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Agricultural Practices for Growing Kenaf (Hibiscus cannabinus L.) in Iowa: I. Morphology, Stem, and Fiber Yield

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Abstract

Kenaf (Hibiscus cannabinus L.) is a promising biorenewable resource for producing natural fibers but few studies have investigated the crop when grown in cooler climates, such as the American Midwest. The objectives of this study were to: 1) determine the agricultural practices (row spacing, seed, and N rates) leading to optimal kenaf dry matter (DM) stem and fiber yield in 'Tainung 2' and 'Whitten'; 2) evaluate stem height, basal diameter, and leaf area index (LAI) over the growing season; and 3) assess the influence of management practices on fiber (bast and core lignocellulose) composition, and carbon (C), N, and total ash concentration. Kenaf cultivars Tainung 2 and Whitten were planted in Boone County, IA in 2014 and 2015 at 247,000 or 371,000 seed ha-1, in 38-cm or 76-cm rows that received 0, 56, 112, 168, or 224 kg N ha-1. Stand density, core:bast fiber ratio, and basal stem diameter were influenced by three-way interactions. Stem height at harvest was influenced by the main effects of row spacing, seeding rate, and N fertilization rate. Nitrogen fertilization did not influence stem DM yield, regardless of application rate. Kenaf is a promising multi-purpose crop that could contribute to the natural fiber marker, as well as diversifying the landscape. Kenaf is well adapted to Iowa and can be produced with a range of management practices.

Keywords

ash, kenaf, N rates, row spacing, seeding rate, variety

Disciplines

Agriculture | Agronomy and Crop Sciences | Climate | Soil Science

Comments

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Agricultural Practices for Growing Kenaf (*Hibiscus cannabinus* L.) in Iowa: I. Morphology, Stem, and Fiber Yield

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ABSTRACT

Kenaf (*Hibiscus cannabinus* L.) is a promising biorenewable resource for producing natural fibers but few studies have investigated the crop when grown in cooler climates, such as the American Midwest. The objectives of this study were to: 1) determine the agricultural practices (row spacing, seed, and N rates) leading to optimal kenaf dry matter (DM) stem and fiber yield in 'Tainung 2' and 'Whitten'; 2) evaluate stem height, basal diameter, and leaf area index (LAI) over the growing season; and 3) assess the influence of management practices on fiber (bast and core lignocellulose) composition, and carbon (C), N, and total ash concentration. Kenaf cultivars Tainung 2 and Whitten were planted in Boone County, IA in 2014 and 2015 at 247,000 or 371,000 seed ha^{-1}, in 38-cm or 76-cm rows that received 0, 56, 112, 168, or 224 kg N ha^{-1}. Stand density, core:bast fiber ratio, and basal stem diameter were influenced by three-way interactions. Stem height at harvest was influenced by the main effects of row spacing, seeding rate, and N fertilization rate. Nitrogen fertilization did not influence stem DM yield, regardless of application rate. Kenaf is a promising multi-purpose crop that could contribute to the natural fiber marker, as well as diversifying the landscape. Kenaf is well adapted to Iowa and can be produced with a range of management practices.

Keywords: ash, kenaf, N rates, row spacing, seeding rate, variety

Abbreviations: C, carbon; DAP, day after planting; DOY, day of the year; DM, dry matter; LAI, leaf area index.

Natural fibers have recently received great attention for biobased composites production because they are renewable, environmentally friendly alternative resources to petroleum-based products. There are about 6,000 items made from petroleum (Gironi and Piemonte, 2011). The production of these objects requires high energy inputs and results in important environmental and health issues. Reducing the amount of non-biodegradable plastics in the environment, maintaining an appropriate landfill space, decreasing gas emissions due to incineration, and avoiding dependence on finite petroleum resources are some of the reasons that compel the use of biorenewable, environmentally compatible resources (Mohanty et al., 2005).

Agricultural production of natural fibers is done from crop residues and dedicated energy crops (Brown and Brown, 2014). Traditional synthetic fibers can be substituted with lignocellulosic fibers from flax (*Linum usitatissimum* L.), hemp (*Cannabis sativa* L.), sisal (*Agave sisalana* P.), jute (*Corchorus olitorius* L.), or kenaf (*Hibiscus cannabinus* L.). Natural fibers compare favorably with glass fibers and are promising replacements with similar strength and wear characteristics (Wambua et al., 2003). Kenaf shows promising potential in the American Midwest, including Iowa (Bourguignon et al., 2016a).

Kenaf is an annual, herbaceous dicot originating in Africa (Cheng et al., 2004), but now mostly grown in India and China (44% and 29%, respectively of world kenaf production; I.N.F.O., 2016). Bast fibers located in the outer layer phloem vessels of the kenaf stem are the most used portion of the plant for the industrial production of paper, pulp, textile, and rope (Bel-Berger et al., 1999). The core, the inner part of the stem, has often been considered a byproduct by industry; however, the core has potential to be used other ways, such as absorbent material applications because of its short and porous fibers (Monti and Alexopoulou, 2013). Bast and core can be used separately or together in the production of bioplastics, biocomposites, or biofuels (Saba et al., 2015a,b) and contribute to global sustainability because the entire aboveground part of the stem can be used as substrate. Kenaf was introduced and grown in the U.S. during the Second World War to produce cordage (Dempsey, 1975), but has received little attention since. It is still grown in the U.S., mostly in southern states such as Georgia, Texas, Mississippi, and New Mexico.

Optimal management practices have been studies for kenaf yield in the U.S., but primarily results are from southern states. Studies have focused on management practices, such as planting time, row spacing, population density, fertilization, irrigation, or crop rotation practices in Florida (Joyner and Wilson, 1967), Nebraska (Williams, 1966), California (Bhangoo et al., 1986), Mississippi (Baldwin and Graham, 2006), Maryland (Massey, 1974; Campbell and White, 1982), New Mexico (Lauriault and Puppala, 2009), and North Carolina (Jordan et al., 2005). Numerous studies on kenaf management were conducted outside of the U.S., i.e., Spain (Manzanares et al., 1997; González Moreno et al., 2004; Wood et al., 1983), Italy (Mambelli and Grandi, 1995), Greece (Alexopoulou et al., 2000; Alexopoulou et al., 2009; Danalatos and Archontoulis, 2010), and Australia (Carberry et al., 1992; Muchow and Carberry, 1993). Kenaf has shown great potential for agriculture production in these various regions. Other investigations in the U.S. have reported kenaf responses to N fertilization, but results have been inconsistent. Some reports found that adding N increased yield (Adamson et al., 1979; Anfinrud et al., 2013; White and Higgins, 1964) but others reported that N fertilization was not necessary

(Danalatos and Archontoulis, 2010; Massey, 1974; Webber, 1996). Investigations specifically conducted in Iowa or the Midwest have not addressed optimal N fertilization.

The few studies conducted in northern U.S. regions have had disparate results and largely did not focus on bast and core fiber yields. When grown in North Dakota, Berti et al. (2013) showed that kenaf can produce yields of 10 Mg ha^{-1}, estimating that it could produce 1,400 L ha^{-1} of biofuel. They also recommended planting kenaf at 10,000 to 32,000 seed ha^{-1} in 30-cm rows (Berti et al., 2013). However, this research employed the variety 'Dowling', which was not the highest performing cultivar in a study conducted in Iowa (Bourguignon et al., 2016a). Therefore, the recommendations provided by Berti et al. (2013) may result in different outcomes when other cultivars are used (Alexopoulou et al., 2000; White et al., 1971).

In field studies conducted in Iowa, the varieties 'Tainung 2' and 'Whitten' were the most promising varieties (Bourguignon et al., 2016a). The cultivar Tainung 2 is one of the most commercialized cultivars in the world; however, 'Whitten', a variety developed by Mississippi State University also has shown potential (Baldwin et al., 2006). In contrast to Tainung 2 that has deeply divided leaves, Whitten retains the juvenile leaf shape, common to most kenaf varieties. This shape is undivided and does not resemble marijuana (*Cannabis sativa* L.), avoiding confusion and potential trouble with law enforcement agencies. Whitten could be more competitive than Tainung 2, as Baldwin et al. (2006) suggested it generally attains greater stem height and has better resistance to powdery mildew than other cultivars.

Finally, phenological development of kenaf has not been studied in Iowa, and plant growth and morphological characteristics may be sensitive to agricultural management practices. Plant height, for instance, was influenced by management practices in central Greece (Danalatos and Archontoulis, 2010).

In light of previous research, we hypothesized that variety, row spacing, and seeding rate would influence kenaf stem yield and morphology and that N application rate would influence yield. The specific objectives of this study then were to determine: 1) agricultural practices (row spacing, seed, and N rates) leading to optimal kenaf dry matter (DM) stem and fiber yield in 'Tainung 2' and 'Whitten'; 2) evaluate stem height, basal diameter, and leaf area index (LAI) over the growing season; and 3) the influence of management practices on fiber (bast and core lignocellulose) composition, and C, N, and total ash concentrations.

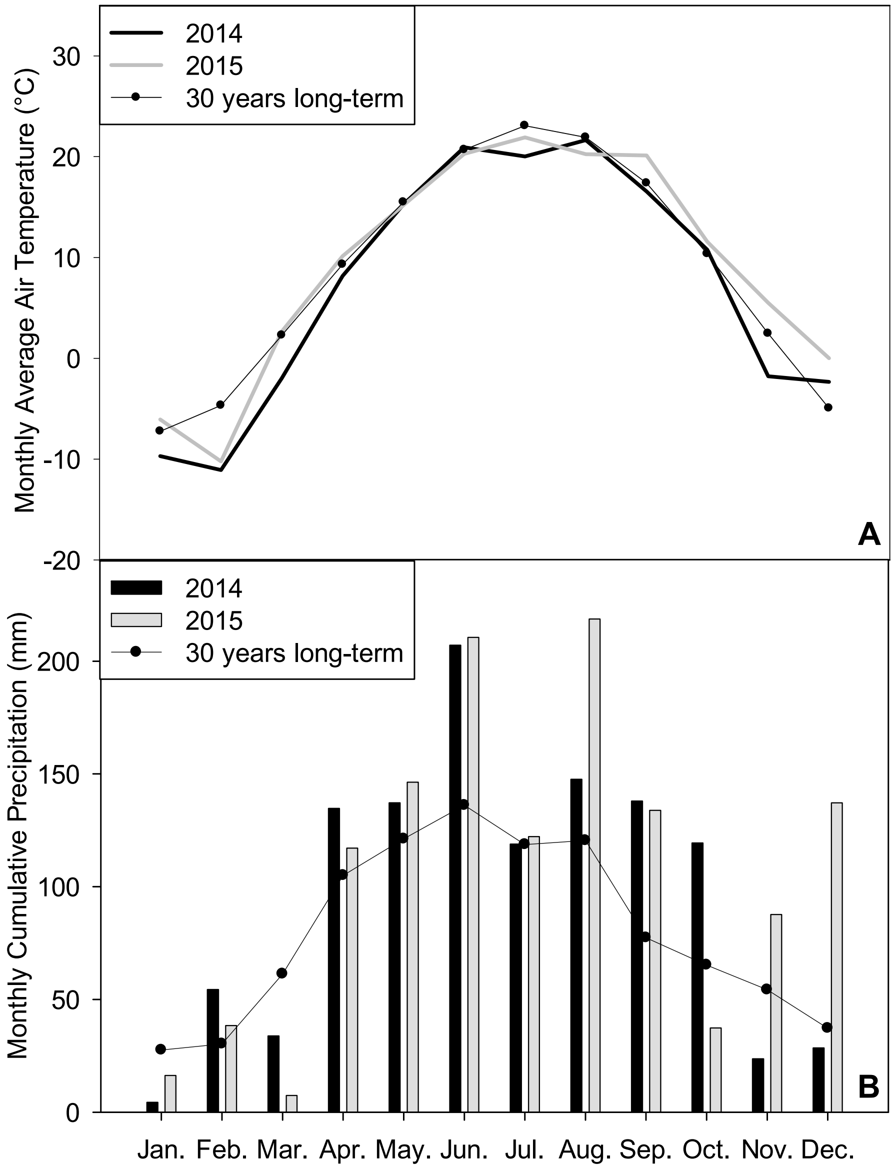
MATERIAL AND METHODS

Site, Experiment, and Local Climate

A field study was conducted at the Iowa State University Agronomy and Agricultural Engineering Research Farm, near Boone, IA (42°01'N, 93°46'W) on a Nicollet loam soil (fine-loamy, mixed, mesic Aquic Hapludoll). The local air temperature and monthly cumulative precipitation were collected by an automated weather station [A130209] located at the Agricultural Research Farm (ISU Ag Climate, 2014), approximately 3 km from the research site (Fig. 1).

