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Evaluation of winter annuals for biomass production in rotation with traditional summer row crops in the Southeast United States

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Abstract

Encouraging progress in commercial production of cellulosic biofuels, together with a need to avoid disruption of current food, feed and fiber supplies, could rapidly lead to a shortage of land to produce biomass. However, millions of acres used for production of traditional summer row crops in the Southeast United States are idle during the winter, and could be used to produce biomass from winter annuals. This 3-yr small plot study evaluated three winter annuals (black oat (*Avena strigosa* Schreb.), rye (*Secale cereale* L. subsp. *cereale*) and annual ryegrass (*Lolium multiflorum* Lam.)) for biomass production, in rotation with three summer row crops (cotton (*Gossypium hirsutum* L.), peanuts (*Arachis hypogaea* L.) and soybeans (*Glycine max* (L.) Merr.)) that are widely grown in the Southeast United States. All plots were disked and fertilized during the summer. Rye provided higher ($p<0.10$) biomass yield over the three years (9.0, 5.9 and 4.6Mg/ha in 2007-08, 2008-09 and 2009-10 winter seasons, respectively) than black oat and ryegrass. The variation in biomass yields over time was related to low temperature and solar radiation. Yields of the three summer crops were higher following rye, relative to yields following black oat and ryegrass in 2008 and 2010. In 2009, this trend was not observed, possibly because of the very high rainfall during the summer growing season. It is concluded that, compared to black oat and ryegrass, rye was the most suitable winter crop for biomass production in rotation with the three summer crops evaluated in this study.

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Introduction

First generation bioenergy feedstock's include food crops such as sugarcane, corn and soybeans, which are high in sugar, starch and/or oil content, and can be converted into liquid biofuels using existing technology. Two well-known processes in commercial production of first-generation biofuels are sugarcane-to-ethanol in Brazil and corn-to-ethanol in the United States. Unlike first-generation bioenergy feedstocks, next-generation bioenergy feedstocks, (i.e., ligno-cellulosic biomass) are derived from non-food sources, including wood, tall grasses, and forestry and crop residues, which are harvested for their cellulosic biomass and can only be converted into liquid biofuels by more complex conversion technologies that are still under development. Advances in recent years have indicated that numerous technologies which can use a variety of cellulosic biomass feedstocks to produce various liquid biofuels, including cellulosic ethanol, green gasoline, diesel and jet fuel, are currently under development (Kunkes *et al.*, 2008; Regalbuto, 2009; Brown and Brown, 2013; Knoll *et al.*, 2015). Commercial production of cellulosic drop-in replacement biofuels at a cost that is competitive with fossil fuels is only a matter of time (Solecki *et al.*, 2012), thus increasing the need to develop economically viable and environmentally sustainable cellulosic biomass supply chains.

The Energy Independence and Security Act of 2007 (EISA) mandated that 16 billion gallons of biofuel be produced from cellulosic biomass and used in the US by 2022. At a conversion ratio of 90 gallons per dry ton of cellulosic biomass, this means that 180 million dry tons of cellulosic material will have to be available annually by 2022 (USDA, 2010). Together with a need to avoid disruption of current food, feed and fiber supplies, this could rapidly lead to a shortage of land to produce cellulosic biomass. Meeting the ambitious targets that have been set by EISA is a major challenge. Some have suggested using tall grasses such as switchgrass and giant reed to establish low-input prairie on degraded agricultural lands for cellulosic biomass production (Bransby and Huang, 2014; Huang *et al.*, 2014; Tilman *et al.*, 2006), but others argue that this approach is inadequate to meet target production (Russelle *et al.*, 2007). With this background of considerable controversy, it is evident that a wide variety of approaches is needed to meet the cellulosic biofuel goals of EISA, and also minimize any negative impacts on existing commodities.

