Yield and Nitrogen Management of Irrigated Switchgrass Systems in Diverse Ecoregions

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ABSTRACT

Climate trends and foreign oil dependency have led to a search for alternative sources of energy, such as biomass energy crops. Switchgrass (*Panicum virgatum* L.) has shown promise as a high yielding energy crop in the United States. The objectives of this study were to evaluate cultivar Trailblazer switchgrass adaptability, biomass yield potential, and response to N fertilization in different ecoregions. Experiments were established in four ecoregions of California in 2007, with five N fertilizer treatments (0 to 300 kg N ha^{-1} yr^{-1}) imposed from 2008 through 2010. The northern-most and coolest temperate continental climate location was terminated after 2009 due to appreciable winter mortality. Yields ranged from 13 to 27.1 Mg ha^{-1} yr^{-1} across locations and years, with greatest yields in the warmer Mediterranean and semiarid climates of the Central Valley and the Desert climate region. Yield response to N was limited in 2008. However, in 2009 and 2010, yields increased linearly in three of four locations, indicating that greater yields could have been possible with greater N fertilization rates. On average across locations, the greatest N rate increased yields by 9.7 and 13 Mg ha^{-1} yr^{-1} and agronomic N use efficiency averaged 30 and 44 kg biomass kg^{-1} N applied in 2009 and 2010, respectively. Average crop N removal was 150 kg N ha^{-1} yr^{-1} for multi-harvest systems, with the first harvest representing 70% of annual yields and 75% of crop N removal. Our results showed that in warm ecoregions with greater yield potential Trailblazer switchgrass required great N fertilization to sustain yields.

Interest in alternative sources of energy has increased in recent years due to increasing prices of petroleum-based fuels, national security concerns in the United States (Kering et al., 2012a), and climate change induced by increasing concentration of greenhouse gases in the atmosphere. Biomass energy crops may provide a viable alternative source of energy (McLaughlin et al., 2002). Potential uses for biomass are electric energy generation through co-firing with coal (Tillman, 2000), gas production by thermo-chemical gasification, and biochemical conversion into liquid fuels such as ethanol (Parrish and Fike, 2005).

Switchgrass is a perennial warm season C_4 grass native to North America, occurring naturally throughout the mainland United States, except California and the Pacific Northwest. It is one of the dominant species in the North American tallgrass prairie and can be found in remnant prairies, native grass pastures, and along roadsides. To date it has primarily been used as forage, ground cover, and wildlife refuge (USDA-Natural Resources Conservation Service. Jimmy Carter Plant Materials Center, 2011). Recently, switchgrass has received considerable attention as one of the most promising energy crops, due to its high yield potential, excellent conservation attributes, good compatibility with conventional agricultural practices, relative ease of establishment, high seed production, adaptability to marginal areas, and high N use efficiency, becoming a model feedstock for energy production (McLaughlin et al., 1999; McLaughlin and Kszos, 2005).

The majority of switchgrass research for biomass energy production has been performed in the Midwest and southern United States under rainfed conditions. Switchgrass biomass yields range from as low as 5.5 to as high as 25 Mg ha^{-1}, depending on stand age, varietal selection, N fertilization, precipitation, and harvest management (Heaton et al., 2004; Sanderson et al., 1999). Similar to biomass yields, biomass N concentration and N removal by harvest vary widely. Depending on yield, N fertilization, and harvest management, biomass N concentration range from 1.7 to 14.5 g kg^{-1} DM and from 28 to 234 kg N ha^{-1} yr^{--1} for N removal by harvest (McLaughlin et al., 1999; Vogel et al., 2002).

Nitrogen fertilizer is the main energy input and source of greenhouse gases emissions from switchgrass cultivation (Adler et al., 2007; Schmer et al., 2008), and an important factor in switchgrass biomass yields (Heaton et al., 2004; Stroup et al., 2003). It is therefore critical to understand how switchgrass responds to N fertilization to develop energy efficient and environmentally benign production systems for biomass energy production. Yield responses to N fertilization are variable and conflicting due to variations in soils, crop management, and climate (Parrish and Fike, 2005). Some have reported limited to no response to N fertilizers (Christian et al., 2002; Garten et al., 2011; Jung and Lal, 2011; Kering et al., 2012b;

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Abbreviations: ANUE, agronomic nitrogen use efficiency; GDD, growing degree days.

Table 1. Climatic characteristics of each location used to evaluate switchgrass production (Source: California Climate Data Archive, 2012).

Characteristics	Tulelake	Davis	Five Points	El Centro
Köppen climate classification†	Dsb	Csa	BSk	BWh
Average annual temperature, °C	8.1	15.7	17.1	22.6
Average max. annual temperature, °C	16.6	23.7	25	31.6
Average min. annual temperature, °C	–0.5	7.7	9.2	13.7
Average annual precipitation, mm	277	445	173	67
Average annual snowfall, cm	54.1	0.5	0.2	0.2
Frost-free days	176	338	335	365
Growing degree days, base temperature 10°C	899	2369	2836	4651
Altitude, m	1230	16	70	13
Latitude	41.7°W	38.5°W	36.4°W	32.7°W

† Peel et al. (2007): Dsb, temperate continental climate; Csa, warm Mediterranean climate; BSk, cool semiarid climate; BWh, hot desert climate.

Table 2. Soil name and properties (0–10 cm) at each location.

