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56 Abstract

The comparative productivity of switchgrass (*Panicum virgatum* L.) and Miscanthus (*Miscanthus* × *giganteus)* is of critical importance to the biofuel industry. The radiation use efficiency (RUE), when derived in an environment with non-limiting soil water and soil nutrients, provides one metric of relative productivity. The objective of this study was to compare giant Miscanthus to available switchgrass cultivars, using established methods to calculate RUE of the two species at two disparate sites. Measurements of fraction intercepted photosynthetically active radiation (PAR) and dry matter were taken on plots at Elsberry, MO (Miscanthus and the switchgrass cultivars Alamo, Kanlow, and Cave-in-Rock) and at Gustine, TX (Miscanthus and Alamo switchgrass, irrigated with dairy wastewater and a non-irrigated control). In MO, Miscanthus mean RUE (3.71) was less than Alamo switchgrass mean RUE (4.30). In TX under irrigation, Miscanthus mean RUE was 2.24 and Alamo switchgrass mean RUE was 3.20. In MO, the more northern lowland switchgrass cultivar, Kanlow, showed similar mean RUE (3.70) as Miscanthus. In MO, the northern upland cultivar Cave-in-Rock had a mean RUE (3.17) that was only 85% of that for Miscanthus at MO. Stress (water and nutrients) had a greater effect on Miscanthus RUE than on switchgrass RUE in TX. These results provide realistic RUE values for simulating these important biofuel grasses in diverse environmental conditions.

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Clash of the Titans: Comparing Productivity Via Radiation Use Efficiency for Two Grass Giants of the Biofuel Field

James Robert Kiniry · Mari-Vaughn V. Johnson · Steve B. Bruckerhoff · Jerry U. Kaiser · R. L. Cordsiemon · R. Daren Harmel

Abstract The comparative productivity of switchgrass (*Panicum virgatum* L.) and Miscanthus (*Miscanthus × giganteus)* is of critical importance to the biofuel industry. The radiation use efficiency (RUE), when derived in an environment with non-limiting soil water and soil nutrients, provides one metric of relative productivity. The objective of this study was to compare giant Miscanthus to available switchgrass cultivars, using established methods to calculate RUE of the two species at two disparate sites. Measurements of fraction intercepted photosynthetically active radiation (PAR) and dry matter were taken on plots at Elsberry, MO (Miscanthus and the switchgrass cultivars Alamo, Kanlow, and Cave-in-Rock) and at Gustine, TX (Miscanthus and Alamo switchgrass, irrigated with dairy wastewater and a non-irrigated control). In MO, Miscanthus mean RUE (3.71) was less than Alamo switchgrass mean RUE (4.30). In TX under irrigation, Miscanthus mean RUE was 2.24 and Alamo switchgrass mean RUE was 3.20. In MO, the more northern lowland switchgrass cultivar, Kanlow, showed similar mean RUE (3.70) as Miscanthus. In MO, the northern upland cultivar Cave-in-Rock had a mean RUE (3.17) that was only 85% of that for Miscanthus at MO. Stress (water and nutrients) had a greater effect on Miscanthus RUE than on switchgrass RUE in TX. These results provide realistic RUE values for simulating these important biofuel grasses in diverse environmental conditions.

Keywords

Abbreviations

PAR	Photosynthetically active radiation in MJ per m^2 ground area
IPAR	Intercepted photosynthetically active radiation in MJ per m^2 ground area
FIPAR	Fraction of intercepted photosynthetically active radiation
RUE	Radiation use efficiency in g of dry biomass per MJ intercepted photosynthetically active radiation

Introduction

Plant productivity of different species can be defined by the potential biomass produced in optimum growing conditions. Similarly, the efficiency of production of plant biomass can be described as per unit water transpired (water use efficiency), per unit nutrient taken up, such as for nitrogen (nitrogen use efficiency), or per unit light intercepted (radiation use efficiency; RUE). The RUE is a measure of stored chemical energy relative to absorbed radiant energy.