One possible approach may be to include cellulosic biomass production in existing summer row crop systems that are currently fallow in winter: millions of acres are currently used for production of traditional summer row crops in the Southeast United States, but are idle during the winter and could be used to produce biomass from winter annuals. Winter crops in a double cropping system are commonly planted as unharvested cover crops to improve soil and water conditions for subsequent summer crops. The benefits of planting winter cover crops include preventing soil erosion and enhancing soil organic matter (SOM), thus improving soil quality and productivity (Calonego and Rosolem, 2010). For example, over-seeding rye into standing corn increased corn yield (Schroder *et al.*, 1996; Kuo *et al.*, 2000; Coelho *et al.*, 2005). Cereal rye, annual ryegrass and oats are common winter cover crop species, and are well adapted to cool conditions that prevail in the fall-winter-spring season in the Southeast U.S. However, little is known about using winter annuals for biomass production in rotation with traditional summer row crops. Therefore, the objective of this study was to evaluate three common winter annuals ((black oat (*Avena strigosa* Schreb.), rye (*Secale cereale* L. subsp. *cereale*) and annual ryegrass (*Lolium multiflorum* Lam.))) for biomass production, in rotation with three summer row crops (cotton (*Gossypium hirsutum* L.), peanuts (*Arachis hypogaea* L.) and soybeans (*Glycine max* (L.) Merr.)) that are widely grown in the Southeast United States.

Materials and methods

Treatments and experimental design

This experiment was initiated in the winter of 2007 and conducted for 3 years at the E.V. Smith Research Center, Plant Breeding Unit of the Alabama Agricultural Experiment Station near Tallassee, Alabama USA. The soil test was performed by Auburn

University Soil Testing Laboratory (Auburn, Alabama USA). The soil was a Wickham sandy loam (fine-loam, mixed, semiactive, thermic Typic Hapludult), containing 25mgkg^{-1} P, 29.5mgkg^{-1} K, 275mgkg^{-1} Ca, 54.5mgkg^{-1}mg, and pH 6.3. The field had been planted with white lupin (*Lupinus albus* L.) in the previous season. The experiment was laid out as a two-factor factorial randomized complete block (RCB) design with four replicates. Nine different double cropping systems evaluated in this study included all combinations of three winter annuals and three summer crops: specifically rye, black oat or ryegrass in winter, followed by cotton, peanuts or soybeans in summer. Plot size was 3.6× 9.0m.

Crop rotation

Tillage operations, fertilizer application and planting were conducted within one day in early November for all winter seasons. Plots were disked to a depth of 10-15cm and chisel plowed to a depth of 15cm, followed by leveling, then fertilization with ammonium nitrate at a rate of 112kg N ha^{-1}. After applying fertilizer, black oat, rye and annual ryegrass were seeded using a grain drill set at a row spacing of 17.8cm. Table 1 presents more details on varieties, seed rate, planting depth, planting and harvesting times.

For the summer season, tillage operations and planting were also conducted within one day in mid-May for all three summer crops. After removing biomass of winter annuals, plots were disked, chisel plowed and leveled as described above for winter season crops, then planted with cotton, peanuts and soybean using a planter set at a row spacing of 91.4cm. More details are presented in Table 1. Given that peanuts and soybean are legumes, N fertilizer was only applied to cotton plots in the form of ammonium nitrate at a rate of 67kg N ha^{-1}. In addition, phosphorus (P) and potassium (K) fertilizers were applied based on soil test results.

Table 1. Varieties, seeding rates, planting and harvest dates of winter annuals and summer crops.

