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Irrigation and cultivar effect on flax fiber and seed yield in the Southeast USA

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ABSTRACT

Flax (*Linum usitatissimum* L.) is a potential winter crop for the Southeast USA that can be grown for both seed and fiber. The objective of this research was to evaluate the effect of irrigation on flax straw, fiber, and seed yield of fiber-type and seed-type cultivars at different flax growth stages. The study was conducted during the winter growing seasons of 2010/2011, 2011/2012, and 2012/2013 near Florence, SC. Four fiber-type cultivars and one seed-type cultivar were grown with and without irrigation for two years. The four fiber-types were evaluated for straw and fiber yield in the third year. Soil water was monitored to trigger irrigations. Irrigation was applied before all four harvests in 2010/2011, before only the last harvest in 2011/2012, and was not applied in 2012/2013. Straw harvests were made at the onset of flowering, 10 days past the onset of flowering, 20 days past the onset of flowering, and when seeds were mature. Seed harvests were made at the end of the 2011/2012 and 2012/2013 growing seasons. In 2010/2011, plots had to be replanted in February so crop development was delayed. Irrigation increased straw yield at the last three harvests in that year. In the other two years, when planting occurred at normal times in the fall, irrigation did not influence straw or fiber yield. Irrigation had no significant effect on seed yield. The fiber-type cultivars did not differ for straw or fiber yield. At the onset of flowering harvest, the seed-type cultivar had similar fiber content to the fiber-type cultivars. The fiber-type cultivars had higher fiber content in later harvests. The results support previous research in that fiber-type cultivars appear viable for production as fiber winter crops in the region. The results also suggest that high straw yielding seed-type cultivars could be used, especially in systems with early straw harvests.

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1. Introduction

Flax (*Linum usitatissimum* L.) is a potential winter crop for the Southeast USA that can be grown for both seed and fiber (Parks et al., 1992; Foulk et al., 2004a). Fiber production has been of particular interest in the region as a feedstock for the paper, composite, and textile industries (Foulk et al., 2007). There are two types of cultivars that can be grown; fiber-type and seed-type (Foulk et al., 2004a). Fiber-type cultivars are taller, have fewer branches, and produce less seed than seed-type cultivars. Research comparing current fiber-type cultivars to seed-type cultivars in the region is limited. Irvine et al. (2010) reported that fiber-type European cultivars had higher fiber yields than seed-type cultivars under Canadian prairie conditions.

Relatively little research has been conducted in the Southeast USA on irrigation for flax fiber production. Rainfall during the flax winter growing period in the Southeast USA usually approaches or exceeds 700 mm, but timing of the precipitation is variable. Flax has been shown to respond to irrigation. Alessi and Power (1970) reported higher seed yield in one of two years with 5.0 cm of irrigation during the seed development period. Similarly, Lisson and Mendham (2000) found that irrigation increased flax straw and seed yield when precipitation was low and with poor distribution. Bauer and Frederick (1997) conducted a two-year study on flax in adjacent irrigated and rainfed areas and found the irrigated flax had approximately 1000 kg ha^{-1} higher straw yield.

When only the fiber is of interest, harvest can be done before seeds are mature (Robinson, 1931) which allows for timelier summer crop planting. Only a limited amount of information is available on how harvest timing affects flax straw and fiber yield in the Southeast (Foulk et al., 2004b). The objective of this research was to evaluate the effect of irrigation on flax straw, fiber, and seed yield of fiber-type and seed-type cultivars.

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2. Materials and methods

Field experiments were conducted near Florence, SC during the 2010–2011, 2011–2012, and 2012–1013 winter growing seasons. The three seasons of the study will be referred to by the year of the spring harvest (2011, 2012, and 2013). The experiments were conducted in a field with a center pivot irrigation system that was modified to allow for site-specific application of water (Camp et al., 1998). The soil was Norfolk loamy sand soil (Typic Kandiudult). Treatments each year were irrigation (irrigated and rainfed) and cultivar. During 2011 and 2012, the experiment included four fiber-type cultivars ('Agatha', 'Caesar Augustus', 'Electra', and 'Melina') and one seed-type cultivar ('Flanders'). Only the four fiber-type cultivars were grown in the 2013 trial. Experimental design was randomized complete block with a split-plot treatment arrangement. Irrigation levels were the main plots and cultivars were the subplots. There were four replicates. Subplot size was 3.05 m wide (16 rows spaced 19.1 cm apart) by approximately 91 m long.