Soil attribute	Tulelake	Davis	Five Points	El Centro
Soil name and description	Tulebasin mucky silty clay loam (fine, mixed, superactive, mesic Aquandic Endoaquoll)	Brentwood silty clay loam (fine, smectitic, thermic Typic Haploxerept)	Cerini clay loam (fine-loamy, mixed, superactive, thermic Fluventic Haplocambid)	Imperial–Glenbar silty clay loam (fine, smectitic, calcareous, hyperthermic Vertic Torrifluvent–fine-silty, mixed, superactive, calcareous, hyperthermic Typic Torrifluvent)
Clay, g kg^{-1}	320	280	310	420
Silt, g kg^{-1}	450	480	340	420
Sand, g kg^{-1}	230	240	350	160
pH (saturated paste extract)	5.9	7.2	7.6	8
CEC, cmol$_c$ kg^{-1}	45.5	35.4	30.7	31.6
Olsen-, mg kg^{-1}	62.5	13.6	7.4	10.7
NO_3–N, mg kg^{-1}	26.5	9.9	10.6	8.8
Extractable K, mg kg^{-1}	367	375	439	409
Organic matter (Walkley-Black), g kg^{-1}	48.5	19.1	9.5	9.8
Total N (combustion), g kg^{-1}	3.4	1.3	0.7	0.7

Thomason et al., 2005) while others have reported significant N responses (Kering et al., 2012a; Lemus et al., 2008; Nikiema et al., 2011; Stroup et al., 2003), with biomass yields increasing up to 168 kg N ha^{-1} yr^{-1} in single-harvest systems (Muir et al., 2001) and 225 kg N ha^{-1} yr^{-1} when biomass was harvested twice a year (Guretzky et al., 2011). In studies that have shown a significant response to N the agronomic nitrogen use efficiency (ANUE), which is the increase in yield per unit of N fertilizer applied, ranged from 12 to 66 kg biomass kg^{-1} N applied (Guretzky et al., 2011; Jung and Lal, 2011; Kering et al., 2012a).

Irrigated agriculture in Mediterranean and semiarid climates are favorable to plant growth and productivity due to high solar radiation. In contrast, cooler temperate continental climates and the hot desert climates may limit switchgrass growth. In addition, the performance of switchgrass in these different ecoregions may be cultivar specific, with lowland varieties performing better than upland ones in warmer locations and vice-versa in cooler climates (Lee et al., 2012). Pedroso et al. (2011) reported average yields of 26 and 19.4 Mg ha^{-1} yr^{-1} for lowland and upland ecotype varieties, respectively, with limited yield response to N fertilization in different ecoregions across California. However, the yields and response to N fertilization reported were obtained only in the establishment year and in the first full year of switchgrass growth. Since switchgrass yields tend to increase until the third year of full production (Heaton et al., 2004), longer-term experiments are required to evaluate the true adaptability, yield potential, and response to N fertilization of switchgrass in the different ecoregions of California.

California's climates allow for higher yield potential but may also require higher inputs of N fertilizer than the more traditional regions where switchgrass is grown. In addition, the yield potential and response to N fertilization may differ among the different ecoregions of California. Therefore, our research focused on evaluating switchgrass as an energy feedstock crop, with the following objectives: (i) to identify the adaptability and yield potential of Trailblazer switchgrass in distinct climatic regions, (ii) to determine the biomass yield response and N removal of switchgrass to N fertilizer rates, and (iii) to develop N fertilization recommendations for the initial years of switchgrass production.

MATERIALS AND METHODS

Description of the Ecoregions

Four switchgrass experiments were established in 2007 in distinct ecoregions of California (Table 1). The experimental fields were located near the cities of Tulelake, the northern-most location in the intermountain region; Davis in the Sacramento Valley; Five Points in the San Joaquin Valley; and El Centro, the southern-most location bordering Mexico (Fig. 1). According to the Köppen–Geiger climate classification (Peel et al., 2007), Tulelake is situated in a temperate continental climate (Dsb), with mild summer temperatures and cold winters, receiving on average 54.1 cm of snowfall from October to April. In this ecoregion, the growing season

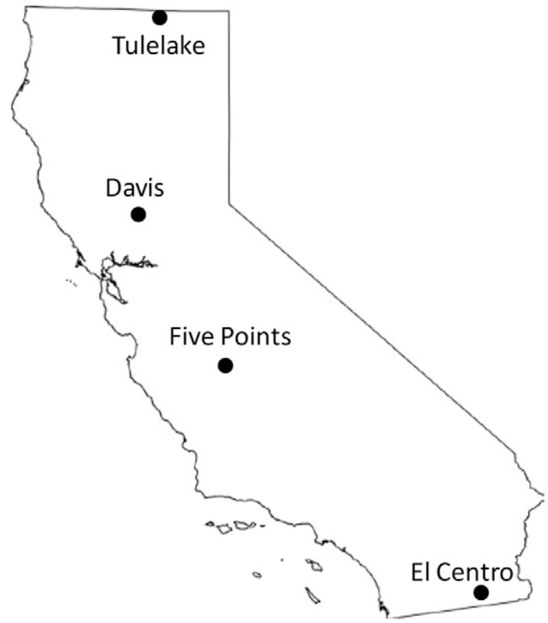

Fig. 1. Location of switchgrass experiments in California.

for warm-season grasses extends only from May until October due to low temperature constraints in the remaining months. Davis is located in a warm Mediterranean climate (Csa), with dry and hot summers and mild and wet winters, receiving on average 445 mm of rainfall during winter and early spring. The growing season at Davis starts in March and ends in early November. Five Points is situated in a cool semiarid climate (BSk), with hot and dry summers and cool and relatively dry winters, receiving 173 mm yr^{-1} of precipitation. Both Davis and Five Points have similar temperatures year-round and are situated in the Central Valley of California. El Centro is located in a hot desert climate (BWh), with hot and dry summers and warm and dry winters, receiving only 67 mm yr^{-1} of precipitation. At El Centro, the growing season for warm-season grasses extends from late January till early December. These locations provide a broad range of climates with altitudes ranging from 13 to 1230 m above sea level, 176 to 365 frost free days per year, and growing degree days (GDD) ranging from 899 to 4651 per year with a 10°C base temperature.