Season	Year	Crop	Variety	Seeding rate	Planting depth (cm)	Planting date	Harvest date
Fall/spring	2007/2008	Black oats	Soil Saver	100kg ha^{-1}	1.9	November 16, 2007	April 29, 2008
		Rye	Elbon	100kg ha^{-1}	1.9	November 16, 2007	April 29, 2008
		Ryegrass	Marshall	11kg ha^{-1}	0.6	November 16, 2007	April 29, 2008
Summer	2008	Cotton	Deltapine 555 BG/RR	179,400 seeds ha^{-1}	1.3	May 14, 2008	October 10, 2008
		Peanuts	Georgia Green	215,300 seeds ha^{-1}	3.2	May 14, 2008	November 4, 2008
		Soybean	MPV 5505 NRRSTS	287,000 seeds ha^{-1}	1.3	May 14, 2008	October 21, 2008
Fall/spring	2008/2009	Black oats	Soil Saver	100kg ha^{-1}	1.9	November 13, 2008	May 6, 2009
		Rye	Elbon	100kg ha^{-1}	1.9	November 13, 2008	May 6, 2009
		Ryegrass	Marshall	11kg ha^{-1}	0.6	November 13, 2008	May 6, 2009
Summer	2009	Cotton	Deltapine 555	179,400 seeds ha^{-1}	1.3	June 4, 2009	December 4, 2009
		Peanuts	Georgia Green	215,300 seeds ha^{-1}	3.2	June 4, 2009	November 18, 2009
		Soybean	AG 6702	287,000 seeds ha^{-1}	1.3	June 4, 2009	November 18, 2009
Fall/spring	2009/2010	Black oats	Soil Saver	100kg ha^{-1}	1.9	December 7,2009	May 5, 2010
		Rye	Elbon	100kg ha^{-1}	1.9	December 7,2009	May 5, 2010
		Ryegrass	Marshall	11kg ha^{-1}	0.6	December 7,2009	May 5, 2010
Summer	2010	Cotton	Stoneville 4498B2RF2	179,400 seeds ha^{-1}	1.3	May 18, 2010	October 26, 2010
		Peanuts	Valencia	215,300 seeds ha^{-1}	3.2	May 18, 2010	September 30, 2010
		Soybean	NK S73-75 Roundup	287,000 seeds ha^{-1}	1.3	May 18, 2010	October 26, 2010

All plots were cultivated, and herbicide and pesticide treatments were applied when necessary over the three years. Glyphosate (Roundup) herbicide was applied to all plots 12 days before planting summer row crops, aldicarb (Temik) pesticide was applied to cotton and peanut plots and pentachloronitrobenzene

(Terraclor) fungicide was applied to all plots at planting. To control leaf spot and white mold diseases, chlorothalonil (Echo/ Equus) fungicides were applied to peanuts six times at two week intervals starting about 35 to 45 days after planting in each summer season.

Data collection

At the end of each growing season, the center six rows of each winter annual plot were cut to a 5-cm stubble height with a sickle bar mower. Fresh biomass weight of harvested material from each plot was measured using a hanging scale in the field. Biomass subsamples taken from each plot were dried at 60°C for 72 h for dry matter determination. At maturity, cotton defoliants including S,S,S-Tributyl phosphorotrithioate (Def-6), ethephon (BollBuster) and Thidiazuron (Takedown) were used for the removal of leaves from cotton plants. Seed cotton was then picked in the central two rows of each cotton plot, using a John Deere 9920 (John Deere, Dumas, Arkansas) two row spindle cotton picker. Cotton lint yield was estimated by assuming a 39% ginning efficiency. Peanuts and soybeans were harvested from the central two rows of each plot with a peanut combine and soybean plot combine, respectively. Grain moisture was measured at harvest using a moisture meter and reported grain yields were adjusted accordingly. After harvesting border rows, cotton, peanut and soybean plots were mowed and prepared for planting winter annuals.

Statistical analysis

Statistical analysis of yield data from both summer and winter seasons were conducted using SAS v9.2 PROC GLIMMIX (SAS Institute, 2009, Cary, NC) procedure. Diagnostic plots were obtained by using the option PLOTS=STUDENTPANEL and were used to evaluate the model assumptions. Block was considered a random factor, whereas year, summer and winter crop factors and their interactions were tested as fixed effects. The critical p-value of 0.10 was used as cutoff for testing these fixed effects, and determination of differences in least-squares means was based on adjusted p-value obtained by using the option ADJUST=SIMULATE in the LSMEANS statement.

Biomass yield data from the 2008-09 and 2009-10 winter seasons were first analyzed to determine the yield performance of the three winter annuals as affected by the different summer row crops. Since there was no difference in biomass yields of the three winter annuals under different summer row crop systems in the 2008 and 2009 winter seasons, all winter biomass yield data were pooled to determine the yield of the three winter annuals over the three years. For each summer crop species, yield data from the three years were also pooled for analysis.