The experimental design was a split-block with four blocks, with the study repeated in 2014 and 2015 on different sites. Each year, prior to treatment imposition, soils were composite sampled by block at the 0 to 15-cm depth and analyzed for total N. Kenaf variety ('Tainung 2', 'Whitten'), seeding rate (247,000 and 371,000 seed ha^{-1}), row spacing (38-cm and 76-cm rows)

Figure 1. Monthly average air temperature (A) and cumulative precipitation (B) in 2014 and 2015, in Boone County, Iowa, compared to the 30-year period (1984 - 2014).



were the whole plot treatments as a factorial combination, and five N fertilization rates (0, 56, 112, 168, 224 kg N ha^{-1} as urea) were broadcast applied with a BEFCO 209 (BEFCO Inc., Rocky Mount, NC) in perpendicular strips to the other treatments across each block on 10 June 2014 and 2 June 2015, respectively. The different N fertilized strips in combination with two varieties, two seeding rates, and two row spacings corresponded to the subplots (n = 160). The cultivars Tainung 2, originally from Taiwan, and Whitten, developed at Mississippi State University (Baldwin, 2006) were used. They were seeded at a depth of 2.5 cm in 2.7 m × 6 m plots on 10 June 2014 and 2 June 2015 when the top 10-cm soil temperature reached 15.6°C. Just prior to planting, an application of formulated pendimethalin (N-(1-ethylpropyl)-3,4-dimethyl-2, 6-dinitrobenzenamine) was applied at 1.048 kg a.i. ha^{-1}, followed by a single pass with a field cultivator for incorporation and to control emerged weeds. The field cultivator also incorporated the urea applied earlier on the same dates.

Data Collection

Kenaf was harvested once each year after killing frost occurred. Two 3-m rows were harvested by hand in each plot, respectively, on 12 November 2014 and 24 November 2015. Stalk number and wet weight were determined in the field at harvest. A subsample of three plants was collected in each plot and combined into one sample. The three stalks were stripped and divided into bast and core for subsequent analyses. Samples were weighed, dried at 60°C until dry matter was constant, and ground to pass a 1-mm sieve in a rotary mill (Thomas Scientific, Swedesboro, NJ). The core:bast ratio was calculated using the dry bast and core weights and the dry stem yield in each plot was based on the dry matter content of the bast and core.

Prior to yield harvest, stem height and basal diameter were measured on three individual stems in each plot every two weeks from emergence to harvest. Height was determined from ground level to stem apex using a measuring tape and basal diameter was measured with a caliper at ground-level. Heights and diameters were averaged over the three individuals. The LAI was measured with a LAI 2000 Plant Canopy Analyzer (PCA, LI-COR, Lincoln, NE) monthly or bimonthly. Following completion of yield harvest, soils were composite sampled by block at the 0 to 15-cm depth and analyzed for total N concentration.

Statistical Analysis

Data were analyzed by PROC GLM to evaluate the agricultural practices effects on stem dry matter (DM) yield and core:bast ratio variables (SAS Institute, Cary, NC) The PDIFF procedure was used for mean separations at P=0.05. Year and block were considered random effects with block nested in year and this was decided because the focus of this study was not on the difference of results between the years of study. A separate analysis by year was performed for stem height, basal diameter, and LAI in order to highlight plant phenological response to treatments during each growing season. In this case, the goals was not to compare the results from one year to another, but to observe and analyze the plant response to the treatments throughout the isolated growing season.

Nitrogen rate, seeding rate, variety, and row spacing were considered as fixed effects. Biweekly stem height, basal diameter, and LAI were analyzed using day after planting (DAP) as a quantitative, continuous variable. Pearson correlation coefficients for fixed variables were also investigated and all tests of significant were made at of $\alpha = 0.05$.

RESULTS AND DISCUSSION

Weather Conditions

The two years of study were colder in July than the 30-year long-term mean, but slightly warmer in December (Fig. 1A). They were in range of what the location has experienced the last 30 years in April, May, June, and October. In 2014, July was 2°C cooler than 2015 and the long-term mean. From mid-August to harvest 2015 was in general warmer than 2014. The two years of the study generally received more precipitation in late spring, June, August, and early fall than the 30-year long-term (Fig. 1B). June had 41% more precipitation than the long-term mean. August 2015 received 33% more rainfall than in 2014.

Agricultural practices leading to optimal kenaf and fiber yield

Stem yield and plant density at harvest

Stem yield (the sum of bast and core components) was only influenced by variety; all other main effects and interactions were non-significant (Table 1). Averaged over years, Tainung 2 yielded 10.1 Mg ha^{-1} of stem whereas Whitten averaged 9.5 Mg ha^{-1} of stem. Tainung 2 has raised much interest in the U.S. because of its excellent yield potential. It was previously reported that Tainung 2 had 18% greater yields than Whitten in Iowa (Bourguignon et al., 2016a). However, in this study, Tainung 2 yield only surpassed Whitten by 6%.

Table 1. Stem dry matter (DM) yield, plant density, core:bast ratio, stem height, and basal diameter influenced by management practices for kenaf. Boone, IA.

		Stem yield	Plant density	Core:bast ratio	Stem height	Basal diameter
		Mg ha^{-1}	plants ha^{-1}		cm	cm
Variety						
Tainung 2		10.1 a†	201,150	1.72 b	259	2.04
Whitten		9.5 b	192,916	1.78 a	258	2.06
Row Spacing						
38-cm		9.9	198,567	1.76	256 b	1.99 b
76-cm		9.7	195,000	1.74	261 a	2.11 a
Seeding Rate						
247,000 seed ha^{-1}		9.6	166,276 b	1.75	262 a	2.12 a
371,000 seed ha^{-1}		10.0	227,791 a	1.75	255 b	1.98 b
Nitrogen Rate						
0 kg ha^{-1} N		9.6	199,671 b	1.75 ab	254 b	1.97 c
56 kg ha^{-1} N		9.8	214,168 a	1.78 a	259 a	1.97 c
112 kg ha^{-1} N		10.4	202,193 ab	1.76 ab	260 a	2.05 b
168 kg ha^{-1} N		9.9	190,118 bc	1.77 a	260 a	2.13 a
224 kg ha^{-1} N		9.4	179,017 c	1.69 b	260 a	2.13 a
				ANOVA		
Source	df					
Variety (V)	1	*	NS	**	NS	NS
Row Spacing (R)	1	NS	NS	NS	**	***
V × R	1	NS	NS	NS	NS	NS
Seeding Rate (S)	1	NS	***	NS	**	***
V × S	1	NS	NS	NS	NS	NS
R × S	1	NS	NS	NS	NS	*
V × R × S	1	NS	**	NS	NS	**
Nitrogen Rate (N)	4	NS	***	NS	NS	***
V × N	4	NS	NS	NS	*	NS
R × N	4	NS	NS	NS	NS	NS
V × R × N	4	NS	NS	NS	NS	NS
S × N	4	NS	NS	NS	NS	NS
V × S × N	4	NS	NS	*	NS	NS
R × S × N	4	NS	NS	NS	NS	NS
V × R × S × N	4	NS	NS	NS	NS	NS

*,**, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively. NS, nonsignificant (*P* > 0.05).

† Different letters denote significant differences between treatments.

Overall, stem biomass yields measured in this study were similar to those of Berti et al. (2013), who reported yields of approximately 10 Mg ha^{-1}. These yields were less than the 13.8 Mg ha^{-1} which was reported from Oklahoma when Tainung 2 was planted at 250,000 seed ha^{-1} in 76-cm rows (Webber, 1993; Williams, 1966). In another study, Tainung 2 had stem yields of 15.6, 13.8, 7.5 Mg ha^{-1} in Mississippi, Oklahoma, and Missouri, averaging 10.6 Mg ha^{-1} over the three locations (Ching et al., 1992). This latter study argued that the higher the latitude, the lower the stem yield; however, we report greater stem yields in Iowa than those from Missouri.

Previous investigations, all conducted outside Iowa, suggested that growing kenaf in narrow rows and at high seeding rate resulted in greatest yields (Baldwin and Graham, 2006; Webber and Bledsoe, 2002) and that under 185,000 plants ha^{-1}, stem yields were reduced because more branching was observed (Higgins and White, 1970). However, the stem yields of kenaf produced in 2014 and 2015 were not sensitive to row spacing or to seeding rate.

Other studies have highlighted the importance of N application to kenaf for increased stem yield (Adamson et al., 1979; Anfinrud et al., 2013; Bhangoo et al., 1986; Webber, 1996; White and Higgins, 1964). However, other reports showed no yield benefits from N fertilizer application to kenaf (Danalatos and Archontoulis, 2010; Manzanares et al., 1997, Massey, 1974; Patanè and Cosentino, 2013; Webber, 1996). Interestingly, when kenaf was grown 10 years earlier in Boone, IA, adding 168 kg N ha^{-1} increased stem DM yield by 15%, but only when kenaf was planted in early May (unpublished results); no N effect was observed on stem yield when kenaf was sown in late May or in early June. Kenaf was sown in early June during our study, and this could explain why N rate did not influence stem yield. Other possible reasons for the lack of kenaf yield response to applied N include the possibility of substantial losses of nitrate from leaching (Hatfield et al., 2009) and denitrification or increased nitrate availability during the growing season from greater than normal organic matter oxidation and nitrification (Reichman et al., 1966; Pilbeam et al. 1993). Soil total N was 1.461 and 2.132 g kg^{-1} in 2014 and 2015, respectively, from pretreatment imposition sampling. When sampled postharvest, soil total N had decreased to 1.381 and 1.858 g kg^{-1} for 2014 and 2015, respectively, indicating substantial turnover of SOM each year that likely provided additional nitrate for kenaf. Precipitation events in June in the northern Corn Belt often are intense, with precipitation rates frequently greater than soil water infiltration and hydraulic conductivity rates, resulting in runoff. Although an important source of P for waterways, runoff rarely results in substantial loss of soil nitrate. Nicollet clay loam soils often occur in shoulder positions in Clarion clay loam-Nicollet-Webster silty clay loam catena with the Nicollet downslope from Clarion loam and upslope from Webster silty clay loam and during periods of drought serve as recharge areas for footslope and toeslope positions (Steinwand and Fenton, 1995). During periods of less than long-term mean rainfall or drought, these soils typically have adequate soil moisture compared to upland Clarion and may still provide substantial nitrate for crop use through microbial organic matter oxidation and nitrification.

Nitrogen fertilization rate influenced kenaf plant density at harvest (Table 1). The greatest plant densities occurred when 56 or 112 kg N ha^{-1} was applied, and stands averaged 214,168 and 202,193 plants ha^{-1}, respectively. Surprisingly, adding 168 kg N ha^{-1} did not increase plant density compared to the control (0 kg N ha^{-1}). Additionally, adding 224 kg N ha^{-1} resulted in decreased plant density since the results indicated that not applying N was 10% better than applying 224 kg N ha^{-1}. A very similar trend was observed for 'Tainung 1' and 'Everglades 41' in Oklahoma for how N fertilization influenced stand density at harvest (Webber, 1996).

Plant density also was influenced by the interaction of variety × seeding rate × row spacing. Greatest plant densities were observed when Tainung 2 was planted at 371,000 seed ha^{-1} in 76-cm rows and when Whitten was seeded at 371,000 seed ha^{-1} in 38-cm (Fig. 2).