Crop Establishment

Soil samples averaged over 10-cm deep were taken before planting in 2007 at all locations. Four samples were collected per location and composited to create one sample. Samples were air dried and ground through a 2-mm mesh screen and analyzed for pH (saturated paste extract), NO_3–N, Olsen-P, extractable-K, CEC, organic matter (Walkley–Black), particle size, and total N (Table 2).

At each location, the northern upland switchgrass variety Trailblazer was established in July of 2007 (Table 3). Although southern lowland varieties tend to achieve greater yields in low to mid-latitudes in the United States (McLaughlin and Kszos, 2005), northern upland varieties are more cold tolerant (Casler et al., 2004) and therefore have greater chances of surviving the cold continental climate winters. Before establishment, the soil was disked and the seedbed was prepared to provide a firm and fine soil surface at all locations. Trailblazer switchgrass was drill seeded at a rate of 3.6 kg ha^{-1} of pure live seeds, to a depth of 0.5 and 25 cm between rows. To ensure uniform germination and crop establishment, the fields were sprinkler irrigated following seeding and through the rest of the establishment year. Weeds were controlled as necessary and no fertilizers were applied in the establishment year. The aboveground biomass was harvested in November of 2007 and removed from the fields, after which the switchgrass plants entered a dormancy period.

In 2008 and for the duration of the experiment, switchgrass was flood irrigated every 2 to 3 wk and no weed control was required. Due to the climatic differences at each ecoregion (Table 1), the locations were managed under different harvest schedules (Table 3). The short growing season at Tulelake only allowed for a single harvest per year. At Davis and Five Points plots were harvested twice a year, whereas at El Centro plots were harvested three times per year in 2008 and 2009, and twice in 2010. Tulelake was harvested at post-anthesis (R5) development stage (Moore et al., 1991) in early October after a killing frost. In Davis and Five Points, the fields were harvested at inflorescence fully emerged stage (R3) in June/July and at post-anthesis stage (R5) in early fall (October/November) before the onset of rains. El Centro was harvested at boot stage (R0) in June, September, and November due to concerns with seed dispersion. Switchgrass went into a dormancy period at all locations after the final harvest of each year. Dormancy break occurred in mid-May,

Table 3. Primary management practices and switchgrass winter dormancy break from 2007 to 2010.

Year	Management	Tulelake	Davis	Five Points	El Centro
2007	Planting	24 July	5 July	17 July	19 July
	Harvest	8 Nov.	19 Nov.	13 Nov.	26 Nov.
2008	Dormancy break	early May	mid-Mar.	late Feb.	early Feb.
	P and K fertilization	5 May	9 Apr.	25 Mar.	27 Mar.
	N fertilization	5 May	9 Apr., 1 May	25 Mar., 22 Apr.	27 Mar., 24 Apr.
	Harvest	1 Oct.	18 July, 30 Oct.	23 July, 19 Nov.	11 June, 5 Sept., 4 Nov.
2009	Dormancy break	Early May	Mid-Mar.	Late Feb.	Early Feb.
	P and K fertilization	22 May	6 Apr.	27 Mar.	24 Mar.
	N fertilization	22 May	6 Apr., 22 June	27 Mar., 22 June	24 Mar., 2 June
	Harvest	22 Oct.	18 June, 12 Oct.	16 June, 9 Nov.	27 May, 20 Aug., 4 Nov.
2010	Dormancy break	Discontinued	mid-Mar.	late Feb.	early Feb.
	P and K fertilization		7 Apr.	30 Mar.	29 Mar.
	N fertilization		7 Apr., 5 July	30 Mar., 29 June	29 Mar., 9 July
	Harvest		30 June, 20 Oct.	24 June, 17 Nov.	6 July, 29 Sept.

Table 4. Summary statistics with significance of fixed effects for switchgrass biomass yield, crop N removal, and biomass N concentration in response to N fertilization rate, year, location, harvest, and respective two- and three-way interactions. Effects with *P* values lower than 0.05 are considered statistically significant, whereas effects with ns are not significant.

		Biomass yield		Crop N removal		Biomass N concentration	
Location/effect	df	*F* value	*P* value	*F* value	*P* value	*F* value	*P* value
All locations							
N treatment	4	51.5	<0.0001	62.28	<0.0001	32.53	<0.0001
Year	2	42.98	<0.0001	62.66	<0.0001	38.52	<0.0001
Location	3	30.45	<0.0001	102.19	<0.0001	325.75	<0.0001
N treatment × year	8	7.88	<0.0001	2.69	0.0087	2.94	0.0044
N treatment × location	12	2.63	0.0031	3.44	0.0002	2.65	0.0029
Year × location	5	35.65	<0.0001	84.63	<0.0001	53.88	<0.0001
N treatment × year × location	20	1.15	ns†	1.21	ns	1.09	ns
Tulelake							
N treatment	4	0.51	ns	0.62	ns	1.59	ns
Year	1	1.19	ns	0.1	ns	0.12	ns
N treatment × year	4	0.73	ns	0.42	ns	0.8225	ns
Davis							
N treatment	4	28.8	<0.0001	108.1	<0.0001	39.88	<0.0001
Year	2	2.47	ns	14.4	<0.0001	7.59	0.0007
Harvest	1	1118.19	<0.0001	3315.27	<0.0001	1303.28	<0.0001
N treatment × year	8	4.69	<0.0001	3.14	<0.0001	2.54	<0.0001
N treatment × harvest	4	0.89	ns	5.9	0.0002	4.78	0.0012
Year × harvest	2	17.78	<0.0001	51.76	0.0026	28.82	0.0127
N treatment × year × harvest	8	1.1	ns	0.9	ns	5.48	<0.0001
Five Points							
N treatment	4	21.74	<0.0001	60.04	<0.0001	41.86	<0.0001
Year	2	61.93	<0.0001	121.13	<0.0001	140.35	<0.0001
Harvest	1	189.56	<0.0001	1035.43	<0.0001	1540.33	<0.0001
N treatment × year	8	1.12	ns	1.16	ns	4.11	0.0004
N treatment × harvest	4	0.37	ns	1.35	ns	12.23	<0.0001
Year × harvest	2	12.56	<0.0001	56.82	<0.0001	204.77	<0.0001
N treatment × year × harvest	8	0.92	ns	1.03	ns	1.93	ns
El Centro							
N treatment	4	43.69	<0.0001	15.81	<0.0001	7.43	<0.0001
Year	2	10.21	0.0002	15.69	0.0003	46.28	<0.0001
Harvest	1	270.6	<0.0001	50.09	<0.0001	60.45	0.0002
N treatment × year	8	17.64	<0.0001	7.51	0.0001	4.16	0.0069
N treatment × harvest	4	2.27	ns	2.05	ns	1.37	ns
Year × harvest	2	52.16	<0.0001	4.1	0.0498	159.63	<0.0001
N treatment × year × harvest	8	1.14	ns	2.05	ns	1.2	ns