Results

Weather conditions

Daily temperature and monthly precipitation patterns are presented in Fig. 1 and Table 2, respectively. Rainfall was close to long term averages in the 2007, 2008 and 2010 growing seasons, but very high in 2009. The summer (May to October) and winter (November to April) growing season rainfall for 2009 was 941 and 814 mm, respectively, which is 324 and 48mm higher than the average rainfall received during the past 10 years. The cumulative chill hours (temperatures below 7.2°C) in the winter season of 2009 was higher than that in winter seasons of 2007 and 2008 (1211, 1171 and 1576 hours in 2007-08, 2008-09 and 2009-10 winter seasons, respectively) (Fig. 2) probably because of lower cumulative solar radiation (Fig. 3). Likewise, monthly minimum temperatures in the winter season of 2008 and 2009 were lower than that in the 2007 winter season (Fig. 4).

Table 2. Monthly and growing season precipitation 2007-2010.

Year	Precipitation (mm)													
	Month												Winter growing season	Summer growing season
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.		
2007											55	94	540	
2008	111	102	77	101	64	50	126	252	19	83	93	82	685	594
2009	52	105	244	109	262	100	75	192	148	164	154	276	814	941
2010	152	76	124	32	176	56	128	122	46	31				560
Average (1997-2006)	107	127	181	129	92	141	118	97	104	65	123	104	766	617

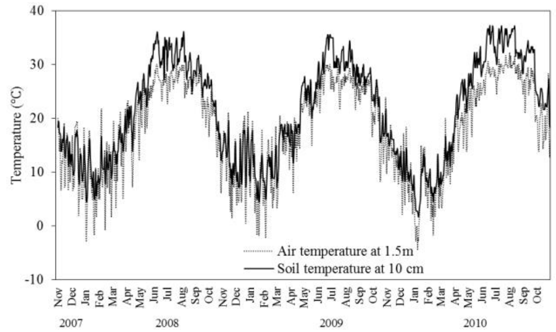

Fig. 1. Average daily air and soil temperatures from November 2007 to October 2010.

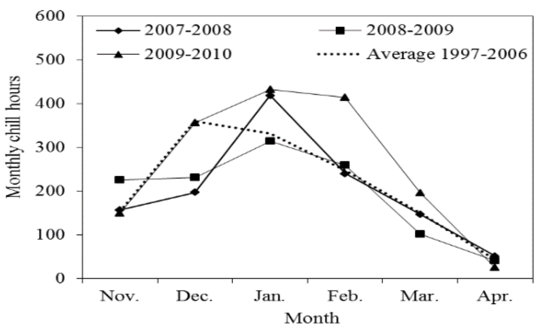

Fig. 2. Monthly chill hours (temperatures below 7.2℃) in winter seasons between 2007 and 2010.

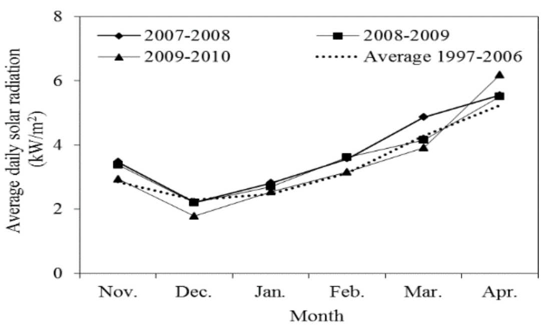

Fig. 3. Average daily solar radiation in each month of winter seasons between 2007 and 2010.

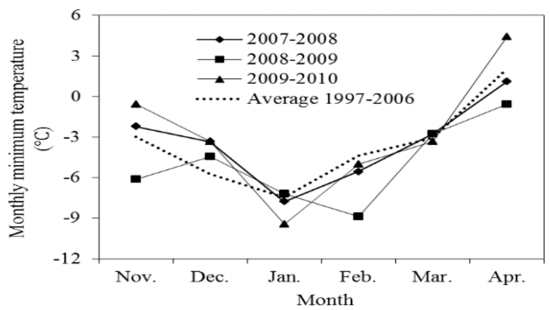

Fig. 4. Monthly minimum air temperature in winter seasons between 2007 and 2010.