The RUE provides a relatively simple means of quantifying net increases in plant dry matter by assuming that the dry weight produced per unit of intercepted photosynthetically active radiation (IPAR) is a constant in non-stress environments [5, 10, 27, 33]. This approach has been used in a number of plant-growth models [8, 10, 34]

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and more recently to quantify growth of cool-season grasses [12] and warm-season grasses [15].

It is especially important not only to characterize typical values for RUE of important plant species, but also to identify variability in RUE when it occurs and the sources of such variability. Maize (*Zea mays* L.) RUE is one standard, with relatively high values of biomass per MJ of intercepted photosynthetically active radiation (IPAR). Kiniry et al. [10] compared published and unpublished values and found a mean maize RUE of 3.5 g per MJ IPAR. Kiniry et al. [16] reported a value of 3.7 g per MJ IPAR for irrigated maize in the High Plains of TX. Lindquist et al. [20] reported a mean of 3.8 g per MJ *absorbed* PAR for irrigated maize in high yielding conditions in NE. Tollenaar and Aguilera [32] reported a value of 3.3 g per MJ IPAR for modern maize in the 6 weeks following silking in the field in Canada, assuming 45% of total solar radiation is PAR as per Meek et al. [25], instead of the 50% value used in that study.

This relatively high value for maize RUE has been supported by successful modeling projects, where a value of 3.5 was applied in models such as ALMANAC [11] and CERES-Maize [8]. Maize was successfully simulated with this RUE value in diverse regions of TX [9], for sites in nine states in the U.S. [14], in high yielding TX environments [16], and in severe drought stressed environments in TX [35].

In contrast, Dohleman and Long [4] reported much lower maize RUE values of 2.5 and 3.0 g per MJ IPAR (as calculated assuming 45% of total solar radiation is PAR, as described above). This maize value is similar to the previously reported mean RUE of 2.8 for RUE of wheat (*Triticum aestivum* L.) [10], a species with much lower productivity than maize.

Switchgrass (*Panicum virgatum* L.) has established itself as a standard for high productivity in terms of RUE, with mean RUE values exceeding those of maize. A mean RUE value of 4.7 g per MJ IPAR for Alamo switchgrass was reported in TX by Kiniry et al. [15]. High values for leaf area index (LAI), low values for light extinction coefficient (*k*) in Beer's Law [26], and the C_4 photosynthetic pathway help explain the mechanisms which allow switchgrass to achieve high biomass production. Its high productivity has led to its predominance as the species of choice for biofuel feedstock production in many environments [22, 23, 29, 30]. Similar to the above discussion of maize modeling, this high value for switchgrass RUE (4.7) was applied in the ALMANAC model to successfully simulate switchgrass at several sites across nine states, extending from TX and LA in the south to ND, SD, NE, and WI in the north [13, 17–19].

Interestingly, some much lower values of switchgrass RUE have been reported. In Canada, Madakadze et al. [21] reported RUE values of 2.38 for "Cave-in-Rock", 2.00 for "Pathfinder", and 1.98 for "Sunburst", in units of g per MJ IPAR. Even lower was the RUE value of 1.2 g per MJ IPAR for Cave-in-Rock switchgrass in Illinois [7].

Miscanthus (*Miscanthus* × *giganteus*) has high biomass potential in the Midwestern U.S. and in Europe [1, 6]. Similar to the above discrepancies for maize and switchgrass, researchers have reported drastically different RUEs for Miscanthus. Heaton et al. [7] reported a relatively high RUE 4.1 for Miscanthus in Illinois, similar to the RUE for switchgrass (4.7) discussed above. In contrast, Clifton-Brown et al. [2] reported Miscanthus RUE of 2.4 in the U. K. and Cosentino et al. [3] reported a RUE of 2.19 in Italy. More recently, Dohleman and Long [4] reported a RUE of 2.3 and 3.0 (corrected assuming 45% of total solar radiation is PAR as discussed above for maize) for Miscanthus in Illinois.