† ns, not significant.

mid-March, late February, and early February at Tulelake, Davis, Five Points, and El Centro, respectively. For each harvest, the central portion of each plot was cut to 10 cm with a self-propelled plot forage harvester, resulting in a harvested area of 4.5 to 6 m^2 depending on the harvester width. Total fresh weight was determined for each plot and a subsample was taken for dry matter determination and nutrient analysis. The subsamples were dried to constant weight at 60°C, weighed, ground, and analyzed for N concentration by combustion in an elemental analyzer at the Stable Isotope facility at UC Davis.

In 2008, the experimental treatments were imposed and laid out as a complete randomized block design with three replications in Tulelake and El Centro, four replications in Five Points, and six replications in Davis, with each plot being 3 by 5 m. At Davis, Five Points, and El Centro, switchgrass received 0, 75, 150, 225 or 300 kg N ha^{-1} yr^{-1}, while at Tulelake 0, 37.5, 75, 112.5 or 150 kg N ha^{-1} yr^{-1} was applied due to the single-harvest system at this location. While N treatments rates were consistent across years, the timing of the N fertilization varied across years in Davis, Five Points, and El Centro. In 2008, the N fertilizer rate was split into two applications with the first being after dormancy break and the second 4 wk later. In 2009 and 2010, the same annual N rates were applied, but half of the N fertilizer was applied in early spring following dormancy break and half of the N fertilizer was applied after the first harvest. In Tulelake, the N fertilizer was applied in a single application in spring of 2008 and 2009. In all cases, N fertilizer was applied as ammonium sulfate [$(NH_4)_2SO_4$] and each individual experimental plot received the same N rate in subsequent years. Phosphorus (triple superphosphate) and K (potassium sulfate) were both applied at a rate of 100 kg ha^{-1} yr^{-1} of P_2O_5 and K_2O simultaneous with the spring N fertilization of each year.

Agronomic N use efficiency represents the increase in yield per unit of fertilized N applied in relation to the zero N treatment and is calculated as follows, where yields and N rates are expressed in kg ha^{-1}:

$$\text{ANUE} = \frac{\text{Yield fertilized treatment} - \text{Yield unfertilized treatment}}{\text{N fertilization rate}}$$

Table 5. Significance of linear and quadratic response of biomass yield and crop N removal to N treatment by location and year. Effects with *P* values lower than 0.05 are considered statistically significant, whereas effects with ns are not significant.

				Biomass yield		Crop N removal	
Location	Year	Effect	df	*F* value	*P* value	*F* value	*P* value
Davis	2008	N Treatment	4	1.32	ns†	18.98	<0.0001
		Linear	1	3.84	ns	40.14	<0.0001
		Quadratic	1	0.09	ns	0.36	ns
	2009	N Treatment	4	8	<0.0001	50.62	<0.0001
		Linear	1	26.69	<0.0001	58.53	<0.0001
		Quadratic	1	0.18	ns	0.28	ns
	2010	N Treatment	4	55.98	<0.0001	55.55	<0.0001
		Linear	1	208.58	<0.0001	118.92	<0.0001
		Quadratic	1	1.61	ns	0.9	ns
Five Points	2008	N Treatment	4	4.11	0.0004	12	<0.0001
		Linear	1	5.98	0.0302	21.23	0.0005
		Quadratic	1	5.93	ns	0.03	ns
	2009	N Treatment	4	25.16	<0.0001	29.11	<0.0001
		Linear	1	73.57	<0.0001	155.06	<0.0001
		Quadratic	1	1.65	ns	0.18	ns
	2010	N Treatment	4	65.38	<0.0001	32.94	<0.0001
		Linear	1	161.37	<0.0001	89.21	<0.0001
		Quadratic	1	0.16	ns	0.11	ns
El Centro	2008	N Treatment	4	0.23	ns	1.42	ns
		Linear	1	0	ns	2.99	ns
		Quadratic	1	0	ns	1.1	ns
	2009	N Treatment	4	21.42	<0.0001	27.88	<0.0001
		Linear	1	73.33	<0.0001	148.69	<0.0001
		Quadratic	1	0.07	ns	1.26	ns
	2010	N Treatment	4	61.93	<0.0001	na	na
		Linear	1	154.88	<0.0001	na	na
		Quadratic	1	0.17	ns	na	na

† ns, not significant.

