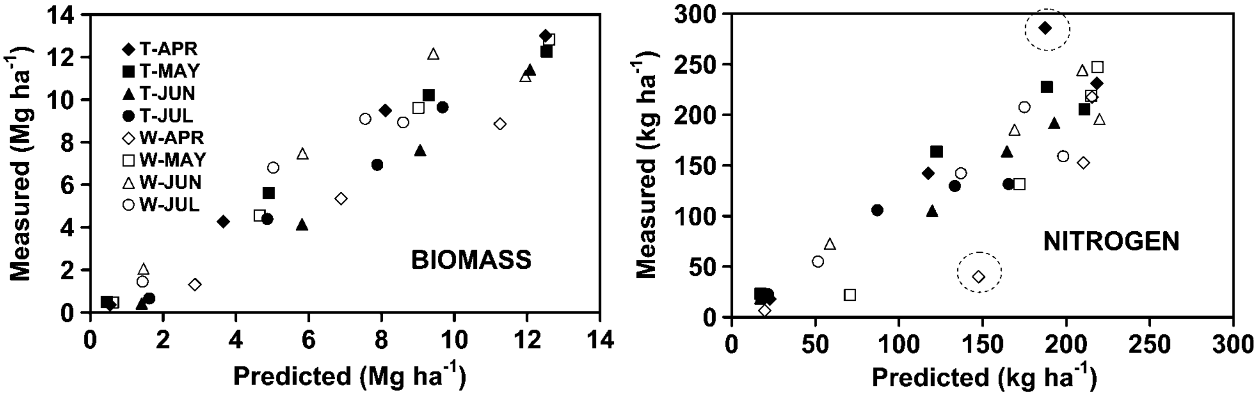

Fig. 3. Comparison of measured versus predicted sunn hemp biomass and total N data from Tifton (T) and Watkinsville (W) using the developed equations. Circled data points in the N graph were not used in fitting the final prediction equation.

0.0001. Measured data from Watkinsville and Tifton appeared to be similarly distributed in the plot of observed vs. predicted values (Fig. 3), indicating that neither location was more over- or underpredicted compared with the other location.

Nitrogen content was best predicted with a quadratic equation that contained CSR and CSR squared (CSR-SQ). The equation is

$$\text{sunn hemp N (kg ha}^{-1}) = -119.7 + 0.2660\ \text{CSR} - 0.00052\ \text{CSR-SQ}$$

Coefficients were significant at $P < 0.001$, and the equation had a root mean square error of 37.3, an adjusted R^2 of 0.79, F value of 58.4, and was significant at $P < 0.0001$. Regression influence diagnostics indicated two data points had a large influence on parameter estimation (Fig. 3). Removing these data improved the fit of the equation as indicated by the root mean square error of 26.6, adjusted R^2 of 0.88, F value of 108.5, and significance at $P < 0.0001$. The second N equation which we used for further evaluations is

$$\text{sunn hemp N (kg ha}^{-1}) = -115.5 + 0.2634\ \text{CSR} - 0.000052\ \text{CSR-SQ}.$$

Coefficients for this equation were significant at $P < 0.0001$.

Cherr et al. (2006) also found that dry weight and total N accumulated can be estimated as functions of climatic variables. They showed that differences in sunn hemp total plant dry weight and N accumulation between years, when evaluated as a function of time after emergence, could be eliminated when evaluated as a function of intercepted photosynthetically active radiation. However, this required measurements of leaf area during the growing season because intercepted photosynthetically active radiation was estimated as the incident photosynthetically active radiation divided by leaf area index. The change in leaf area index followed a quadratic response when evaluated as a function of CDD. Their equations can be combined to estimate both dry weight and total N as functions of CDD and CSR; however, the combined equations are more complex than those we have presented.

Test of Prediction Equations

We tested the robustness of the above equations for predicting sunn hemp biomass and N with data from Alabama, Florida, and Virginia (Fig. 4). For predictions of biomass accumulation, the relationship between estimated and predicted values had a slope of 0.96, which was not different from 1 ($P = 0.74$). The adjusted R^2 of