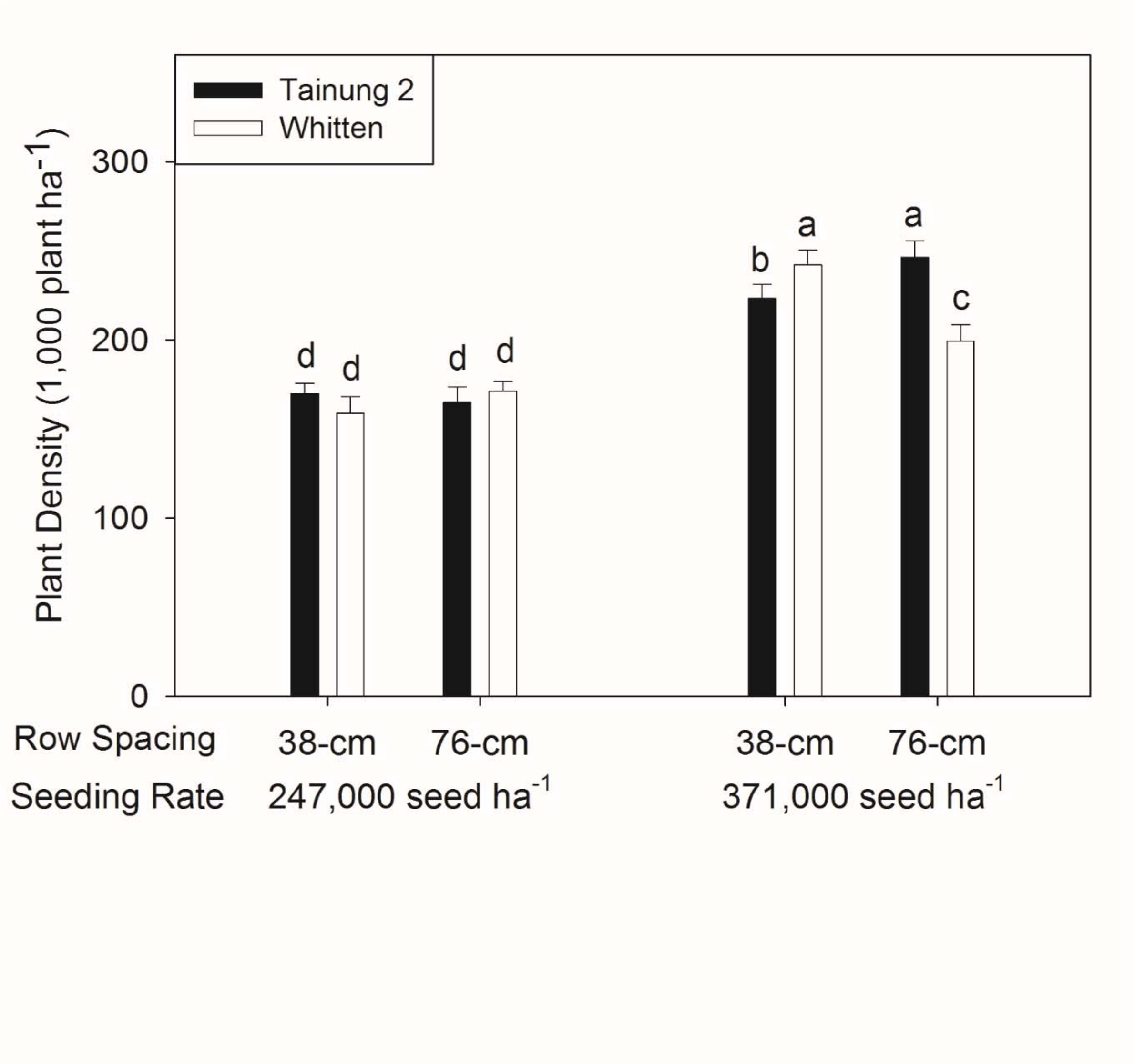


Figure 2. Plant density influenced by variety × row spacing × seeding rate (mean ± S.E) for Tainung 2 and Whitten plants grown at Boone, IA in 2014 and 2015. Different letters on top of the bars denote significant differences between variety × seeding rate × row spacing treatments.

Fiber yield

The core:bast ratio is directly linked to the partitioning of bast and core in the plant. The increase in core:bast ratio can occur from either a greater amount of core produced for the same amount of bast produced, or a decreased amount of bast was produced for a fixed quantity of core. In our study, the kenaf core:bast ratio was sensitive to the interaction of variety × seeding rate × N rate (Table 1, Fig.3), which has not been reported before. When kenaf was planted at 247,000 seed ha^{-1}, Whitten had 11% greater core:bast ratio (and therefore produced 11% more core for a fixed amount of bast) than Tainung 2, but only at the highest N rate applied. For the other N rates, there was no significant difference between the two varieties. When comparing the response of N rates on Tainung 2, the core:bast ratio was 10% greater when 112 kg N ha^{-1} was applied than when 224 kg N ha^{-1} was used (Fig. 3). When kenaf was planted at 371,000 seed ha^{-1}, Tainung 2 produced 13% more core when N was applied at 58 kg ha^{-1} than Whitten grown with the same amount of N.

Our study showed that the core:bast ratio varied from 1.6 to 1.9. Similarly, Baldwin and Graham (2006) report that core:bast ratios of kenaf planted in 35.5-cm and 71.0-cm rows were 1.82 and 1.78, respectively. However, in our study row spacing did not influence the core:bast ratio, contrary to what Wilson and Joyner (1969) reported, in which planting kenaf in narrow rows and high plant populations resulted in a greater bast percentage, probably because the stalk diameter was smaller.

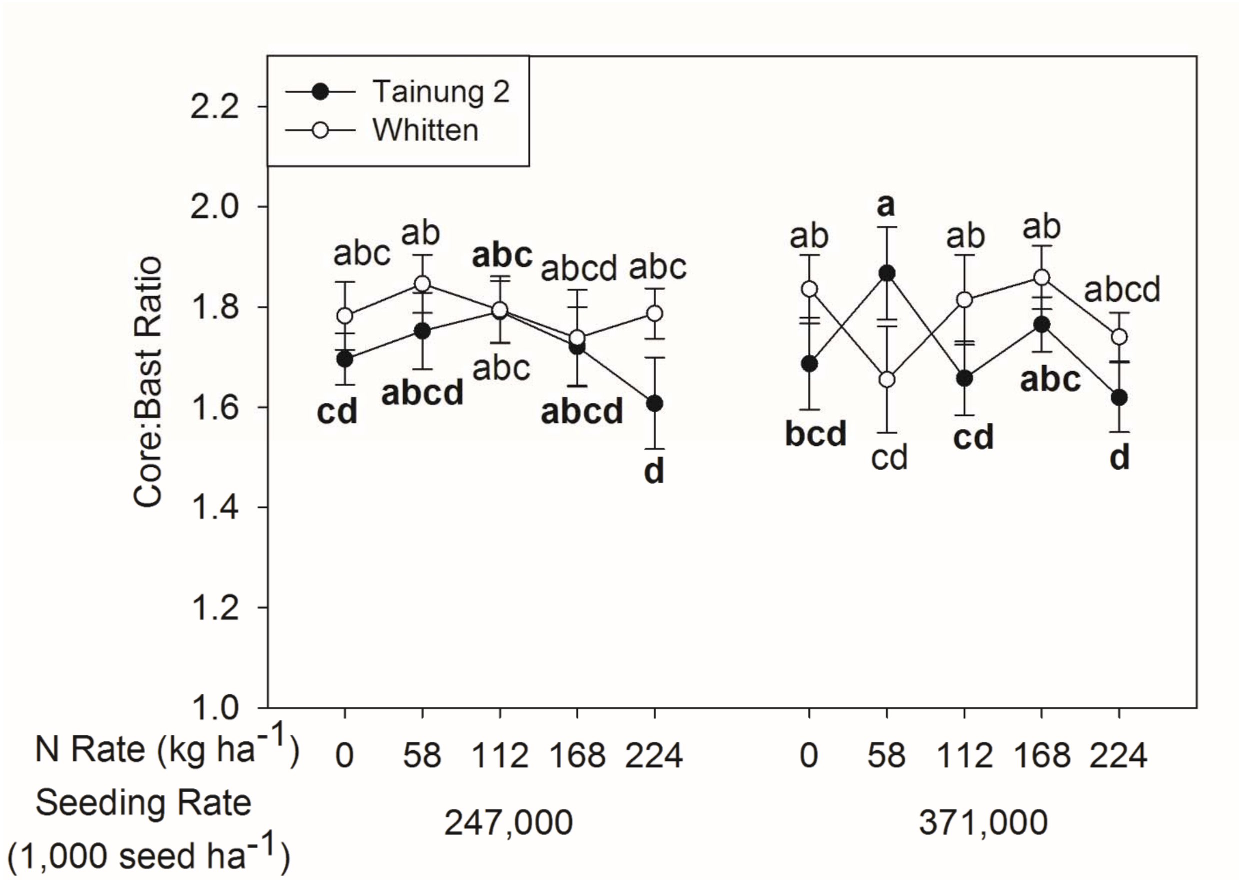


Figure 3. Core:bast ratio influenced by variety × row spacing × N rate (mean ± S.E) for Tainung 2 and Whitten plants grown at Boone, IA in 2014 and 2015. Different letters on top of the bars indicate differences between seeding rate × N rate × variety (Tainung, bold; Whitten, standard).

Similarly to Baldwin and Graham (2006), the core:bast ratio was variety-dependent, since Tainung 2 tended to have a greater core:bast ratio than Whitten. Few other studies have focused on the core and bast partitioning of Whitten in response to management practices. Bourguignon et al. (2016b) investigated the core:bast ratio of Tainung 2 and Whitten over time and showed that Whitten had a greater core:bast ratio than Tainung 2 during the growing season. However, the current study showed that Whitten had a lower core:bast ratio than Tainung 2 at the end of the growing season.

Overall, these results document that bast and core partitioning was not solely influenced by genotype. The genotype × environment interaction was highly important, as evidenced by variety, seeding and N rate. Kenaf is mainly cultivated for its bast fiber located on the outer part of the stem because bast fibers have greater economic value. The inner part of the stem contains core fiber, which has potential for biofuel (Bourguignon et al., 2016a) or for manufacturing biocomposite (Saba et al., 2015a), but currently is less valuable economically.

Kenaf height, diameter, and LAI change with time and the influence of the management practices

In-season changes

Morphological measurements were made every two weeks from planting to harvest, evaluating the response of kenaf to multiple combinations of management practices. Nitrogen rate was the most important factor affecting kenaf growth because it had a strong influence on height, diameter, and LAI in both years, (Supplemental Table 1; Fig. 4A). In mid-July 2015, kenaf receiving N fertilizer were approximately 5% taller than the control, regardless of N rate ($P < 0.0001$, Supplemental Table 1; 195 DOY, Fig. 4B). In general, kenaf grew very fast from 190 to 280 DOY, different than what was observed by Danalatos and Archontoulis (2005). In their study, kenaf grew quickly between 190 and 220 DOY and reached a plateau at 300 DOY. This may be explained by differences of latitude and climate. Also, in their study, applying 50, 100, or 150 kg N ha^{-1} did not influence kenaf development, which is not congruent with our results.

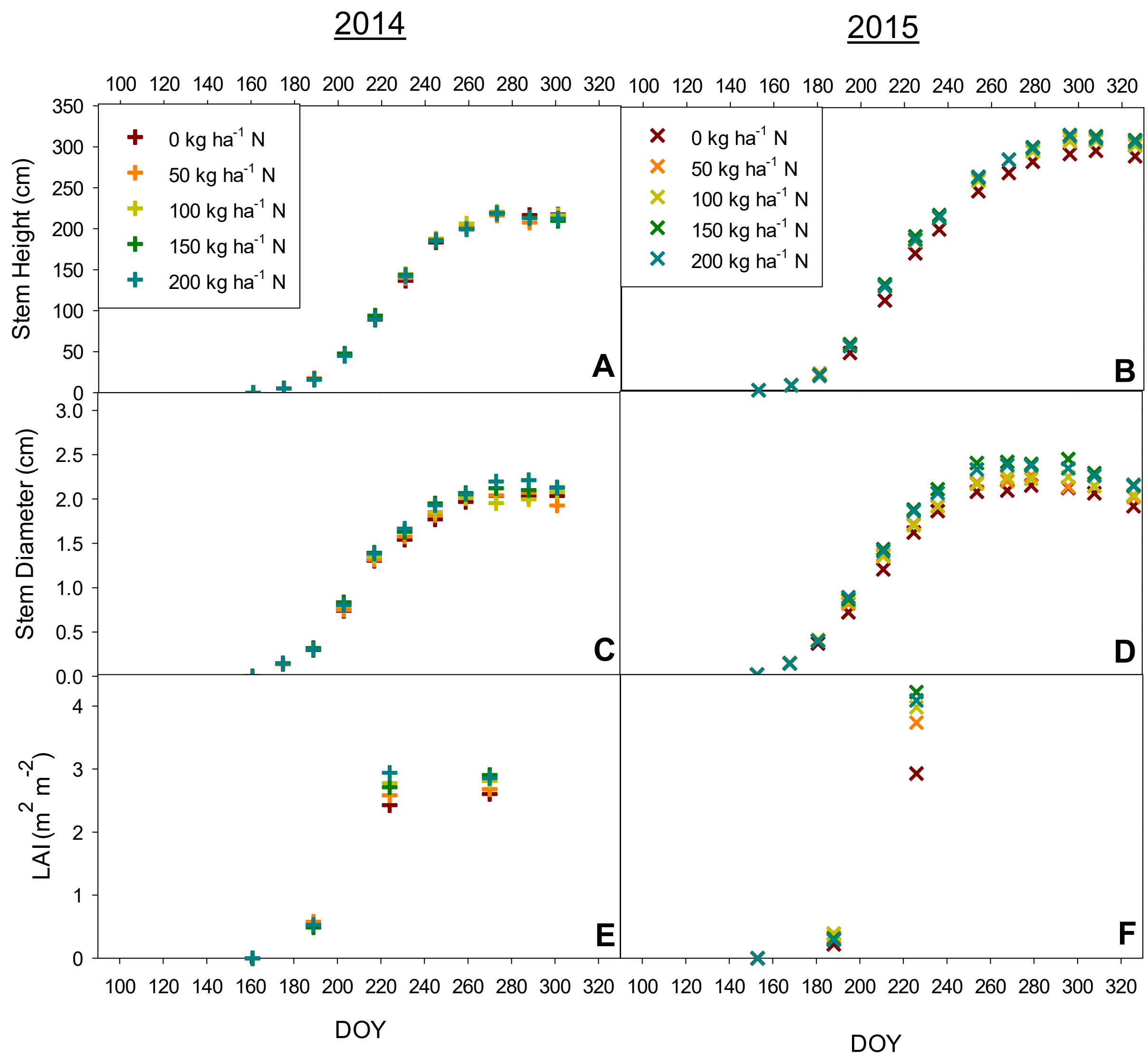


Figure 4. Stem height (mean; 2014, A and 2015, B), basal diameter (mean; 2014, C and 2015, D), and LAI (mean; 2014, E and 2015, F) of kenaf plants on various days of the year (DOY) that have received five different N rates, when grown in Boone, IA, in 2014 and 2015. Values averaged over variety, seeding rate, and row spacing.