Statistical Analysis

The data were analyzed for normality and constant variance of errors, and log-transformations were performed when assumptions were violated. Analysis of variance on year-total biomass yields and crop N removal (sum of same-year harvests), and average biomass N concentration (average of same-year harvests) data were performed using the Mixed Procedure in SAS. Nitrogen treatment, year, location, and the interactions between N treatment × year, N treatment × location, year × location, and N treatment × year × location were considered fixed effects. Block was considered a random effect. Due to the significant interactions data was analyzed by location (Table 4). The single-harvest location Tulelake was analyzed with N treatment, year, and the interaction between N treatment × year as fixed effects, and block as a random effect. The multi-harvest locations Davis, Five Points, and El Centro were analyzed with N treatment, year, harvest, and the interactions between N treatment × year, N treatment × harvest, year × harvest, and N treatment × year × harvest as fixed effects, and block as a random effect. The interaction between N treatment × year was significant at Davis, Five Points, and El Centro (Table 4), while the interaction between N treatment × harvest was not significant (i.e., the effect of N fertilization was similar between same-year harvests) at those locations. Therefore, the effect of N fertilization was analyzed by year on year-total biomass (sum of same-year harvests). However, data are presented by harvest and year-total to emphasize significant differences in biomass yield and N removal between same-year harvests. An additional analysis of variance on biomass yield data from Davis, Five Points, and El Centro was performed using the Mixed Procedure in SAS to evaluate N treatment × location interaction at each year. The type of response (i.e., linear vs. quadratic) to N fertilization was tested using orthogonal contrasts in SAS (Table 5). Differences were considered to be significant at the 5% probability level.

RESULTS AND DISCUSSION

Switchgrass Yields and Adaptability in Different Ecoregions

On average across N fertilization rates and years, Five Points (semiarid climate) had the greatest yield (18.9 Mg ha^{-1} yr^{-1}), followed by Davis (warm Mediterranean climate) at 16.5 Mg ha^{-1} yr^{-1}, El Centro (hot desert climate) at 15.8 Mg ha^{-1} yr^{-1}, and Tulelake (temperate continental climate) at 14.3 Mg ha^{-1} yr^{-1} (Fig. 2). Across years and N rates, Five Points had the greatest average yield mainly because of greater yields in 2008 (25.6 Mg ha^{-1}). In 2009 and 2010 average annual yields across N rates were the greatest at Davis.

The lowest yields were recorded in Tulelake in 2008 and 2009. Tulelake is located in the ecoregion with the least annual temperature and shorter growing season of this study (Table 1). In 2010 at Tulelake, the experiment was discontinued due to

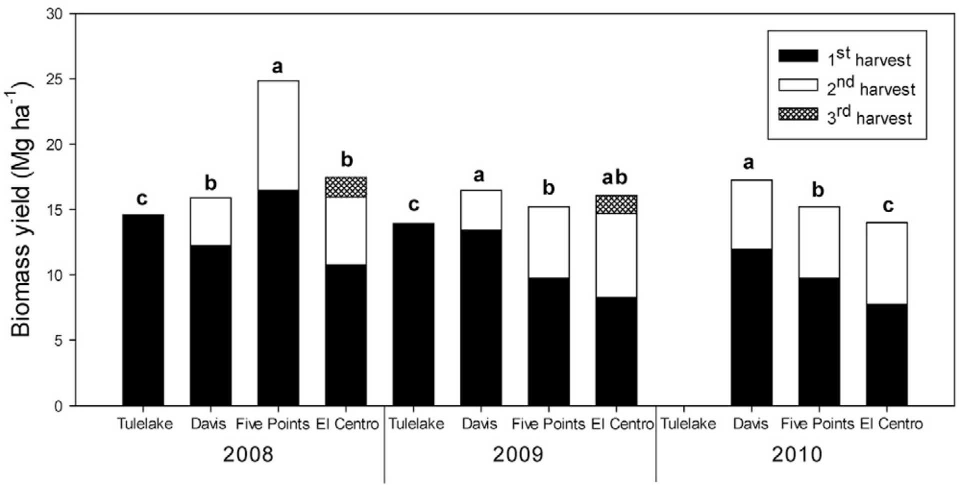

Fig. 2. Biomass yields averaged across N treatments by location, year, and harvest. The experiment at Tulelake was discontinued in 2010 due to high winter mortality rates. Mean separation of year-total biomass yield was performed within years. Different letters within a given year indicate that mean annual yields are statistically different (*P* < 0.05).

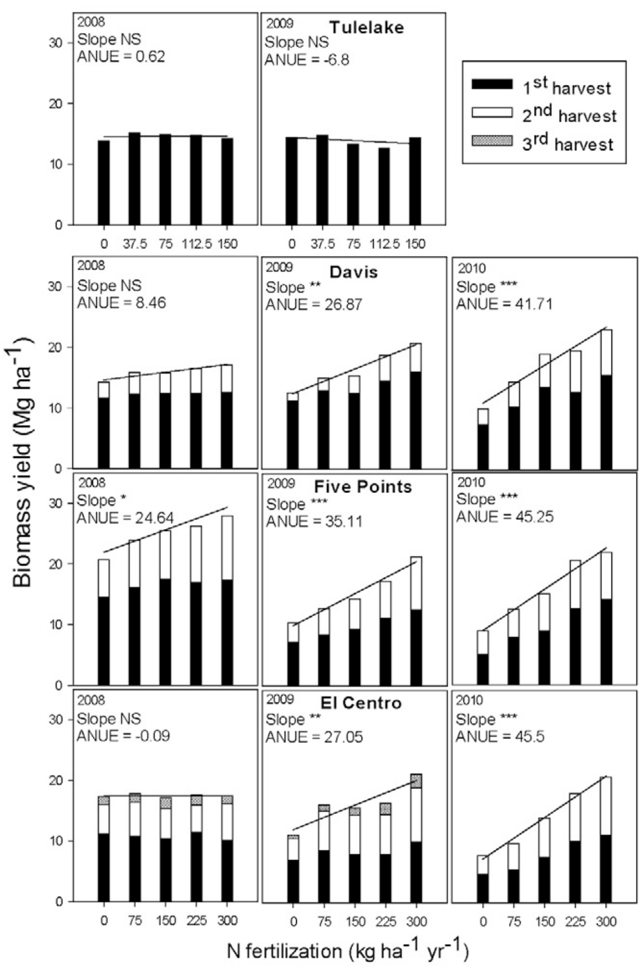

Fig. 3. Biomass yields by year, location, harvest, and year-total. Tulelake was discontinued in 2010 due to winter mortality. Nitrogen treatment effect (slope) and agronomic nitrogen use efficiency (ANUE) refer to year-total biomass yields. The ANUE has been multiplied by 1000 and is expressed in kilogram of biomass yield increased per kilogram of N applied. The symbols *, **, * indicate that N fertilization effect on year-total biomass yield is significant at *P* < 0.05, < 0.001 and < 0.0001, respectively.**

increased mortality rates in the 2009/2010 winter, indicating that Trailblazer switchgrass is not adapted to this cooler continental climate, despite being a northern upland variety. However, there is a range in winter survival among northern upland varieties (Casler et al., 2004), and a more cold-tolerant variety might be able to survive the winters in this climate.