Given these discrepancies in RUE values among studies for these two highly productive grass species, we conducted a side-by-side comparison of Miscanthus with upland and lowland switchgrass cultivars, using established methods of measurements to allow calculation of RUE. The objective of this project was to measure the fraction of intercepted PAR (FIPAR) and biomass of Miscanthus and switchgrass at two divergent sites (one in central TX and one in northeastern MO), each with high available soil water and nutrients. This enabled direct comparison of the RUE of each species. Such RUE values not only provide a means of comparing the two species productivity per unit light intercepted, but improve realistic predictions of biofuel plant production under various environmental conditions via correctly populating simulation models.

Materials and Methods

The data sets for this study consisted of repeated measurements of FIPAR and end of the growing season values for above-ground dry matter. Measurements were per unit ground area, as 1 m^2 of ground area. Seasonal values for summed intercepted PAR (IPAR) were determined by calculating daily values for FIPAR, by linearly interpolating between measurement dates, and using the incident PAR (taken as 45% of incident daily total solar radiation, as described above). The RUE was calculated as the ratio of the final dry matter (g per m^2 ground area) divided by the summed IPAR (taken over the growing period). The end of the growing period was assumed to be when the maximum FIPAR was attained. In TX in 2009, we assumed growth of all plots ended on the same date as did irrigated Miscanthus in 2008.

Two sites of different latitudes were used. The southern site (Fig. 1) was near Gustine, TX (31°53′32″N 98°22′29″ W, 358 masl) on a Pedernales loamy fine sand (fine, mixed, superactive, thermic Typic Paleustalfs). This soil has a pH

Fig. 1 Miscanthus at Elsberry, Missouri in 2009

of 7.5 and a soil organic matter of 0.55%. Two treatments were applied: one with unlimited water and nutrients under a center pivot irrigation used to apply dairy waste water, and one immediately outside the irrigated area, on the same soil, that was not irrigated with the same combination of plots. Within each of these two areas, there were five replicates of Miscanthus and Alamo switchgrass planted in 5-by-5-m plots with plants spaced on 1-m centers. Irrigated plots received 51 to 108 kg N ha^{-1} year^{-1} from the dairy waste water and 13 to 27 kg P ha^{-1} year^{-1} (Table 1). Non-irrigated plots were never fertilized.

The northern site (Fig. 2) was at the USDA-NRCS Plant Materials Center at Elsberry, MO (39°9′25″N 90°46′55″W, 144 masl) and had four replicates of Alamo, “Kanlow”, and Cave-in-Rock switchgrass and Miscanthus. Alamo originates from TX, Kanlow from OK, and Cave-in-Rock from IL. Miscanthus was planted in 0.91 m rows, with 0.91 between plants. Switchgrass cultivars were seeded in 0.91 m rows with 164 seeds (p.l.s.) per meter of row. Plots received 112 kg N ha^{-1} year^{-1} as NH_4NO_3 prior to the initiation of growth in the spring. Genetic analysis of the Miscanthus material used indicated that the plant material at both sites were identical and came from the same genotype (Michael Casler, pers. comm.). Soil type was a Menfro silt loam (fine-silty, mixed mesic Typic Hapludalf). This soil has a pH of 6.5 and a soil organic matter of 0.73%.

Table 1 Annual applied N and P (kg ha^{-1}) delivered through the dairy waste irrigation water at Gustine, TX in 2008, 2009, and 2010

	$N\text{-}NO_3$	$N\text{-}NH_4$	N Total	$P\text{-}PO_4$
2008	13	38	51	13
2009	27	80	108	27
2010	14	40	54	14