Applying 168 or 224 kg N ha^{-1} often resulted in thicker stem diameter, especially for September and October dates in 2014 (273 – 288 DOY, Fig. 3C) and from mid-August to the end of the growing season in 2015 (225 - 326 DOY, Fig. 3D). Few studies have followed kenaf stem diameter throughout the growing season. Hossain et al. (2010) measured stem diameter every seven days, but they averaged their results over the replications of their study for all dates. Therefore, it was not possible to understand height and diameter trends during the growing season. The current study contradicted Danalatos and Archontoulis (2005) who reported that stem diameter did not vary with N rate.

The LAI was also influenced by N fertilization and it was greater in both years when N rates higher than 112 kg ha^{-1} were applied; LAI was lowest when no N was applied (Supplemental Table 1; Fig. 4E, F). These findings confirmed several earlier reports on N fertilization rate influences on kenaf LAI. Kenaf LAI attained 4 and 6 m^2 m^{-2} and it was significantly enhanced when N was applied in Australia (Muchow, 1990; Carberry and Muchow, 1992). Also, applying 100 or 150 kg N ha^{-1} resulted in a 18% increase of LAI from 220 to 260 DOY in Greece (Danalatos and Archontoulis, 2005).

Nitrogen fertilization was not the only treatment that influenced plant morphology during the growing season. In the first year, kenaf planted at 247,000 seeds ha^{-1} had slightly taller and thicker stems than when planted at 371,000 seeds ha^{-1}, especially at the end of the growing season (Fig. 5A, C). In the second year, Tainung 2 generally produced taller stalks than Whitten, but growing Tainung 2 at 247,000 seed ha^{-1} in 76-cm rows was the best combination of treatments to reach the greatest stem height, which was observed from October 2015 to the final harvest (from 296 to 326 DOY; Fig. 5B). That same year, stem diameter was less sensitive to management practices than stem height, as kenaf planted at 247,000 seeds ha^{-1} consistently presented thicker stem than when planted at 371,000 seeds ha^{-1} (Fig. 5D). Moreover, kenaf planted at 76-cm row spacing almost always had thicker stems than when planted in 38-cm rows (Fig. 5E, F).

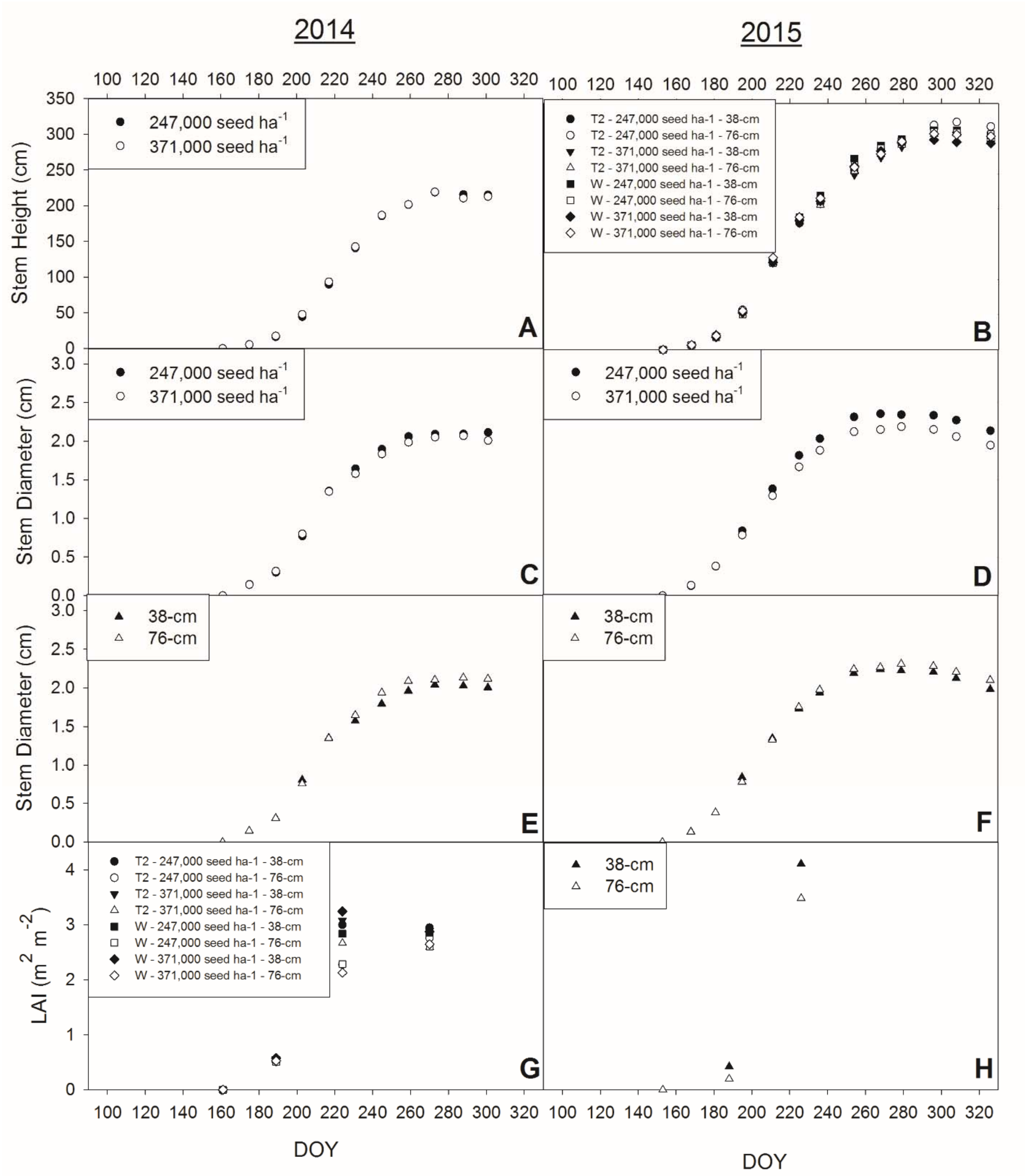


Figure 5. Kenaf stem height influenced by seeding rate (mean; 2014, A) and by the interaction between variety seeding rate, and row spacing (mean; 2015, B); basal diameter influenced by seeding rate (mean; 2014, C and 2015, D) and by row spacing (mean; 2014, E and 2015, F), and LAI influenced by the interaction between variety seeding rate, and row spacing (mean.; 2014, G) and by row spacing (mean; 2015, H) on various days of the year (DOY).

Previous studies demonstrated that narrow rows and greater seeding rates increased stem yield, but that individual stems were smaller and thinner (White et al., 1971; Bhangoo et al., 1986), similar to what we report. In general, this study found that the less dense the plant stand, stems were taller and thicker, particularly in the second half of the growing season when competition likely increased for environmental resources such as light and water. Bhangoo et al. (1986) did not find any significant interaction between row spacing, seeding rate, and cultivar for stem height and diameter. However, they only reported results for final height and diameter.

In 2014, LAI varied between 2 and 3.5 m^2 m^{-2} in mid-August (224 DOY; Fig. 5G) and Tainung 2 generally that had the greater LAI. Tainung 2 and Whitten are known for their drastically different leaf shape: Tainung 2 has a deeply divided leaf and Whitten an the undivided leaf shape (Baldwin et al., 2006). This difference of shape, and potentially different leaf angle, may have played a role in the variation in LAI observed between the two varieties. Within varieties, low seeding rate and wide rows resulted in lower LAI than the high seeding rate and narrower rows. For Whitten, there was less variation among treatments than for Tainung 2. Contrary to stem height and basal diameter, LAI was greatest when kenaf was planted in 38-cm rows because the canopy was denser than in 76-cm rows (Fig. 5H).

End-of-season

At final harvest, stem height was influenced by row spacing, seeding rate, and the interaction of variety × N rate (Table 1). Kenaf height was 2% greater when grown in 76-cm rows than in 38-cm rows, and 3% greater when the initial seeding rate was 247,000 seed ha^{-1}

than 371,000 seed ha^{-1}. The interaction between seeding rate and row spacing was not significant. Therefore, potential recommendations would be to choose either row spacing or seeding rate to improve the stem height, which was positively correlated to stem yield (r = 0.46, Supplemental Table 2). However, it is important to note that seeding rate and row spacing effects on stem height were biologically small.

Stem height was sensitive to the variety × N rate interaction, contrary to stem yield which was not influenced by N application rate. Tainung 2 presented 3% taller stems than Whitten when 112 kg N ha^{-1} was applied (Fig. 6). However, when 224 kg N ha^{-1} was applied, Whitten had 3% taller stems than Tainung 2. In the light of these results, Whitten should be fertilized with an N rate ranging from 56 to 224 kg N ha^{-1} while Tainung 2 should receive 56 to 168 kg N ha^{-1}.

At harvest, the basal diameter was influenced by N rate and the interaction of variety × row spacing × seeding rate (Table 1). Kenaf diameter increased with increasing N application rate and time (Fig. 4). Tainung 2 had a smaller basal diameter when grown at 371,000 seed ha^{-1} compared to the other treatments regardless of row spacing (Fig. 7). Under the same seeding rate, Whitten had smaller stem diameter when grown in 38-cm rows (1.8 cm, Fig. 7). In general,

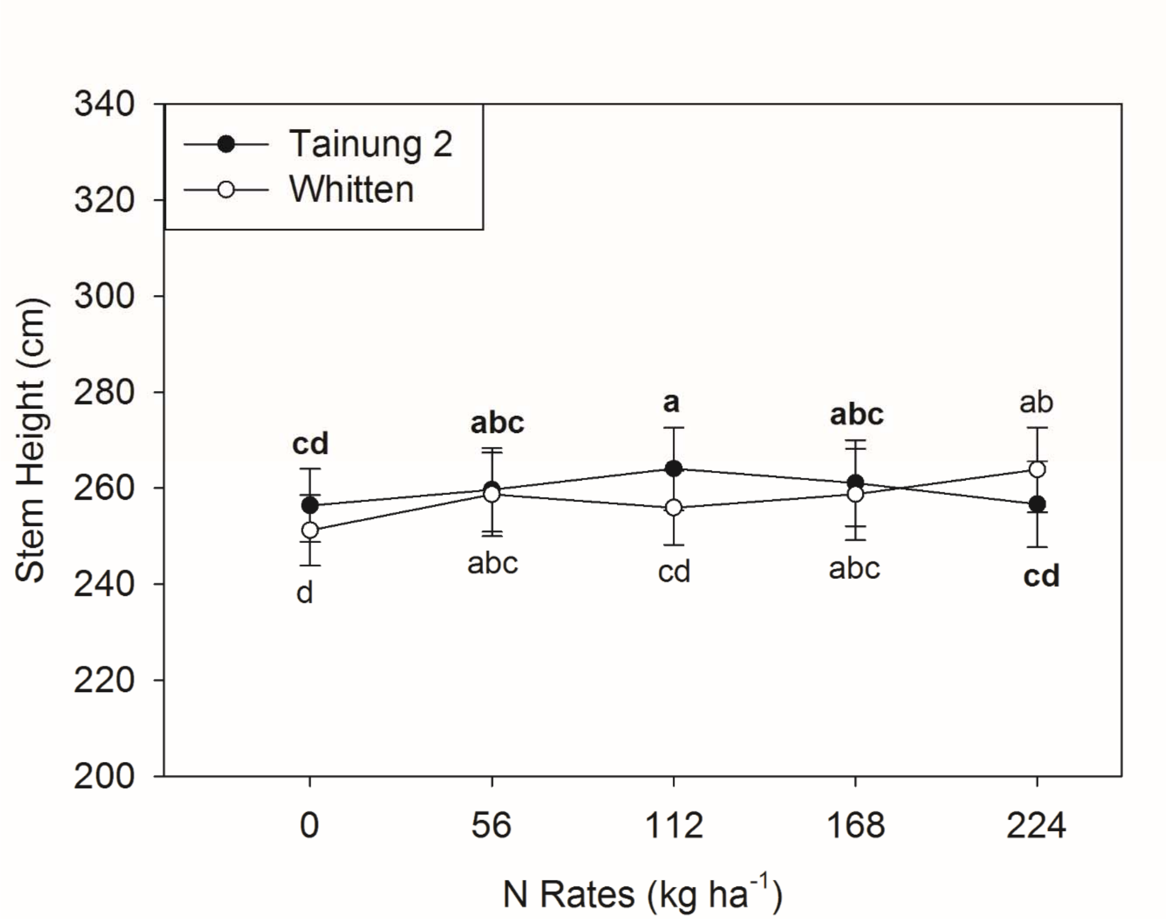


Figure 6. Stem height influenced by variety × N rate (mean ± S.E), when Tainung 2 and Whitten plants were grown at Boone, IA in 2014 and 2015. Different letters indicate significant differences between variety × seeding rate.