In the first year of the study, the experiment was planted on 9 November 2010. Severe stand reductions occurred due to an ice storm in early January 2011; therefore the experiment was replanted on 15 February 2011. Planting date was 3 November 2011 for the 2012 season. For the 2013 season, planting began on 14 November 2012 but was interrupted by heavy rain. Planting was resumed and finished on 19 November 2012. Planting was done each year with a John Deere model 750 grain drill (Deere and Co., Moline, IL). Seeds were planted approximately 2 cm deep at a rate of 134 kg seed ha^{-1}. Soil samples were collected prior to planting each season and lime, P, and K were broadcast applied based on soil test results. 22 kg N ha^{-1} was applied in the preplant fertilizer application. Additional N fertilizer (as urea-ammonium nitrate) was applied via the irrigation system during the spring each year. During the first two seasons, 88 kg N ha^{-1} was applied in April 2011 and in February 2012. During the 2013 season, an 88 kg N ha^{-1} application was made in February. Significant amounts of precipitation occurred following the N application and much of the N could have been lost as plants appeared N deficient in late March. An additional 44 kg N ha^{-1} was applied at that time.

Weeds were managed with preplant and post-emergent herbicides. Rashid (1998) reported first observing powdery mildew (*Oidium lini* Skoric) on flax in Canada in 1997. We had not observed this disease in previous research, but in both 2011 and 2012 we observed powdery mildew on some of the plants. In 2013, two fungicide (pyraclostrobin) applications were made (early March and early April) to control this disease.

Soil water at the 30-cm depth was monitored with tensiometers in each subplot of the irrigated plots to trigger irrigation events. Tensiometers were placed in the plots in the spring of each year after any threat of hard freezes. Irrigation (1.2 or 2.5 cm) was applied when tensiometers averaged −30 kPa. In the 2011, 1.2 cm of irrigation was applied on 20 and 29 April and on 4, 9, 12, 13, 23, and 25 May. In addition, 2.5 cm of irrigation was applied on 28 April and 6 May. In 2012 season, 1.2 cm of irrigation was applied on 12, 13, 18, and 20 May and 2.5 cm of irrigation was applied on 16 May. All of these occurred after the third harvest that year. Tensiometers did not reach −30 kPa in 2013 so no irrigation applications were made. Rainfall and temperature data were collected with a weather station in an adjacent field.

The first harvest each year was made at the onset of flowering (when a majority of the plants had blooms). Two subsequent harvests were made at approximately ten day intervals. A fourth harvest was made when seeds were mature. Cutting dates for the harvests were 27 April, 5 and 16 May and 14 June in 2011; 22 March, 2 and 12 April, and 29 May in 2012; and 11 and 22 April, 2 and 29 May in 2013.

In 2011, a 60 m^2 area of each subplot (3 m × 20 m) at each harvest date was cut with a 1.5 m wide disc mower. The flax straw was left on the soil surface to dew ret. When the straw was well-retted, it was raked into windrows and baled. The bales were weighed and a 200–500 g sample of the straw was collected for determining water content. Water content was determined by drying the samples at 60 °C for three days in a forced-air oven. The bales were transported to the Cotton Quality Research Station in Clemson, SC, where they were processed at USDA Flax Fiber Pilot Plant to separate fiber from the stalks using procedures described by Akin et al. (2005). Fibers obtained from the process were weighed to calculate fiber content. The USDA Flax Fiber Pilot Plant was not available for the last two seasons of the study. In those seasons, a 60 m^2 area of each plot was cut with the disc mower and the flax was allowed to dry on the soil surface for several days. During the first three harvests of 2012, the flax straw in each plot was baled and the bales weighed as in 2011. At the last harvest in 2012 and all four harvests in 2013, yield was determined on only a portion of each 60 m^2 area. For those harvests, straw in a 9.2 m^2 area (1.5 m × 6.2 m) was hand-raked onto a tarp and weighed. Samples were collected as in 2011 for determining water content.

A second straw sample was collected from each plot in 2012 and 2013 for determining fiber content. These samples were water-retted in 19 L buckets for three to five days. Water in the buckets was changed after two days. Retted samples were then air-dried. Fiber was separated from the stems by breaking a 50 g sample of the retted straw on a flax break and passing the straw through a chain-drive bench carder (Strauch Fiber Equipment Co., New Castle, VA) four times. Fibers obtained after carding were weighed.