Regardless of the longer growing season and greater GDD of the hot desert ecoregion, switchgrass yields at El Centro were similar to or less than in the Mediterranean and semiarid locations of Davis and Five Points (Fig. 2). The failure to achieve greater yields in El Centro may be due to the hot summer temperatures, which may have negatively affected yields. Average maximum temperatures at El Centro are 39.5, 42.2, 41.5 and 39.0°C in June, July, August, and September, respectively. Pedroso et al. (2011) found that in warmer ecoregions of California southern lowland varieties performed better than the northern upland varieties such as Trailblazer used in this study. In addition to the high summer temperature, the harvest management system adopted at that location may have limited yields. Due to concerns with seed dispersion, harvests at El Centro were performed at boot developmental stage (R0). However, maximum biomass yield of switchgrass occurs at the full panicle emergence to postanthesis developmental stages (Vogel et al., 2002). Delaying harvests until full panicle emergence would probably have resulted in greater yields at that location.

The average yields achieved in this study were significantly greater than the average switchgrass yields reported in the literature. Average yield of switchgrass from 21 studies, representing 174 observations, was 10.3 ± 0.7 Mg ha^{-1} (Heaton et al., 2004). Fike et al. (2006a) reported comparable average switchgrass yields ranging from 10.4 to 19.1 Mg ha^{-1} across eight locations in the upper southeastern United States, which included different varieties, N fertilization rates, and harvest management systems. Pedroso et al. (2011) reported 34% greater yields with lowland (26 Mg ha^{-1} yr^{-1}) vs. upland (19.4 Mg ha^{-1} yr^{-1}) ecotype varieties in two- and three-harvest systems in the Central Valley and Desert region of California. Therefore, yields at Davis, Five Points, and El Centro could have been greater with the use of a better adapted variety such as the southern lowland variety Alamo.

At the multi-harvest locations, the first harvest produced significantly more biomass than the following harvest in the same year (Fig. 2). Approximately 76, 64, and 55% of the year-total biomass yield was obtained in the first harvest at Davis, Five Points, and El Centro, respectively. The third harvest at El Centro produced only 8% of the year-total biomass. These results were consistent across N rates and years. The lesser yields of the additional same-year harvests at Davis, Five Points, and El Centro raises concerns about the sustainability of the multi-harvest system employed at those locations. Harvesting and baling biomass comprises approximately 25% of its production cost (Perrin et al., 2008) and 82% of the CO_2 emissions occurring from machinery use during switchgrass production (Adler et al., 2007). Therefore, a production system that minimizes the number of harvests, without a significant decrease in yield, may be more economically efficient and environmentally benign.

Yield Response to Nitrogen Fertilization

Yield responses to N fertilization varied across ecoregions and years as indicated by significant N treatment × location and N treatment × year interactions (Table 4). Yield response to N fertilization data are therefore presented by location and year (Fig. 3). Within the same year, the response to N for the first harvest was the same as for the second harvest (nonsignificant N treatment × harvest interaction) (Table 4); hence, the effect of N fertilization on yield was analyzed for the year-total biomass (sum of all same-year harvests). The orthogonal contrast results showed linear responses to N fertilization at all locations, years, and harvests that a significant response was detected (Table 5).

In Tulelake, the northern-most and only single-harvest system, yield response to N fertilization was not significant in 2008 and 2009 (Fig. 3). Average yields were 14.6 and 13.9 Mg ha^{-1} yr^{-1} in 2008 and 2009, respectively. It is probable that the cooler continental climate of Tulelake has a lower yield potential due to the shorter growing season and lower GDD (Table 1). In addition, the soil at Tulelake has high level of organic matter (Table 2), which is related to N availability through mineralization during the growing season (Paul, 1984). Furthermore, Stout and Jung (1995) reported that total soil N concentration above 2 g kg^{-1} might negatively impact the response of switchgrass to applied N. At the beginning of the experiment at Tulelake, total soil N concentration was 3.4 g kg^{-1} (Table 2). Therefore, the lack of N response may be a result of the reduced yield potential coupled with adequate soil N supply, as evidenced by the relatively high N uptake in the zero N treatment (Table 6).

In 2008, there was no significant yield response to N fertilization at Davis and El Centro (Fig. 3). However, at Five

Table 6. Nitrogen treatment effect on biomass N concentration by location averaged across years and on crop N removal by location and year.