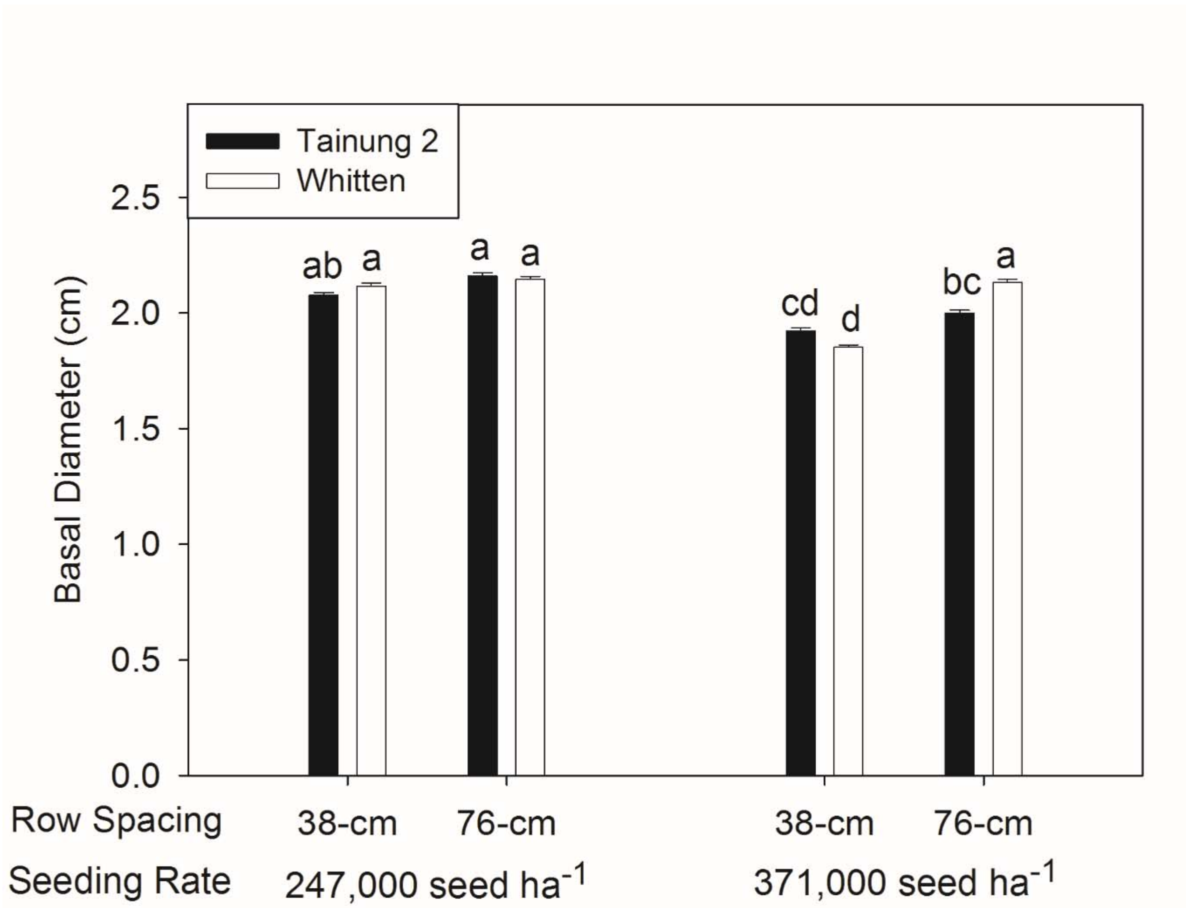


Figure 7. Basal diameter sensitive to variety × row spacing × seed rate (mean ± S.E.), when Tainung 2 and Whitten plants were grown at Boone, IA in 2014 and 2015. Different letters indicate significant differences between variety × row spacing × seeding rate.

stem diameter of both varieties was similar when grown with the 247,000 seed ha^{-1} (approximately 2.2 cm, Fig. 7). Again, this confirmed that, even at the last harvest, that denser stands produced thinner stems (Bhangoo et al., 1986). Basal diameter was not correlated with stem yield, but it was negatively correlated with plant density (Table 2).

Table 2. Pearson correlation coefficients for stem fiber yield, plant density, stem height, stem basal diameter, and core:bast fiber ratio across kenaf cultivars, planting rate, row spacing, N fertilization rate, and years.

		1	2	3	4
1	Stem DM Yield	1			
2	Plant Density	0.28**			
3	Stem Height	0.46**	0.10		
4	Basal Diameter	0.06	-0.43**	0.14*	
5	Core:Bast Ratio	0.27**	0.14*	0.60**	-0.10

**, * Significant at the 0.01 and 0.05 probability levels, respectively.

The greatest stem diameters occurred when 168 and 224 kg N ha^{-1} was applied (Table 1), supporting results of Houssain et al. (2010), but differing from those of Webber (1996). Surprisingly, in an earlier study in Iowa, diameters were not impacted by N rates (unpublished results), but this could be explained by the measurement of stem diameter at the mid-point instead of the basal end.

CONCLUSIONS

This study is a useful complement to previous work on kenaf research in Iowa by focusing on previously unresearched varietal and N rate effects. Variety × management interactions often influenced kenaf stem morphology. For instance, Tainung 2 was the best variety for Iowa with respect to stem yield but Whitten was more promising than Tainung 2 for bast fiber production based on the core:bast ratio results. The most striking result was that N fertilization did not increase stem yield. However, N rate did increase stem height and diameter during the growing season, as well as did plant density, which combined may improve standability and reduce pre-harvest lodging. We provide the first results on how management practices influence kenaf productivity and morphology during the growing season. Overall, we document that kenaf is well adapted to Iowa and could be an alternative crop once markets are established.

ACKNOWLEDGMENTS

This project was supported by the Iowa Agriculture Experiment Station and the Department of Agronomy, Iowa State University. The authors would like to thank the staff members who worked on this project: planting and management was done by Roger Hintz and Luke Hodnefield and field measurements were performed in part by Jérémie Bouriot in 2014.

REFERENCES

Adamson, W., F. Long, and M. Bagby. 1979. Effect of nitrogen fertilization on yield, composition, and quality of kenaf. Agron. J. 71:11-14.

Alexopoulou, E., M. Christou, M. Mardikis, and A. Chatziathanassiou. 2000. Growth and yields of kenaf varieties in central Greece. Ind. Crop. Prod. 11:163-172.

Alexopoulou, E., S.L. Cosentino, N. Danalatos, G. Venturi, A.L. Fernando, J.L. Tenorio, S. Cadoux, M. Veccheit, and E. Kipriotis. 2009. Biomass yields of kenaf in Europe: effect of site, year and cultural practices on yields. Proceedings of the 17th European biomass conference and exhibition, from research to industry and markets pp. 138-141

Anfinrud, R., L. Cihacek, B.L. Johnson, Y. Ji, and M.T. Berti. 2013. Sorghum and kenaf biomass yield and quality response to nitrogen fertilization in the Northern Great Plains of the USA. Ind. Crop. Prod. 50:159-165.

Baldwin, B., J. Hollowell, J. Mosley, and R. Cossar. 2006. Registration of 'Whitten' kenaf. Crop Sci. 46:988-989.

Baldwin, B.S., and J.W. Graham. 2006. Population density and row spacing effects on dry matter yield and bark content of kenaf (*Hibiscus cannabinus* L.). Ind. Crop. Prod. 23:244-248.

Bel-Berger, P., T. Von Hoven, G. Ramaswamy, L. Kimmel, and E. Boylston. 1999. Textile technology. J. Cotton Sci. 3:60-70.

Berti, M.T., S.R. Kamireddy, and Y. Ji. 2013. Row spacing affects biomass yield and composition of kenaf (*Hibiscus cannabinus* L.) as a lignocellulosic feedstock for bioenergy. J. Sustain. Bioenerg. Syst. 3:68-73.

Bhangoo, M., H. Tehrani, and J. Henderson. 1986. Effect of planting date, nitrogen levels, row spacing, and plant population on kenaf performance in the San Joaquin Valley, California. Agron. J. 78:600-604.

Bourguignon, M., K. Moore, R. Brown, K.H. Kim, B. Baldwin, and R. Hintz. 2016a. Variety trial and pyrolysis potential of kenaf grown in Midwest United States. Bioenerg. Res. J.:1-14.

Bourguignon, M., K. Moore, A. Lenssen, S. Archontoulis, B. Goff, and B. Baldwin. 2016b. Kenaf productivity and morphology, when grown in Iowa and in Kentucky. Ind. Crop. Prod. 94:596-609.

Brown, R.C., and T.R. Brown. 2014. Biorenewable resources: Engineering new products from agriculture. John Wiley & Sons, New York, NY.

Campbell, T., and G. White. 1982. Population density and planting date effects on kenaf performance. Agron. J. 74:74-77.

Carberry, P., and R. Muchow. 1992. A simulation model of kenaf for assisting fibre industry planning in Northern Australia. II. Leaf area development. Crop Pasture Sci. 43:1515-1526.

Carberry, P., R. Muchow, R. Williams, J. Sturtz, and R. McCown. 1992. A simulation model of kenaf for assisting fibre industry planning in northern Australia. I. General introduction and phenological model. Crop Pasture Sci. 43:1501-1513.

Cheng, Z., B.-R. Lu, K. Sameshima, D.-X. Fu, and J.-K. Chen. 2004. Identification and genetic relationships of kenaf (*Hibiscus cannabinus* L.) germplasm revealed by AFLP analysis. Genet. Resour. Crop. Ev. 51:393-401.

Ching, A., C.L. Webber, and S.W. Neill. 1992. Effect of location and cultivar on kenaf yield components. Ind. Crop. Prod. 1:191-196.

Danalatos, N., and S. Archontoulis. 2005. Irrigation and N-fertilization effects on kenaf growth and biomass productivity in central Greece. *In* M.J. Pascual-Villalobos, F.S. Nakayama, F.S. Bailey, C.A. Correal, and E. Schloman (eds) Proc. 2005 Annual meeting of the Assoc. Adv. Ind. Crops: Int. Conf. Ind. Crops Rural Devl, 17-21 September 2005, Murcia, Spain. pp. 879-888.

Danalatos, N., and S. Archontoulis. 2010. Growth and biomass productivity of kenaf (*Hibiscus cannabinus* L.) under different agricultural inputs and management practices in central Greece. Ind. Crop. Prod. 32:231-240.

Dempsey, J. 1975. Kenaf. Fiber crops. The University Presses of Gainesville, Gainesville, FL. 203-302.

Gironi, F., and V. Piemonte. 2011. Bioplastics and petroleum-based plastics: strengths and weaknesses. Energ. Source. A Recover. Utiliz. Environ. Eff. 33:1949-1959.