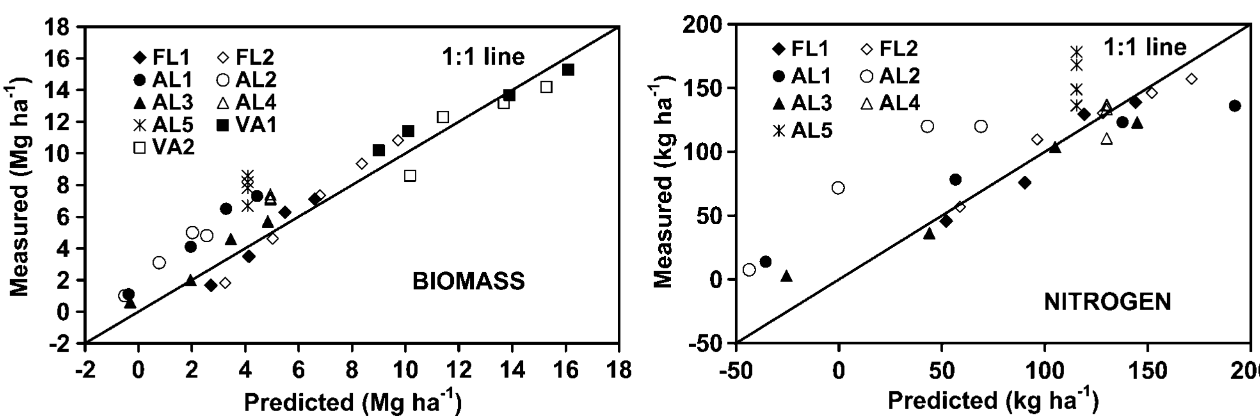

Fig. 4. Comparison of measured versus predicted sun hemp biomass and total N data from studies in Alabama, Florida, and Virginia. Nitrogen data were not available for the Virginia study.

0.70 indicated that additional factors not accounted for in the model influenced biomass accumulation. Largest deviations from the 1-to-1 line occurred for the Alabama data, where our equation underpredicted biomass for four of the five studies (Fig. 4). Other factors not included in the equation like water availability, residual soil N, or management differences may have been contributing factors. We believe underprediction of biomass for the Alabama data was most likely related to differences in planting methods and seeding rates. Sunn hemp was planted with a grain drill at 56 kg ha^{-1} in the Alabama studies, which was >3 times the seeding rate used in our study. Sunn hemp leaf area increases rapidly during early stages of vegetative growth, increasing its ability to intercept photosynthetically active radiation and produce biomass (Cherr et al., 2006). This, along with the greater population density, probably explains why our equation consistently underestimated total plant dry weight for the Alabama studies even though they were grown under dryland conditions. Estimations of biomass were in closer agreement for the Florida and Virginia data (Fig. 4).

For predictions of N accumulation, the relationship between estimated and predicted values had a slope of 0.71, which was different from 1 ($P = 0.0006$). This indicates that our relationship was not a good predictor of sunn hemp N. However, as with the biomass data there were large deviations from the 1-to-1 line for the Alabama data, with N contents being underpredicted. Again this was most likely related to rapid biomass accumulation and increases in N due to the greater planting density compared with the other studies. An additional unknown would be the ability of sunn hemp to scavenge residual N remaining following the previous summer crop (Dabney et al., 2001). The adjusted R^2 of 0.77 indicated that additional factors unaccounted for influenced estimation of N contents. Estimations of the amount of N in sunn hemp were in closer agreement for the 2 yr of data from the Florida study (Fig. 4).

CONCLUSIONS

Sunn hemp appears to be well suited for use as a short rotation cover crop during the spring through late summer in the southeastern USA. Date of planting and length of growing period significantly influenced biomass and N content of sunn hemp when grown in the Piedmont or Coastal Plains. Although best growth was obtained when sunn hemp was allowed to grow for 120 d, significant biomass accumulated after only 60 d. Plantings from mid April to mid July at Tifton and Watkinsville produced sufficient biomass (>4.5 Mg ha^{-1}) 60 d to provide good cover and green manure for a subsequent vegetable crop. Nitrogen accumulated in this period averaged 130 kg ha^{-1}. Assuming 50% availability, this would provide 1/3 to 1/2 of the N needed to grow most vegetables. For maximum biomass and N benefit, it would be best to kill sunn hemp at 90 DAP or later. Climatic differences among planting dates and locations were used to model biomass and N accumulation as linear and quadratic functions of CDD and CSR. Tests of these equations with independent data indicated they were accurate at estimating biomass accumulation, and although they did not appear to work as well for N accumulation, could still be useful. Our results suggest sunn hemp can fit well into short-rotation sustainable vegetable production systems in the Southeast and that producers may easily estimate the potential growth and N accumulation of sunn hemp as a cover crop.

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