Location	N rate	N concentration (averaged across years)	N removal by year 2008	2009	2010
	kg ha^{-1}	g kg^{-1}		–kg ha^{-1}–	
Tulelake	0†	5.9	81	90	na‡
	37.5	5.8	86	88	na
	75	6.6	105	82	na
	112.5	6.7	93	90	na
	150	7.3	103	105	na
	Significance	ns§	ns	ns	–
Davis	0	5.8(3.1)	59(8)	62(5)	50(8)
	75	5.9(3.0)	64(10)	86(5)	62(13)
	150	7.1(3.2)	72(13)	99(10)	99(17)
	225	7.8(3.3)	76(16)	137(14)	100(18)
	300	8.4(3.4)	89(21)	153(17)	133(32)
	Significance	***(*)	**	***	***
Five Points	0	6.4(2.8)	131(16)	36(9)	25(15)
	75	7.1(2.9)	163(34)	52(12)	38(20)
	150	8.3(2.7)	230(20)	62(14)	46(22)
	225	9.3(2.9)	244(24)	87(16)	72(29)
	300	10.8(4.0)	281(83)	121(30)	91(34)
	Significance	***(***)	*	***	***
El Centro	0	10.1(13.0)[9.7]	110(105)[15]	71(32)[4]	na
	75	10.9(15.5)[9.4]	107(130)[17]	101(78)[7]	na
	150	12.3(14.4)[8.4]	104(108)[18]	116(78)[8]	na
	225	13.3(15.8)[8.4]	132(94)[16]	117(101)[13]	na
	300	12.8(15.6)[9.8]	122(126)[14]	135(134)[20]	na
	Significance	**(*)[ns]	ns	***	–

* Indicates that N fertilization effect on year-total N removal and N concentration is significant at $P < 0.05$.
** Indicates that N fertilization effect on year-total N removal and N concentration is significant at $P < 0.001$.
*** Indicates that N fertilization effect on year-total N removal and N concentration is significant at $P < 0.0001$.
† The first values refer to the first harvest, while the values between parenthesis and brackets refer to the second and third harvests, respectively.
‡ na, not available.
§ ns, not significant.

Points, a significant response to N was observed, with biomass increasing linearly from 20.7 to 27.9 Mg ha^{-1} across the range of N inputs. The response to N at Five Points may be related to the greater yield potential (and hence higher N demand) in that year relative to the other locations. At the other two locations the reduced yield potential in 2008 combined with adequate native soil N resulted in a situation where no fertilizer N was required.

In 2009, the yield response to N fertilization was significant at all multi-harvest locations as indicated by the significant slopes (Fig. 3). The slope of each line represents the ANUE, which is the increase in biomass per unit of N fertilizer added. The response to N was linear at all multi-harvest locations and did not differ among multi-harvest locations. On average across locations that had a significant response to N fertilization, total annual yields increased by 9.7 Mg ha^{-1} and the ANUE was 30 kg biomass kg^{-1} N applied. Likewise in 2010, the response to N fertilizer did not differ among locations and the response to N fertilization remained linear; however the response to N was more pronounced with yields increasing by 13 Mg ha^{-1} and the ANUE increasing to 44 kg biomass kg^{-1} N applied. These ANUE values are within the range reported by others. Guretzky et al. (2011) reported ANUE values for Alamo switchgrass grown in Oklahoma of 39 kg biomass kg^{-1} N applied, in a two-harvest system fertilized with 225 kg N ha^{-1} yr^{-1}. In single harvest systems ANUE values of 59.5 (Jung and Lal, 2011) and 66 kg biomass kg^{-1} N applied (Kering et al., 2012a) have been achieved.

Increasing yield responses to N fertilizer over the 3-yr period in the multi-harvest locations were not due to yield increases. Average annual maximum yields were 20.8, 21.0, and 21.9 Mg ha^{-1} in 2008, 2009, and 2010, respectively. Rather, increased responses to N fertilizer were primarily due to a depletion of available soil N, as yields in the zero N treatment decreased at all locations from an average of 17.4 Mg ha^{-1} yr^{-1} in 2008 to 8.9 Mg ha^{-1} yr^{-1} in 2010.

Despite differences in temperature, length of the growing season, number of frost-free days, and GDD between the warm Mediterranean (Davis), semiarid (Five Points), and hot desert (El Centro) ecoregions, the response to N fertilizer and ANUE were generally similar, being different only in 2008. As Davis and Five Points are analogous ecoregions, switchgrass yields and responses to N fertilizer were expected to be similar. On the other hand, the hot desert climate at El Centro has a longer growing season and greater GDD that could potentially allow for greater yields and greater yield response to N. It is possible that the harvest management system and hotter summer temperatures may have limited the yield of Trailblazer switchgrass at that location, consequently reducing yield response to N fertilizer and ANUE.

Despite the relatively excessive N rates, it was not possible to determine the maximum attainable yields at the ecoregions of the Central Valley and the hot desert of California. The linear yield response to N in the three multi-harvest locations (Fig. 3) indicates that maximum achievable yields may have been greater in 2009 and 2010 with greater N rates. The greatest yields achieved were 15.2, 20.7, 27.9, and 21.1 Mg ha^{-1} yr^{-1} at Tulelake, Davis, Five Points, and El Centro, respectively. Greater yields of up to 39.1 Mg ha^{-1} yr^{-1} have been reported in Tennessee by West and Kincer (2011) in a 4-yr study with the lowland variety Alamo. In Ohio, yields of 26.1 Mg ha^{-1} yr^{-1} were achieved with the upland variety Cave in Rock (Jung and Lal, 2011). Likewise, Guretzky et al. (2011) in Oklahoma reported yields of up to 22.2 Mg ha^{-1} yr^{-1} in a two-harvest system with the lowland variety Alamo. In addition to greater N fertilization rate, the use of a southern lowland variety could have resulted in greater yields across all these warm ecoregions (Pedroso et al., 2011).

Biomass Nitrogen Concentration and Crop Nitrogen Removal

Crop N removal is a function of yield and biomass N concentration. Biomass N concentration was positively related to N rate at all locations, except for Tulelake (Table 6). Biomass N concentrations ranged from as low as 2.7 g kg^{-1} DM in the zero N treatment to as high as 15.8 g kg^{-1} DM in the highest N treatment.