González Moreno, A., F.F. de Andrés, I. Walter, and J.L. Tenorio. 2004. Kenaf responses to irrigation and nitrogen fertilization in central region of Spain. Proceeding of the 2nd World Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection, Rome, Italy.

Hatfield, J.L., L.D. McMullen, and C.S. Jones. 2009. Nitrate-nitrogen patterns in the Raccoon River Basin related to agricultural practices. J. Soil Water Cons. 64:190-199.

Higgins, J., and G. White. 1970. Effects of plant population and harvest date on stem yield and growth components of kenaf in Maryland. Agron. J. 62:667-668.

Hossain, M.D., M.H. Musa, J. Talib, and H. Jol. 2010. Effects of nitrogen, phosphorus and potassium levels on kenaf (*Hibiscus cannabinus* L.) growth and photosynthesis under nutrient solution. J. Agric. Sci. 2:49.

I.N.F.O. 2016. Kenaf. International Natural Fiber Organization, http://www.naturalfibersinfo.org/natural-fibers/kenaf/ (accessed 28 Feb. 2017)

ISU Ag Climate. 2014. www.mesonet.agron.iastate.edu/agclimate/info.txt.

Jordan, D.L., J.S. Barnes, C.R. Bogle, T.M. Marshall, T. Corbett, C.R. Crozier, B. McLawhorn, and L. Fisher. 2005. Influence of cultural practices and crop rotation on kenaf yield in North Carolina. Crop Manag. 4:1.

Joyner, J., and F. Wilson. 1967. Effects of row and plant spacing and time of planting on seed yield of kenaf. Econ. Bot. 21:99-102.

Lauriault, L., and N. Puppala. 2009. The influence of rainfed and limited irrigation conditions and early vs. late plantings on kenaf as a potential industrial crop in the southern High Plains, USA. Ind. Crop. Prod. 29:549-553.

Mambelli, S., and S. Grandi. 1995. Yield and quality of kenaf (*Hibiscus cannabinus* L.) stem as affected by harvest date and irrigation. Ind. Crop. Prod. 4:97-104.

Manzanares, M., J. Tenorio, and L. Ayerbe. 1997. Sowing time, cultivar, plant population and application of N fertilizer on Kenaf in Spain's central plateau. Biom. Bioenerg. 12:263-271.

Massey, J.H. 1974. Effects of nitrogen levels and row widths on kenaf. Agron. J. 66:822-823.

Mohanty, A.K., M. Misra, and L.T. Drzal. 2005. Natural fibers, biopolymers, and biocomposites CRC Press.

Monti, A., and E. Alexopoulou. 2013. Kenaf: A multi-purpose crop for several industrial applications. New insights from the biokenaf project. Springer, Verlag, London.

Muchow, R. 1990. Effect of leaf nitrogen and water regime on the photosynthetic capacity of kenaf (*Hibiscus cannabinus* L.) under field conditions. Crop Pasture Sci. 41:845-852.

Muchow, R., and P. Carberry. 1993. A simulation model of kenaf for assisting fibre industry planning in northern Australia. V. Impact of different crop traits. Crop Pasture Sci. 44:731-744.

Patanè, C., and S.L. Cosentino. 2013. Yield, water use and radiation use efficiencies of kenaf (*Hibiscus cannabinus* L.) under reduced water and nitrogen soil availability in a semi-arid Mediterranean area. Eur. J. Agron. 46:53-62.

Pilbeam, C.J., B.S. Mahapatra, and M. Wood. 1993. Soil matric potential effects on gross rates of nitrogen mineralization in an orthic Ferralsol from Kenya. Soil Biol. Biochem. 25:1409-1413.

Reichman, G.A., D.L. Grunes, and F.G. Viets, Jr. 1966. Effect of soil moisture on ammonification and nitrification in two northern plains soils. Soil Sci. Soc. Amer. Proc. 39: 363-366.

Saba, N., M. Jawaid, K. Hakeem, M. Paridah, A. Khalina, and O. Alothman. 2015a. Potential of bioenergy production from industrial kenaf (*Hibiscus cannabinus* L.) based on Malaysian perspective. Renew. Sust. Energ. Rev. 42:446-459.

Saba, N., M. Paridah, and M. Jawaid. 2015b. Mechanical properties of kenaf fibre reinforced polymer composite: A review. Constr. Build. Mater. 76:87-96.

Steinwand, A.L., and T.E. Fenton. 1994. Landscape evolution and shallow groundwater hydrology of a till landscape in central Iowa. Soil Sci. Soc. Am. J. 59:1370-1377.

Wambua, P., J. Ivens, and I. Verpoest. 2003. Natural fibres: Can they replace glass in fibre reinforced plastics? Compos. Sci. Technol. 63:1259-1264.

Webber, C.L. 1993. Yield components of five kenaf cultivars. Agron. J. 85:533-535.

Webber, C.L. 1996. Response of kenaf to nitrogen fertilization. Progress in new crops. Wiley, New York, NY. 404-408.

Webber, C.L., and V.K. Bledsoe. 2002. Kenaf yield components and plant composition. Trends New Crop. Prod. 348-357.

White, G., W. Adamson, and J. Higgins. 1971. Effect of population levels on growth factors in kenaf varieties. Agron. J. 63:233-235.

White, G., and J. Higgins. 1964. Growing kenaf for paper. 2nd International Kenaf Conference, US Department of State, Agency for International Development.

Williams, J. 1966. Influence of row spacing and nitrogen levels on dry matter yields of kenaf (*Hibiscus cannabinus* L.). Agron. J. 58:166-168.

Wilson, F.D., and J. Joyner. 1969. Effects of age, plant spacing, and other variables on growth, yield, and fiber quality of kenaf, *Hibiscus cannabinus* L. US Dept. of Agriculture.

Wood, I., R. Muchow, and D. Ratcliff. 1983. Effect of sowing date on the growth and yield of kenaf (*Hibiscus cannabinus*) grown under irrigation in tropical Australia II. Stem production. Field Crops Res. 7:91-102.

Table 1. Stem dry matter (DM) yield, plant density, core:bast ratio, stem height, and basal diameter influenced by management practices for kenaf. Boone, IA.

		Stem yield	Plant density	Core:bast ratio	Stem height	Basal diameter
		Mg ha^{-1}	plants ha^{-1}		cm	cm
Variety						
Tainung 2		10.1 a†	201,150	1.72 b	259	2.04
Whitten		9.5 b	192,916	1.78 a	258	2.06
Row Spacing						
38-cm		9.9	198,567	1.76	256 b	1.99 b
76-cm		9.7	195,000	1.74	261 a	2.11 a
Seeding Rate						
247,000 seed ha^{-1}		9.6	166,276 b	1.75	262 a	2.12 a
371,000 seed ha^{-1}		10.0	227,791 a	1.75	255 b	1.98 b
Nitrogen Rate						
0 kg ha^{-1} N		9.6	199,671 b	1.75 ab	254 b	1.97 c
56 kg ha^{-1} N		9.8	214,168 a	1.78 a	259 a	1.97 c
112 kg ha^{-1} N		10.4	202,193 ab	1.76 ab	260 a	2.05 b
168 kg ha^{-1} N		9.9	190,118 bc	1.77 a	260 a	2.13 a
224 kg ha^{-1} N		9.4	179,017 c	1.69 b	260 a	2.13 a
				ANOVA		
Source	df					
Variety (V)	1	*	NS	**	NS	NS
Row Spacing (R)	1	NS	NS	NS	**	***
V × R	1	NS	NS	NS	NS	NS
Seeding Rate (S)	1	NS	***	NS	**	***
V × S	1	NS	NS	NS	NS	NS
R × S	1	NS	NS	NS	NS	*
V × R × S	1	NS	**	NS	NS	**
Nitrogen Rate (N)	4	NS	***	NS	NS	***
V × N	4	NS	NS	NS	*	NS
R × N	4	NS	NS	NS	NS	NS
V × R × N	4	NS	NS	NS	NS	NS
S × N	4	NS	NS	NS	NS	NS
V × S × N	4	NS	NS	*	NS	NS
R × S × N	4	NS	NS	NS	NS	NS
V × R × S × N	4	NS	NS	NS	NS	NS

*,**, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively. NS, nonsignificant ($P > 0.05$).

† Different letters denote significant differences between treatments.

Table 2. Pearson correlation coefficients for stem fiber yield, plant density, stem height, stem basal diameter, and core:bast fiber ratio across kenaf cultivars, planting rate, row spacing, N fertilization rate, and years.

		1	2	3	4
1	Stem DM Yield	1			
2	Plant Density	0.28**			
3	Stem Height	0.46**	0.10		
4	Basal Diameter	0.06	-0.43**	0.14*	
5	Core:Bast Ratio	0.27**	0.14*	0.60**	-0.10

**, * Significant at the 0.01 and 0.05 probability levels, respectively.

Figure Captions

Figure 1. Monthly average air temperature (A) and cumulative precipitation (B) in 2014 and 2015, in Boone County, Iowa, compared to the 30-year period (1984 - 2014).

Figure 2. Plant density influenced by variety × row spacing × seeding rate (mean ± S.E) for Tainung 2 and Whitten plants grown at Boone, IA in 2014 and 2015. Different letters on top of the bars denote significant differences between variety × seeding rate × row spacing treatments.

Figure 3. Core:bast ratio influenced by variety × row spacing × N rate (mean ± S.E) for Tainung 2 and Whitten plants grown at Boone, IA in 2014 and 2015. Different letters on top of the bars indicate differences between seeding rate × N rate × variety (Tainung, bold; Whitten, standard).

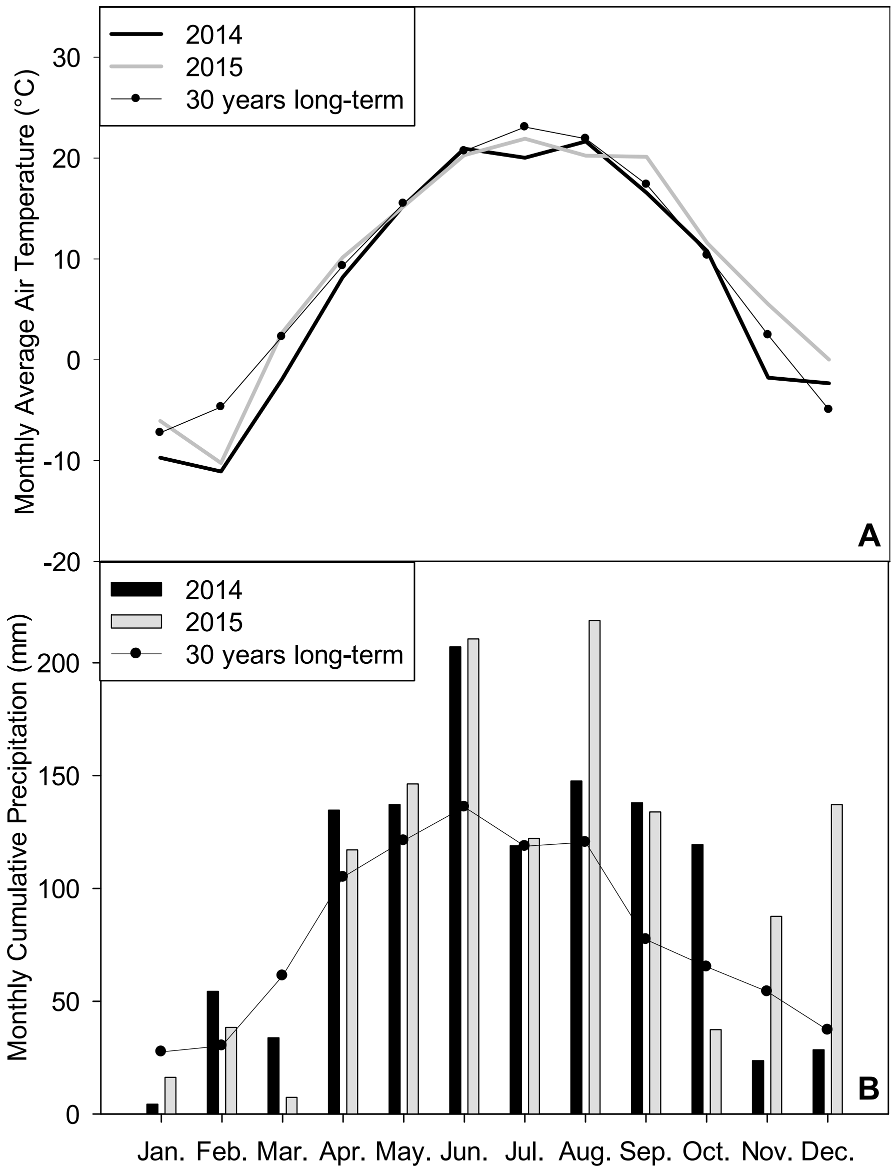
Figure 4. Stem height (mean; 2014, A and 2015, B), basal diameter (mean; 2014, C and 2015, D), and LAI (mean; 2014, E and 2015, F) of kenaf plants on various days of the year (DOY) that have received five different N rates, when grown in Boone, IA, in 2014 and 2015. Values averaged over variety, seeding rate, and row spacing.