All data were subjected to analysis of variance. To compare irrigation and cultivar-type effects on flax, analysis was conducted on the data from 2011 and 2012 at each harvest in each year because the irrigation timings and amounts vastly differed among harvests and years. Single degree of freedom contrasts were conducted to compare the mean of the four fiber-type cultivars to the seed-type cultivar in the 2011 and 2012 seasons. Because no irrigations were applied and Flanders was not grown in 2013, analysis of variance was conducted to compare the four fiber lines for productivity under Southeast USA growing conditions without water deficit stress. Using just the irrigated data from 2011 and 2012 and all data from 2013, analysis was conducted across all harvest dates and the three years for straw yield, fiber content, and fiber yield. Analysis across 2011 and 2012 was conducted to evaluate whether differences occurred for irrigated seed yield and 100 seed weight among the four fiber-type cultivars.

3. Results

3.1. Irrigation effects on flax

The three years had quite dissimilar rainfall amount and distribution resulting in different amounts and timings of spring irrigation applications. In 2011, irrigation applications began prior to the onset of bloom and continued through the rest of the season. A total of 12 cm of irrigation water was applied in 10 applications. Irrigation application increased flax straw yield in three of the four harvests and fiber yield in two of the four harvests (Table 1). In 2012, no irrigation applications were made prior to the first three harvests. Between the third harvest and the last harvest in that year, 7.3 cm of irrigation was applied in five applications, but these applications did not result in a significant straw or fiber yield difference from the rainfed flax (Table 1). In 2013, tensiometers never reached −30 kPa, so no irrigation was applied. The irrigation applications in 2011 and 2012 did not influence the straw fiber content (Table 1).

Table 1
Influence of irrigation on flax straw yield, percent fiber, and fiber yield for harvests that received irrigation prior to harvest.

Year	Harvest	Straw yield			Percent fiber		Fiber yield		
		Irrigated (kg ha^{-1})		Rainfed (kg ha^{-1})	Irrigated (%)	Rainfed (%)	Irrigated (kg ha^{-1})		Rainfed (kg ha^{-1})
2011	1	1855		1577	41.4	40.2	771		657
	2	3256	**	2180	39.9	39.2	1309	**	858
	3	3375	*	2731	35.8	34.9	1184		983
	4	5145	**	3378	31.5	31.4	1624	**	1070
2012	4	7030		6364	26.6	25.3	1865		1598

*,** indicate irrigated differed from rainfed at $P \leq 0.05$ and 0.01, respectively.

Table 2
Effect of irrigation on seed yield and one-hundred seed weight in 2011 and 2012.

Irrigation level	2011			2012	
	Seed yield (kg ha^{-1})	100-seed wt (g)		Seed yield (kg ha^{-1})	100-seed wt (g)
Irrigated	785	0.451	**	977	0.451
Rainfed	661	0.424		866	0.446

** indicates irrigated differed from rainfed at $P \leq 0.01$.

Irrigation did not significantly impact flax seed yield. Although not significant, average seed yield with irrigation was 19% higher than rainfed in 2011 and 13% higher than rainfed in 2012 (Table 2). Irrigation increased seed weight by 6% in 2011 (Table 2) but did not influence seed weight in 2012.

All five cultivars responded similarly to irrigation. No irrigation × cultivar interactions occurred for straw yield, fiber content, or fiber yield at any of the harvests in which irrigation was applied. Similarly, no irrigation × cultivar interactions occurred for seed yield or 100 seed weight in either year.

3.2. Comparison of fiber-type cultivars

Averaged over years and harvest dates, all four fiber-type cultivars had similar straw and fiber yield (Table 3). No year × cultivar, harvest × cultivar, or year × harvest × cultivar interactions were significant ($P \leq 0.05$) for straw or fiber yield. Averaged over 2011 and 2012, no significant differences occurred among the four fiber-type cultivars for seed yield or 100 seed weight (Table 3).

3.3. Comparison of fiber-type to seed-type cultivars

The seed-type cultivar was only evaluated during the first two growing seasons of this study. At each harvest time in the first year, when the experiment was replanted in February, the fiber-type cultivars had higher straw yield (Table 4). The yield advantage of the fiber-type cultivars in that season ranged from 38% at the third harvest to 50% at the first harvest. On the other hand, in the second year of the study with a normal planting date, the seed-type cultivar had 15% higher straw yield than the fiber-type cultivars at the third harvest time and similar yield at the other three harvests (Table 4).