Plots were established from seeds (for switchgrass in MO), from seedlings (for switchgrass in TX), and from plantlets (for Miscanthus at both sites) in 2007. All Miscanthus × giganteus plants were the Illinois clone started from rhizomes in the greenhouse and transplanted to the field. Field measurements were taken in 2008 and 2009 at both sites, with additional measurements in 2010 at TX. Because of the different methods of establishment of switchgrass (seeds and seedlings), we felt the most meaningful comparison between locations involved the last 2 years at TX, after plants were well established and had tillered sufficiently to provide full canopy by the end of the growing season. On several dates during the growing seasons, direct measurements of FIPAR were taken as three sets of PAR measurements in quick succession under the leaf canopy using a 0.8 m long Sunfleck Ceptometer (Decagon Devices Inc., Pullman, WA) to enable calculation of FIPAR. This consisted of measurements at several positions under the leaf canopy, with the sensor positioned to account for light transmission directly below plants and below the interplant areas. Thus fraction interception represented the whole plot area. An external sensor was used in conjunction with the ceptometer to allow concurrent above and below canopy PAR readings. For Elsberry in 2008, FIPAR was measured on 29 May, 25 June, 2 July, 14 July, 14 Aug., 25 Aug., and 9 Sept. For Elsberry in 2009, FIPAR was measured on 29 May, 30 June, 20 July, 9 Sept., and 15 Sept. For Gustine in 2008, FIPAR was measured on 24 April, 8 May, 20 May, 3 June, 18 June, and 7 July. For Gustine in 2009, FIPAR was measured on 16 July and 28 Sept. In 2010, FIPAR measurements were taken on 15 April, 28 April, 11 May, 27 May, and 9 June. Daily values for fraction intercepted in 2009 at Gustine were based on the 2008 Gustine measurements. We assumed a similar pattern of development of leaf cover between the 2 years.

Fig. 2 Miscanthus (*on left*) and Alamo switchgrass (*on right*) at Gustine, Texas

We used a factor for each treatment of each plant species, calculated as the ratio of the mean July FIPAR value in 2009 divided by the mean July FIPAR value in 2008. This factor was used to change the daily fraction intercepted values of 2008 for use in 2009. These factors to increase FIPAR from the 2008 values were 1.04 for irrigated switchgrass, 1.48 for non-irrigated switchgrass, 1.19 for irrigated Miscanthus, and 1.87 for non-irrigated Miscanthus.

Above-ground plant material at approximately 15 cm above ground level from 1 m by 1 m of ground area (at Gustine) and from 4.4 m by 0.91 m area (at Elsberry) was collected on the dates of FIPAR measurement at Gustine and on the final dates of FIPAR measurement at Elsberry and dried in a forced air oven until constant dry weight was achieved. Plots in 2008 and 2010 at Gustine were different in that biomass samples were taken on each date of FIPAR measurement. Adjacent areas were not sampled on successive dates in order not to bias measurements. Thus, only for these 2 years at this site, RUE values were the slopes of the regressions of dry matter (g per m^2) as a function of summed IPAR (MJ per m^2). For the other analyses, end of season biomass was used to calculate RUE as the ratio of dry matter over summed IPAR.

Statistical analysis for each year at each location (other than 2008 and 2010 at Gustine) consisted of comparing RUE values with a *t* test using the Bonferroni (Dunn) procedure of SAS [31]. Differences were tested at the 95% confidence level among all entries (or entries by treatment at Gustine) within each year.

For the 2 years with repeated measurements during the growing season at Gustine, differences among entries by treatments were done with regression analysis, using indicator variables for slopes and intercepts [28]. Differences among entry by treatment were considered at the 95% confidence level.

Results

General Description of Plots

Dry matter production of these plots was sufficiently great to indicate that plants were not limited by water or nutrients. Appearance (Figs. 1 and 2) demonstrated that plants were in near-optimum conditions at the two locations. Thus, the values reported below should be representative of the potentials for feedstock production in these two regions.

Climatic Conditions

Temperatures were much warmer at the TX site, with mean annual monthly maximums of 35.2 to 37.4 C and mean annual monthly minimums of −0.6 to −0.7 C (Table 2). At the MO site, mean annual monthly maximums were 30.0 to 30.8 C and mean monthly minimums were −6.4 and −8.9 C.