Figure 5. Kenaf stem height influenced by seeding rate (mean; 2014, A) and by the interaction between variety seeding rate, and row spacing (mean; 2015, B); basal diameter influenced by seeding rate (mean; 2014, C and 2015, D) and by row spacing (mean; 2014, E and 2015, F), and LAI influenced by the interaction between variety seeding rate, and row spacing (mean.; 2014, G) and by row spacing (mean; 2015, H) on various days of the year (DOY).

Figure 6. Stem height influenced by variety × N rate (mean ± S.E), when Tainung 2 and Whitten plants were grown at Boone, IA in 2014 and 2015. Different letters indicate significant differences between variety × seeding rate.

Figure 7. Basal diameter sensitive to variety × row spacing × seed rate (mean ± S.E.), when Tainung 2 and Whitten plants were grown at Boone, IA in 2014 and 2015. Different letters indicate significant differences between variety × row spacing × seeding rate.

Figure 1



2014
2015
30 years long-term
Monthly Average Air Temperature (°C)
30
20
10
0
-10
-20
A
2014
2015
30 years long-term
Monthly Cumulative Precipitation (mm)
200
150
100
50
0
B
Jan. Feb. Mar. Apr. May. Jun. Jul. Aug. Sep. Oct. Nov. Dec.

Figure 2.

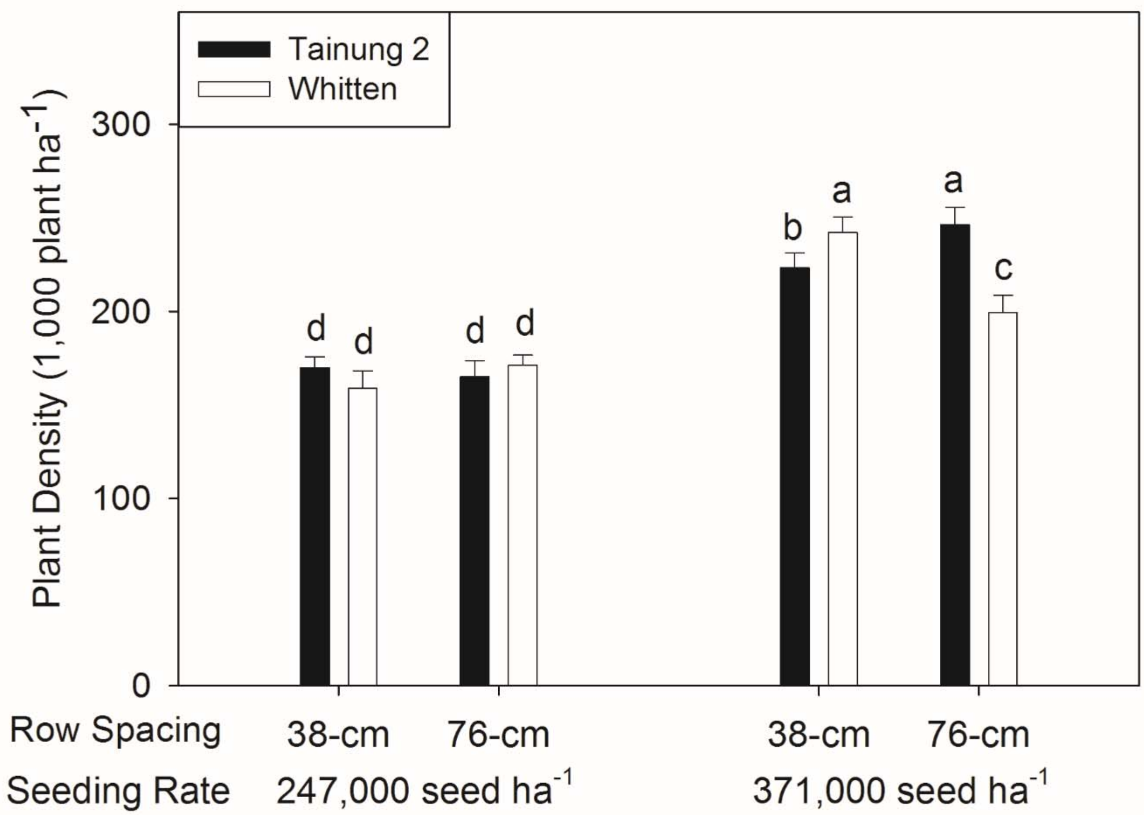

Tainung 2
Whitten
Plant Density (1,000 plant ha^{-1})
300
200
100
0
d
d
d
d
b
a
a
c
Row Spacing
38-cm
76-cm
38-cm
76-cm
Seeding Rate
247,000 seed ha^{-1}
371,000 seed ha^{-1}

Figure 3

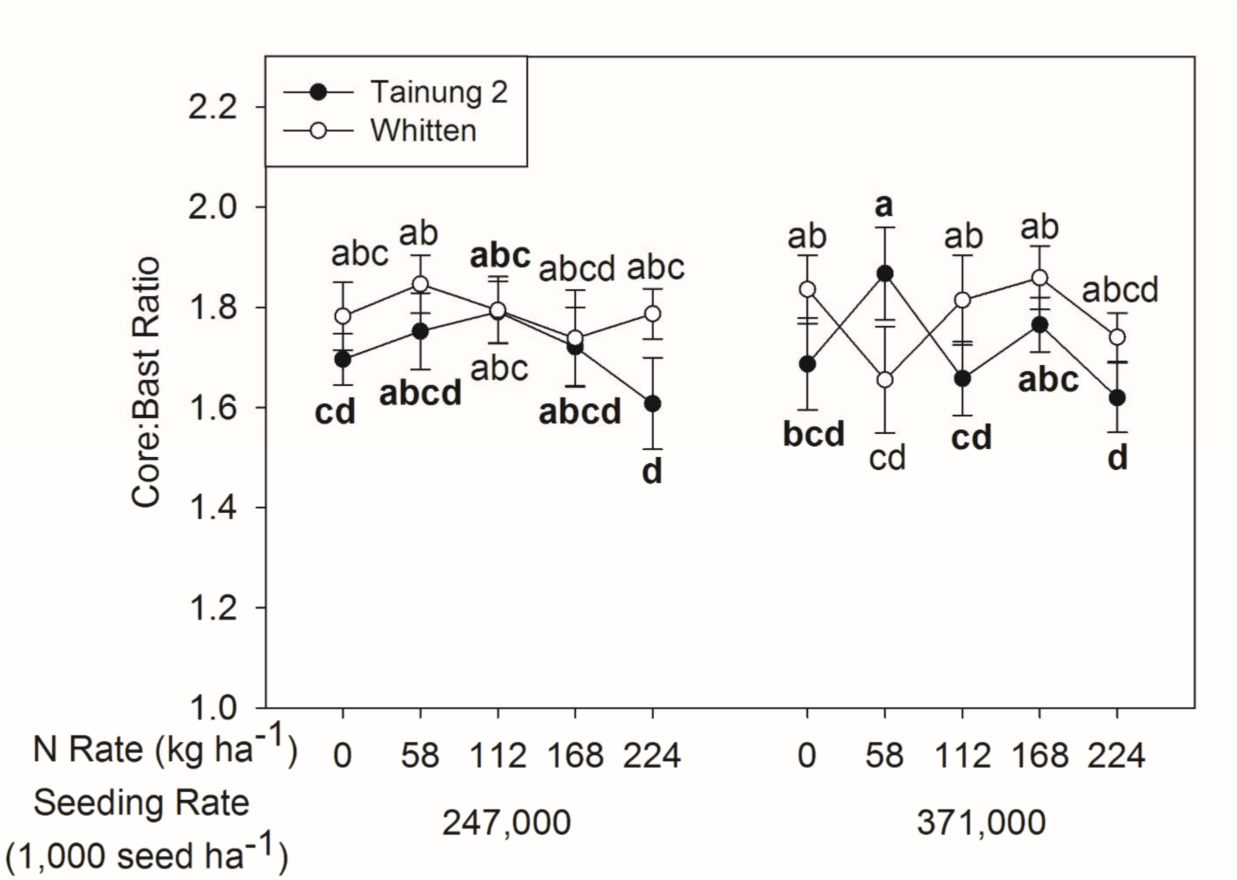
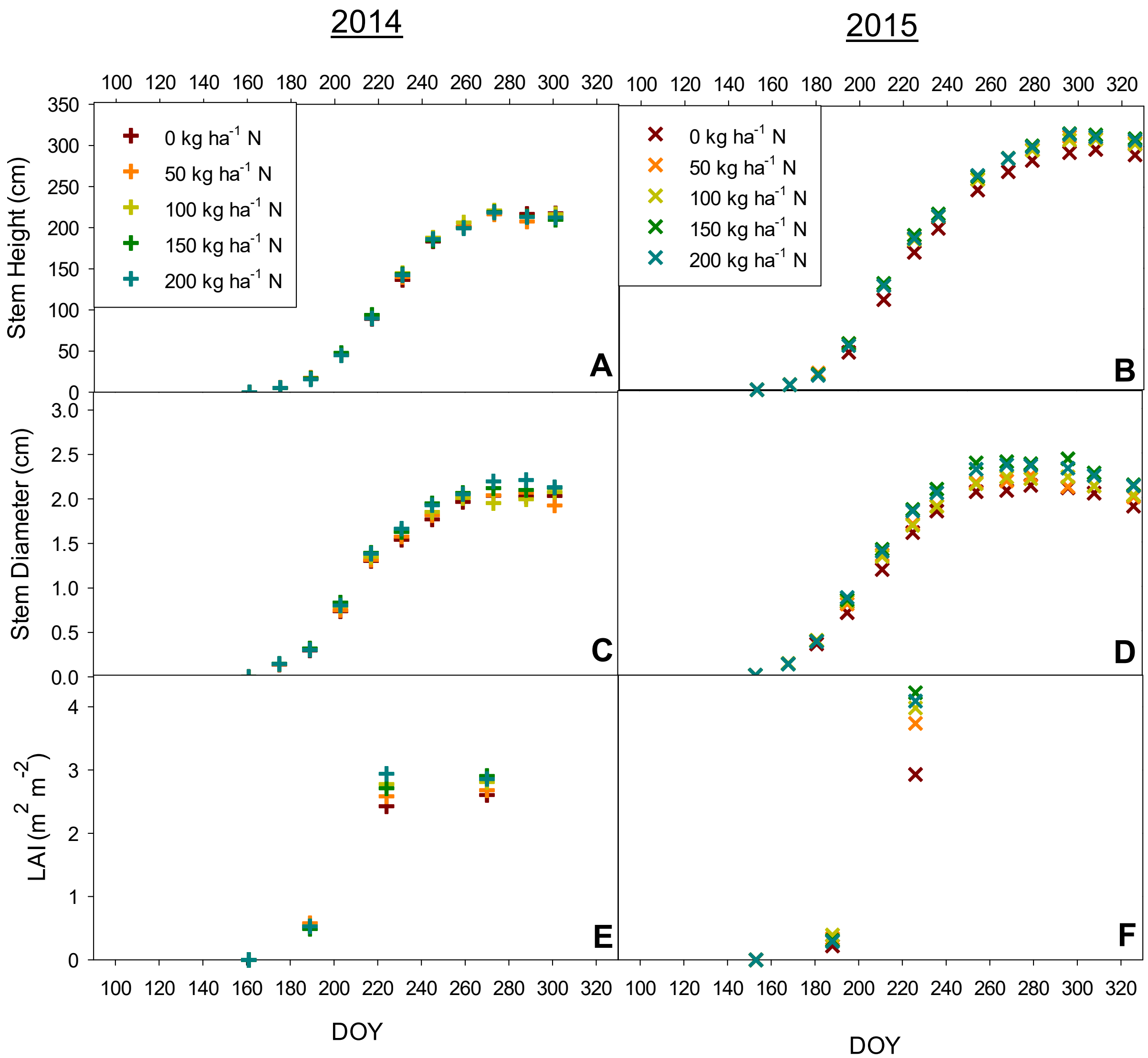
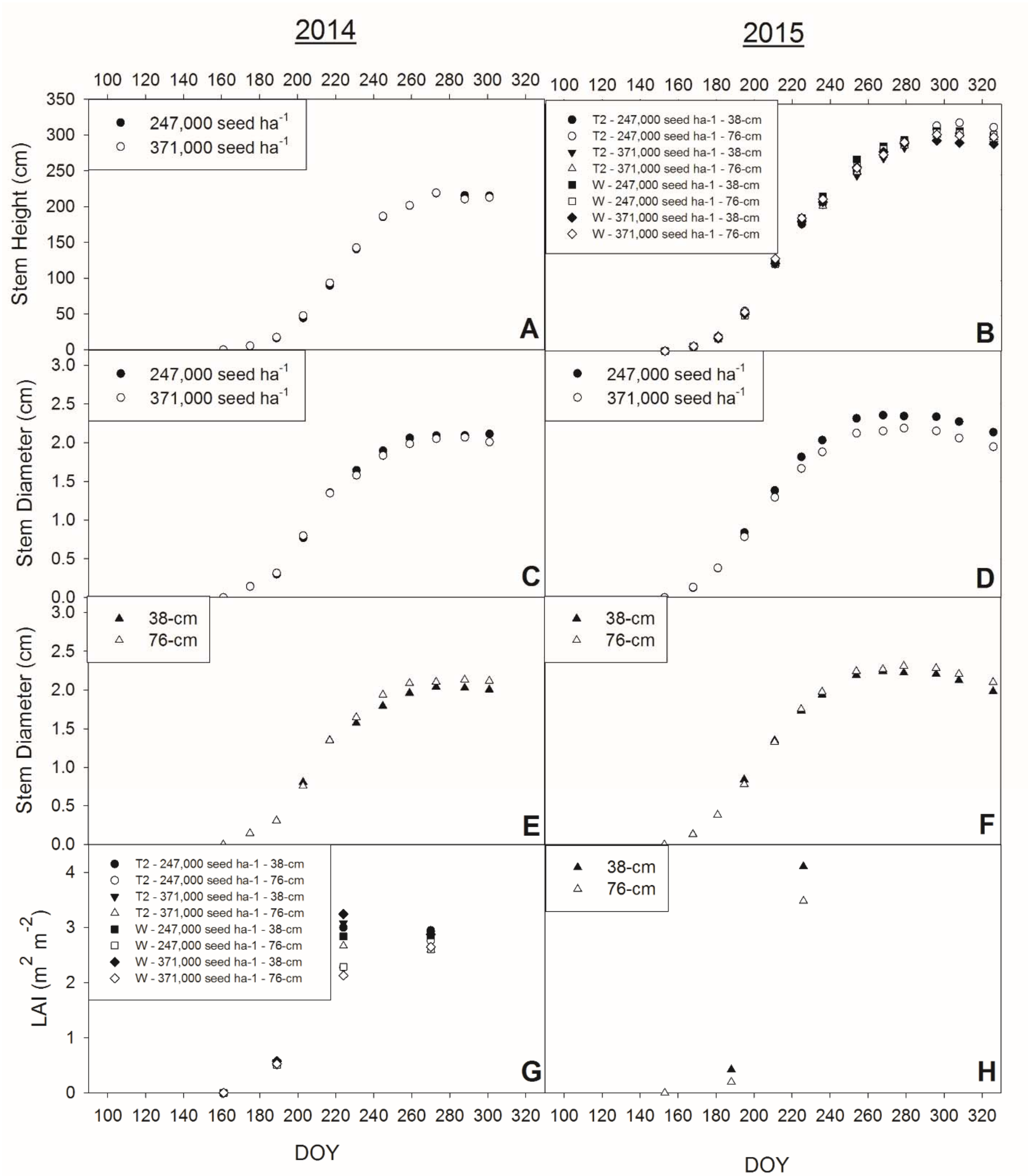