Winter biomass yield

Biomass yield of winter annuals was not affected by summer crop factor and its interaction terms, but a year × winter crop interaction was observed. In all three growing seasons, biomass yield was higher for rye than for annual ryegrass and black oat for which yield did not differ (p<0.10) (Fig. 5). In addition, yield of the three annuals decreased significantly over the three years (p<0.10) (Fig. 6), with yield of rye decreased relatively less with lower temperatures and less sunlight than that of black oat and annual ryegrass (Figs. 2-4 and 6). In particular, biomass yields for rye, black oat and ryegrass in the 2009-10 winter season decreased by 17%, 68% and 68%, respectively, when compared to yields in the 2008-09 season.

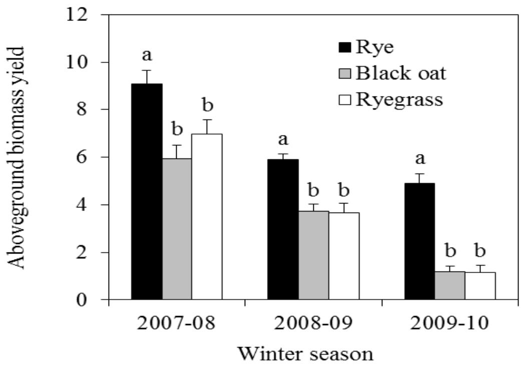

Fig. 5. Biomass yields of the three winter annuals within each winter growing season. Means within each year with different letters differ significantly (p<0.10). The error bars show standard errors.

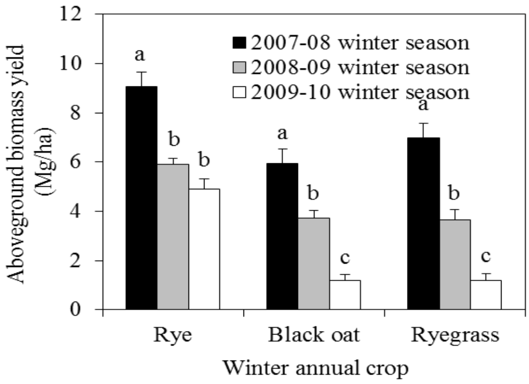

Fig. 6. Biomass yields of each winter annual crop across the three winter growing seasons. Means within each winter annual crop with different letters differ significantly (p<0.10). The error bars show standard errors.

Summer row crop yield

A year × winter crop interaction was observed for summer row crop yields. All three summer crop yields were highest after rye, followed by yields after black oat and ryegrass in 2008 and 2010 (Table 3). In 2010, particularly, yields for cotton, peanuts and soybeans after black oats decreased by 33%, 36% and 12%, respectively, when compared to yields after rye; and so did for the summer crop yields after ryegrass by 46%, 38% and 38%, respectively (Table 3). In 2009, the same differences in yield of summer crops following the three winter crops were not observed (Table 3).

Table 3. Yields of summer row crops in 2008-2010.

Year	Winter crop	Yield of summer row crop (kg ha^{-1})		
		Cotton lint	Peanut grain	Soybean grain
2008	Ryegrass	893±79^{a}	3746±222^{b}	2080±153^{c}
	Black oat	951±79^{a}	3864±222^{b}	2757±210^{b}
	Rye	1001±144^{a}	4905±222^{a}	3244±66^{a}
2009	Ryegrass	57±25^{a}	2300±49^{a}	1654±295^{a}
	Black oat	68±25^{a}	1894±222^{b}	1816±210^{a}
	Rye	60±25^{a}	2582±427^{a}	1051±210^{b}
2010	Ryegrass	286±25^{b}	214±49^{b}	1221±210^{b}
	Black oat	360±79^{ab}	221±49^{b}	1675±210^{ab}
	Rye	534±79^{a}	343±49^{a}	1960±295^{a}

Means within each column and in the same year with different letters differ significantly ($p<0.10$).

± numbers after means represent standard errors.