Fiber content did not differ between the two cultivar types at the first harvest date in either year (Table 4). This was not expected as fiber-type cultivars generally have higher fiber content. At all subsequent harvests in both years, the fiber-type cultivars had higher fiber content than the seed-type cultivar. In 2011, the higher fiber contents along with the higher straw yields resulted in the fiber-type cultivars yielding 60–70% more fiber than the seed-type cultivar. In 2012, fiber yield of the fiber-type cultivars was higher than the seed-type cultivar only at the second harvest time (Table 4).

As expected, the seed-type cultivar had higher seed yield than the fiber-type cultivar both years (Table 5). Seed weight for the seed-type cultivar was higher than the fiber-type cultivar in 2012 when flowering began in late March but not in 2011 when the late planting time delayed onset of flowering until late April (Table 5).

4. Discussion

The Southeast USA is a high rainfall area but a significant portion of the production fields have irrigation machines that are used primarily for summer crops. For winter flax, precipitation generally exceeds potential evapotranspiration from planting in the fall through early spring at Florence when stem growth is occurring, but potential evapotranspiration on average exceeds precipitation during the seed development period in April and May (unpublished data). Thus, it is not surprising that the response of flax to irrigation was not found for any harvest that occurred in March or April in any year suggesting that for flax grown for fiber with a normal planting date and harvested before seed maturity, supplemental irrigation is not necessary in most years. On the other hand, since potential evapotranspiration exceeds precipitation in April and May supplemental irrigation in flax fields grown for seed may be warranted. Flax responds to irrigation (Alessi and Power, 1970;

Table 3
Straw yield, fiber content, fiber yield, and seed yield of four European flax cultivars grown as winter crops. Straw and fiber data are from the irrigated plots only and are averaged over all three years and all four harvests. Seed yield data are averaged over 2011 and 2012. Means followed by the same letter are not significantly ($P = 0.05$) different.

Cultivar	Straw yield (kg ha^{-1})	Fiber content (g kg^{-1})	Fiber yield (kg ha^{-1})	Seed yield (kg ha^{-1})	100 Seed weight (g)
Agatha	4412 a	362 a	1569 a	655 a	0.462 a
Caesar Augustus	4235 a	358 a	1480 a	627 a	0.443 a
Electra	4334 a	357 a	1517 a	839 a	0.450 a
Melina	4223 a	343 a	1419 a	776 a	0.432 a

Table 4
Effect of cultivar type on straw yield, fiber content, and fiber yield in 2011 and 2012.

Harvest	Cultivar type	2011 Straw yield (g kg^{-1})	2011 Fiber content (kg ha^{-1})	2011 Fiber yield (kg ha^{-1})	2012 Straw yield (g kg^{-1})	2012 Fiber content (kg ha^{-1})	2012 Fiber yield
1	Fiber	1840**	412	774**	3584	286	1027
	Seed	1223	391	478	3999	301	1207
2	Fiber	2904**	406**	1180**	4104	308**	1271**
	Seed	1972	356	699	4356	229	985
3	Fiber	3233**	365**	1179**	4413**	307**	1339
	Seed	2335	305	712	5091	249	1263
4	Fiber	4502**	326**	1462**	6710	273**	1827**
	Seed	3300	269	885	6645	204	1348

** indicates the fiber-type cultivars differed from the seed-type cultivar at $P \leq 0.01$.

Table 5
Effect of cultivar type on seed yield and one-hundred seed weight in 2011 and 2012.

Cultivar type	2011 Seed yield (kg ha^{-1})	2011 100-seed wt (g)	2012 Seed yield (kg ha^{-1})	2012 100-seed wt (g)
Fiber	613**	0.437	748**	0.443**
Seed	1165	0.438	1348	0.476

** indicates the fiber-type cultivars differed from the seed-type cultivar at $P \leq 0.01$.

Lisson and Mendham, 2000) and although irrigation did not significantly increase seed production in this study, the average seed yield was 10–20% greater with irrigation than without (Table 1). Research on winter wheat in the region showed that supplemental water during the grain filling period increases the rate and duration of leaf photosynthesis (Frederick and Camberato, 1995).

The onset of flowering (in the two years when planting was in November) occurred in late March of 2012 and early April of 2013. This is about 60 days earlier than winter cereals in the region are normally harvested for grain. Thus, the ability to harvest flax fiber at this time allows for in-season management to optimize returns from both winter and summer crops that is not available with winter cereals. Deciding when to harvest would depend on potential yield of the flax straw, summer crop choice, the yield response to planting date of the summer crop, and prices of both crops.