Correspondingly, rainfall sums in TX were less than the MO site, with the annual sums in 2008 and 2009 both 71% of the MO site. The 725 mm of rainfall in 2010 (by the end of August) in TX was less than the 825 mm for this period in 2008 and greater than the 576 mm for this period in 2009. The irrigation values during the growing season in TX were similar among years (Table 3), with 2009 and 2010 having the same amount of irrigation by the end of August.

Final Dry Matter

Miscanthus had greater final dry matter than Alamo both years in Elsberry, while the opposite was true at Gustine for the irrigated treatment in 2009 and 2010 (Table 4). The average Miscanthus final dry matter was 158% of the value for Alamo in MO. For the second year after establishment (2008), when plants had not yet reached their full potential size, Miscanthus in TX was 105% of Alamo for the irrigated treatment. However, in the second, more representative year in TX, irrigated Miscanthus was only 81% of that for Alamo. In TX in 2010, irrigated Miscanthus yield was only 75% of that for Alamo.

The two more northern switchgrass types, Cave-in-Rock and Kanlow, always produced less dry matter than Alamo in MO. The mean biomass for Cave-in-Rock was only 65% of the mean for Alamo. Kanlow mean biomass was only 86% of the mean for Alamo.

Lack of dairy waste water irrigation caused a much greater reduction and variability in the final dry matter of Miscanthus than of Alamo switchgrass in TX. Non-irrigated switchgrass was 50% as productive as irrigated in 2008, 59% as productive in 2009, and 25% as productive in 2010. In contrast, non-irrigated Miscanthus was 18% of irrigated in 2008, 42% of irrigated in 2009, and 11% of irrigated in 2010.

Radiation Use Efficiency

The Miscanthus RUE was more variable between locations, with the mean of 3.71 for MO and 2.24 for the last 2 years in TX (Table 5). The mean for MO was similar to the 4.1 value reported by Heaton et al. (2007), while the mean for the irrigation treatment in TX was closer to the lower values reported elsewhere, as described above. Miscanthus RUE was 58% to 103% of corresponding Alamo switchgrass RUE for all measurements.

The mean Alamo switchgrass RUE (excluding the irrigated treatment in TX in 2008 and all years of the non-irrigated treatment in TX) was 3.75 g per MJ IPAR.

t2.1 **Table 2** Monthly rainfall, maximum temperature, and minimum temperature for Gustine, TX in 2008, 2009, and 2010 and Elsberry, MO in 2008 and 2009

	Gustine, TX			Elsberry, MO			t2.2
	Rain mm	Max C	Min C	Rain mm	Max C	Min C	t2.3
2008							t2.4
January	31	14.2	−0.7	40	6.4	−6.4	t2.5
February	41	20.0	2.7	113	4.3	−6.1	t2.6
March	137	22.4	7.3	122	13.0	6.8	t2.7
April	70	25.8	10.7	127	18.6	6.3	t2.8
May	40	30.9	17.0	153	23.0	10.5	t2.9
June	105	36.2	22.0	94	29.9	18.2	t2.10
July	8	36.9	21.9	264	30.8	19.4	t2.11
August	393	34.1	21.5	42	29.5	17.8	t2.12
September	82	30.9	15.6	295	25.5	14.6	t2.13
October	63	27.2	10.0	16	19.9	7.4	t2.14
November	26	22.2	5.2	30	12.5	1.0	t2.15
December	1	16.9	−0.5	101	5.6	−5.1	t2.16
Annual sum	997			1,397			t2.17
2009							t2.18
January	17	17.3	−0.6	12	3.0	−8.9	t2.19
February	29	21.3	4.6	34	10.1	−3.0	t2.20
March	15	22.6	8.4	73	15.7	2.2	t2.21
April	7	25.4	11.2	138	18.7	5.9	t2.22
May	137	29.1	16.2	148	25.3	11.5	t2.23
June	155	34.0	20.2	142	30.0	18.0	t2.24
July	192	36.3	21.8	169	27.6	17.0	t2.25
August	22	37.4	21.3	81	28.5	17.5	t2.26
September	153	30.3	17.6	94	25.3	13.3	t2.27
October	178	23.6	10.7	294	15.4	6.4	t2.28
November	74	22.2	6.0	133	16.1	4.6	t2.29
December	37	12.9	−0.7	109	3.9	−4.1	t2.30
Annual sum	1,018			1,425			t2.31
2010							t2.32
January	164	13.5	−0.6				t2.33
February	66	11.2	0.1				t2.34
March	138	20.1	5.2				t2.35
April	44	24.7	12.3				t2.36
May	49	30.8	17.2				t2.37
June	77	35.2	22.1				t2.38
July	169	34.7	22.8				t2.39
August	18	40.2	23.9				t2.40
Annual sum	725						t2.41