Discussion

The overall objective of this study was to evaluate double cropping systems with selected winter annuals for biomass production in rotation with summer row crops that are widely grown in the Southeast United States. Our results demonstrated that biomass yield of selected winter annuals was not affected by the three common summer row crops evaluated in this study, but yield of the three summer row crops was affected by selected winter annuals. In this 3-year field study, rye provided significantly higher biomass yield than annual ryegrass and black oats for which yield did not differ. Biomass yield of the three annuals varied over time, with yields significantly higher in 2007 than in 2008 and 2009. This variation in biomass yield of winter annuals over time was not related to planting summer crops. In the 2008 winter season, biomass yields of the same varieties of black oats and rye from the Alabama Variety Testing Program without planting summer crops at the same experiment station were 3.48 and 5.56mg ha^{-1} (Glass and van Santen, 2009), which were slightly lower than that of black oats and rye in the 2008 winter season in this study. The variation in biomass yield of winter annuals over time was possibly because of the changes in weather conditions at the experiment station over the three years. Much lower monthly minimum temperature and average daily solar radiation were recorded at the experiment station in the 2008 and 2009 winter seasons than in the 2007 winter season, resulting in significant lower biomass yields in 2008 and 2009 when compared to 2007. In addition, yield of rye decreased relatively less than that of black oat and annual ryegrass. This suggests that rye is more cold tolerant than the other two winter annuals, which is consistent with the observations of others (Stichler, 1997; Lemus, 2008).

In contrast to winter annuals, yields of summer row crops were affected by winter annuals. All three summer row crop yields were higher after rye than yields after black oat and ryegrass in 2008 and 2010. Based on studies by Barnes and Putnam (1986), Bauer and Reeves (1999), and Price *et al.* (2008), this result could be due to differences among these winter crops in allelopathic effects. In 2009, the same differences in yield of summer crops following the three winter crops were not observed, possibly because of the very high rainfall during the summer growing season which could have reduced allelopathy, as observed by Eerens *et al.* (1998).

Summer crop yields varied over time, with yields higher in 2008 than in 2009 and 2010. The variation in summer crop yields over time was not related to planting winter annuals. In the 2010 summer season, cotton lint and soybean grain yields of the same varieties from the Alabama Variety Testing Program without planting winter annuals at the same experiment station were 536 and 1836kg ha^{-1} (Glass *et al.*, 2010 (a); Glass *et al.*, 2010 (b)), which were very close to or slightly lower than of cotton lint and soybean yields after rye, but greatly higher than the yields after black oats and annual ryegrass in 2010 in this study.

The variation in summer crop yields over time was possibly because different varieties for all three summer crops were used over time. It is well known that summer crop yields vary greatly with different varieties due to their adaptations to climate and soil conditions, and disease-resistant ability. For example, 'Valencia' peanut used in 2010 has a much lower yield potential than 'Georgia Green' used in 2008 and 2009. Under the best circumstances, the yield potential for a 'Valencia' peanut is half or less than that of 'Georgia Green' (Putnam *et al.*, 1991; 2019 variety guide). 'Georgia Green' is a tomato spotted wilt virus (TSWV)-resistant, runner-type peanut cultivar, whereas 'Valencia' is not a disease-resistant peanut cultivar. Compared to 'Valencia' peanut, 'Georgia Green' is also less susceptible to white mold and early and late leaf spot diseases that are common at the experiment station. In the 2010 summer season, leaf spot and white mold were relatively high and may have been responsible for the much lower peanut yields when compared to peanut grain yields in 2008 and 2009. Besides crop varieties, the changes in weather conditions at the experiment station over the three years could also contribute to the variation in summer crop yields over time. Total solar radiation of early summer season (May and June) was much higher in 2008 than in 2009 and 2010. Compared to 2008 and 2010, rainfall was much higher in May 2009 resulting in very wet soil conditions, which may have contributed to poor germination for summer row crops in 2009, especially for cotton. Consequently, much lower cotton lint yields were observed in 2009 when compared to 2008 and 2010.

Conclusion

Overall, due to rye providing the highest biomass yield and having the lowest negative impact on summer row crop yield, rye appears to be better for winter biomass production than black oat and annual ryegrass when grown in rotation with cotton, peanuts or soybeans in the Southeast U.S.

Conflicts of interest

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

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