Flax straw is separated into fiber and shive during processing. Shive has much lower economic value than the fiber. Similar fiber content of the seed-type cultivar to the fiber-type cultivars at the onset of flowering (Table 4) suggests for harvests at this time high straw yielding seed-type cultivars could be an alternative to fiber-type cultivars. In addition, growing high straw-yielding seed-type cultivars provides growers the opportunity to grow the crop to seed maturity and have increased returns from the seed. Growing seed-type cultivars for fiber would require much less land area in the region for planting seed production. The seed-type cultivar had 80–90% higher seed yields than the fiber-type cultivars in this study (Table 5).

In summary, differences among the four fiber-type cultivars in this study were not substantial. A larger number of cultivars need to be evaluated to determine the level of variability among European fiber-type cultivars for productivity in the region. The results indicate that both fiber-type and seed-type cultivars appear viable for production as fiber winter crops in the region. The effect of irrigation on flax was not consistent across the three years of this study. In the year that planting occurred late and both vegetative and reproductive growth occurred late in the spring, irrigation had a substantial impact on straw and fiber yields. With normal planting dates in the last two years of the study, soil water at the 30-cm depth failed to reach levels that would trigger an irrigation application before seven of the eight harvests. Future research needs to be conducted on the quality of fibers in these different production scenarios to determine their suitability for use in the different fiber industries.

References

Akin, D.E., Dodd, R.B., Foulk, J.A., 2005. Pilot plant for processing flax fiber. Ind. Crops Prod. 21, 369–378.

Alessi, J., Power, J.F., 1970. Influence of row spacing, irrigation, and weeds on dryland flax yield, quality, and water use. Agron. J. 62, 635–637.

P.J. Bauer, J.R. Frederick. Winter crop effect on double-cropped cotton grown with and without irrigation. Pages 220–222 in: Proc. of the 20th Ann. Southern Conservation Tillage Conf. for Sustainable Agric., June 24–26, 1997. R.N. Gallaher and R. McSorley eds. University of Florida Special Series SS-AGR-60.

Camp, C.R., Sadler, E.J., Evans, D.E., Usrey, L.J., Omary, M., 1998. Modified center-pivot irrigation system for precision management of water and nutrients. Appl. Eng. Agric. 14, 23–31.

Foulk, J.A., Bauer, P.J., Akin, D.E., Busscher, W.J., Camp, C.R., Ayala-Silva, T., Dodd, R.B., 2007. Effect of tillage on double-cropped flax/cotton production and fiber properties. Online Crop Manage., http://dx.doi.org/10.1094/CM-2007-0803-01-RS.

Foulk, J.A., Akin, D.E., Dodd, R.B., 2004a. Fiber flax farming practices in the Southeastern United States. Online Crop Manage., http://dx.doi.org/10.1094/CM-2003-0124-01-MG.

Foulk, J.A., Akin, D.E., Dodd, R.B., Frederick, J.R., 2004b. Optimizing flax production in the South Atlantic region of the USA. J. Sci. Food Agric. 84, 870–876.

Frederick, J.R., Camberato, J.J., 1995. Water and nitrogen effects on winter wheat in the southeastern Coastal Plain: II. Physiological responses. Agron. J. 87, 527–533.

Irvine, R.B., McConnell, J., Lafond, G.P., May, W.E., Hultgreen, G., Ulrich, A., Stonehouse, K., Chalmers, S., Stevenson, F.C., 2010. Impact of production practices on fiber yield of oilseed flax under Canadian prairie conditions. Can. J. Plant Sci. 90, 61–70.

Lisson, S.N., Mendham, J.J., 2000. Agronomic studies of flax (*Linum usitatissimum* L.) in south-eastern Australia. Aust. J. Exp. Agric. 40, 1101–1112.

Parks, C.L., Frederick, J.R., Porter, P.M., Murdock, E.C., 1992. Growing Flax in South Carolina. Clemson Univ. Cooperative Extension Service, Clemson, SC, pp. 16 pp.

Rashid, K.Y., 1998. Powdery mildew on flax: a new disease in western Canada. Can. J. Plant Pathol. 20, 216.

Robinson, B.B., 1931. The Time to Harvest Flax. Tech. Bull 236. United States Department of Agriculture, Washington, DC.