Tainung 2
Whitten
Core:Bast Ratio
2.2
2.0
1.8
1.6
1.4
1.2
1.0
abc
ab
abc
abcd
abc
cd
abcd
abc
abcd
d
ab
a
ab
ab
abcd
bcd
cd
cd
abc
d
N Rate (kg ha^{-1})
0 58 112 168 224
0 58 112 168 224
Seeding Rate
(1,000 seed ha^{-1})
247,000
371,000

Figure 4



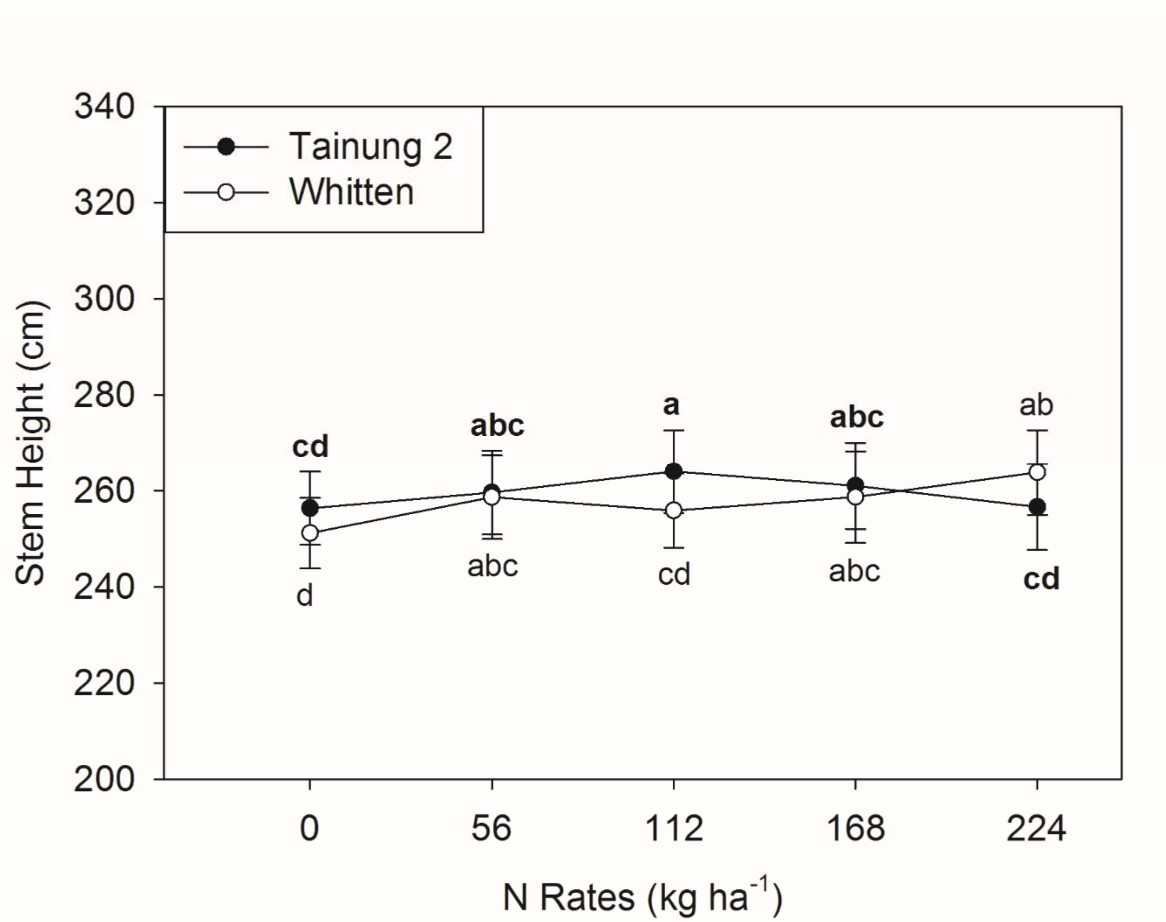
2014
2015
0 kg ha^{-1} N
50 kg ha^{-1} N
100 kg ha^{-1} N
150 kg ha^{-1} N
200 kg ha^{-1} N
Stem Height (cm)
Stem Diameter (cm)
LAI (m^2 m^{-2})
A
B
C
D
E
F
DOY
DOY

Figure 5



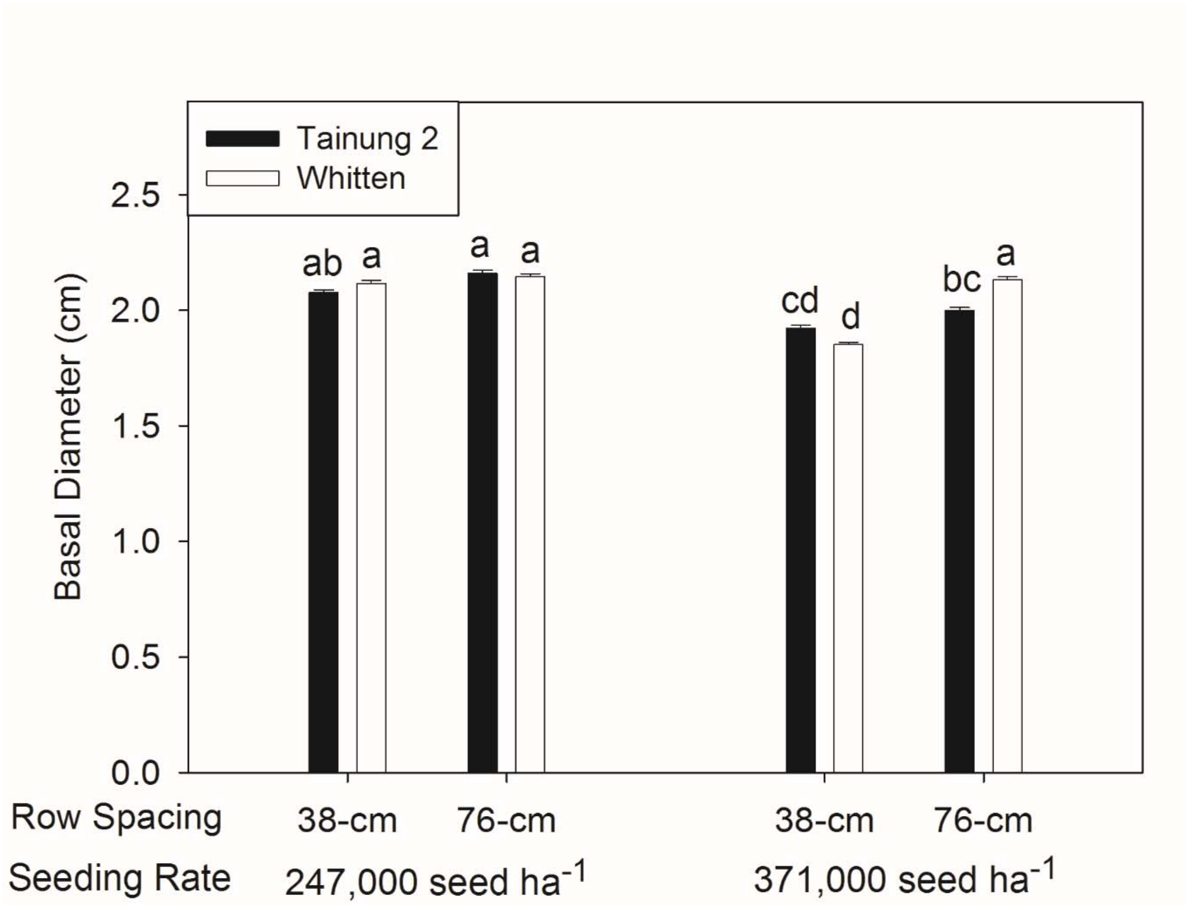
2014
2015
Stem Height (cm)
247,000 seed ha^{-1}
371,000 seed ha^{-1}
T2 - 247,000 seed ha-1 - 38-cm
T2 - 247,000 seed ha-1 - 76-cm
T2 - 371,000 seed ha-1 - 38-cm
T2 - 371,000 seed ha-1 - 76-cm
W - 247,000 seed ha-1 - 38-cm
W - 247,000 seed ha-1 - 76-cm
W - 371,000 seed ha-1 - 38-cm
W - 371,000 seed ha-1 - 76-cm
A
B
Stem Diameter (cm)
C
D
38-cm
76-cm
E
F
LAI (m^2 m^{-2})
G
H
DOY

Figure 6



Tainung 2
Whitten
Stem Height (cm)
340
320
300
280
260
240
220
200
cd
abc
a
abc
ab
d
abc
cd
abc
cd
0
56
112
168
224
N Rates (kg ha-1)

Figure 7



Tainung 2
Whitten
Basal Diameter (cm)
2.5
2.0
1.5
1.0
0.5
0.0
ab
a
a
a
cd
d
bc
a
Row Spacing
38-cm
76-cm
38-cm
76-cm
Seeding Rate
247,000 seed ha-1
371,000 seed ha-1