At the multi-harvest locations at Davis and Five Points, the first harvest had significantly greater biomass N concentration (7.7 g kg^{-1} DM) than the second harvest of each year (3.2 g kg^{-1} DM). Warm-season grasses translocate N during senescence from above- to belowground tissues for use in overwintering and regrowth in the following spring (Clark, 1977), and there is evidence of this in switchgrass (Parrish and Fike, 2005). Since the second harvest was performed at post-anthesis developmental stage at Davis and Five Points, the least aboveground biomass N concentration observed may be due to N translocation during senescence to crown and roots. In contrast, the first harvest was performed at inflorescence fully emerged stage (R3) before senescence, thus resulting in greater biomass N concentration. Similar results have been reported in a two-harvest system in Tennessee (Reynolds et al., 2000), in which average biomass N concentration was 7.2 and 4.3 g kg^{-1} DM at the first and second same-year harvests, respectively.

The greater biomass N concentration in the first harvest at the multi-harvest locations may be a concern for biomass biofuel quality (Adler et al., 2006). Low N content in the biomass is preferred during the thermochemical conversion of biomass into ethanol, because high mineral concentration in the biomass feedstock can cause char formation (Rejai et al., 1992), corrosion, and increased NO_x emissions (Jorgensen, 1997). However, it is possible that the first harvest biomass had high quality for methane production. The first harvest biomass likely had low forage fiber concentration and high digestibility, which are related to high specific methane yields from anaerobically digested switchgrass silage (Bélanger et al., 2012). Therefore, the desirable biomass biofuel quality will be dependent on the technology used for the conversion of biomass into biofuels.

Crop N removal by harvest was significantly affected by N rate at all locations, with the exception of Tulelake (Table 6). At Tulelake, no differences in crop N removal were detected among N treatments in both years of full production, probably due to high total soil N (Table 2). At Davis and Five Points, the response of crop N removal to N fertilization was significant from 2008 onward, while at El Centro, differences were not significant in 2008 but became significant in 2009

(N removal data from El Centro in 2010 are not available). Similar to biomass yields, crop N removal responded linearly to N fertilization rates and increased over the years due to a depletion of available soil N in the zero N treatment (Table 6). On average across years, crop N removal by the greatest N rate compared to the zero N treatment increased by 85, 136, and 100 kg N ha^{-1} yr^{-1} at Davis, Five Points, and El Centro, respectively.

Average annual crop N removal across N rates was 92, 103, 137, and 210 kg ha^{-1} yr^{-1} at Tulelake, Davis, Five Points, and El Centro, respectively (Table 6). In general, more N was removed from multi-harvest locations than from single-harvest systems (Tulelake). Similar results were observed in other studies (Guretzky et al., 2011; Vogel et al., 2002), where multi-harvest systems removed more N than single-harvest systems. At the multi-harvest locations Davis and Five Points, the first harvest accounted for 87 and 84% of the annual N removal, respectively. The greater N removal in the first harvest was due to a combination of greater yields and greater N concentration. Similarly in El Centro, the first two of three harvests accounted for 94% of N removal.

While we did not evaluate single vs. two-harvest systems at the same location, our data indicates that a single harvest in the fall may be a more efficient and sustainable switchgrass production system for the Mediterranean and semiarid ecoregions. Fike et al. (2006a, 2006b) reported gains in yield of 8 to 36% in two- vs. single-harvest systems during the first 5 yr of production. However, differences between the two- and single-harvest systems became less over time. In addition to biomass yields, the timing and number of harvests is also related to the biomass biofuel quality (Adler et al., 2006), such as biomass moisture content and mineral concentration. Biomass moisture content affects transportation costs, safety in storage, and combustion efficiency (Lewandowski and Kicherer, 1997), and a single harvest performed in fall would likely result in lower biomass moisture content due to senesced plants. While yields are generally less in single-harvest systems, a single harvest would allow for N translocation during senescence, lowering N concentration in the biomass and reducing N removal (Guretzky et al., 2011; Parrish and Fike, 2005; Sanderson et al., 1999; Vogel et al., 2002). In addition, N stored in belowground biomass may be used the following growing season, which may decrease fertilizer N requirements and increase long-term system sustainability. Moreover, the additional harvests require increased use of fertilizer and field operations, but only produced 24% of the total annual biomass in the Central Valley of California. The limited increase in yield with the increased use of resources of an additional same-year harvest raises concerns about the sustainability and energy efficiency of multi-harvest systems.

CONCLUSIONS

Our study identified the adaptability and overall yield potential of northern upland switchgrass in different ecoregions of California. The production of Trailblazer switchgrass was not suitable in the temperate continental climate of the intermountain region because of excessive winter mortality. Greater yields were achieved in the warmer Mediterranean, semiarid, and desert ecoregions. Despite the longer growing season in the desert region, yields achieved were similar compared with the Central Valley in 2008 and 2009 but lesser in 2010, possibly due to hotter summer temperatures, unsuitable variety, and the harvest management practice followed at that location.

In the warm ecoregions of the Central Valley and Desert regions, Trailblazer switchgrass required no N fertilization in the first full year of production in two of the three locations. However, in the subsequent years, switchgrass yields increased linearly to N fertilization up to 300 kg N ha^{-1} yr^{-1} and with increasing degree of response with each subsequent year. Results show that ANUE was similar across ecoregions but increased over time, from 30 kg biomass kg^{-1} N applied in 2009 to 44 kg biomass kg^{-1} N applied in 2010. The significant increase in ANUE over time was due to a decrease in yields of the zero N treatment rather than an increase in yields of the greater N treatments.

The range of N fertilizer rates used did not allow us to determine the maximum yield potential in the different ecoregions of California. However, our results clearly indicate that in intensively managed multi-harvest systems, switchgrass requires significant N fertilizer input to sustain greater yields. Because of limited biomass production later in the growing season, single-harvest systems may be more sustainable than multi-harvest systems for the ecoregions of the Central Valley of California, as N fertilizer inputs would be reduced, along with a reduction in fuel and labor costs associated with the additional harvest.

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