This was between the 3.5 reported for maize and the 4.7 reported previously for switchgrass in TX. This was greater than the lower switchgrass RUE reported elsewhere, as described above.

In MO, RUE for the other two switchgrass types was below the mean for Alamo, but still greater than those reported for switchgrass elsewhere. The Kanlow mean RUE of 3.70 was 86% of the corresponding Alamo RUE. The Cave-in-Rock mean RUE of 3.17 was 74% of the corresponding Alamo RUE.

Especially interesting was the relative reductions in RUE for Miscanthus and switchgrass in TX when irrigation was not applied. Stress (water and nutrients) had a greater effect on Miscanthus RUE than on switchgrass RUE in TX. In 2008, non-irrigated switchgrass RUE was similar to irrigated switchgrass while non-irrigated Miscanthus RUE

Table 3 Monthly rainfall and irrigation (mm) at Gustine, TX in 2008, 2009, and 2010

Month	2008		2009		2010	
	Rain	Irrigation	Rain	Irrigation	Rain	Irrigation
January	31	0	17	0	164	50
February	41	12	29	50	66	50
March	137	12	15	75	138	25
April	70	25	7	0	44	25
May	40	75	137	37	49	25
June	105	50	155	87	77	75
July	8	0	192	12	169	12
August	393	25	22	25	18	25
September	82	25	153	100		
October	63	12	178	25		
November	26	12	74	0		
December	1	25	37	162		
Annual sums	997	274	1,018	573	724	286
Sums by end of August	825	199	574	286	725	286

was only 42% of irrigated treatments. In 2009, stressed switchgrass RUE was 68% of that for non-stressed plants while stressed Miscanthus RUE was 59% of that for non-stressed plants. In 2010, stressed switchgrass RUE was 67% of that for non-stressed plants and stressed Miscanthus was 51% of that for non-stressed plants. In 2008, the RUE in TX was taken from plots approaching potential biomass and thus had lower final biomass than for the 2 years in MO or the 2009 and 2010 results for TX. Therefore, we focus our discussion on 2009 and 2010 in TX.

Since two factors are required to calculate RUE, dry matter production and summed IPAR during the production of this dry matter, the more productive grass may not always have the greater RUE. If it takes longer for the dry matter to be produced or if a productive grass has higher FIPAR during the season, the more productive grass may not have the greater RUE.

Differences between Miscanthus RUE and Alamo RUE could not be attributed to the same factors all years or at both locations. At Elsberry, the first-year Miscanthus had greater final biomass than Alamo, but greater FIPAR and longer growth duration (Table 6) resulted in the lower RUE. The second-year Miscanthus at Elsberry also had greater final biomass than Alamo, but the longer growth interval lead to Miscanthus RUE being only 3% greater than Alamo RUE. A different situation occurred in the last 2 years in TX. Final biomass of irrigated Miscanthus was less than that for irrigated Alamo, the growth periods were the same, and the FIPAR was lower for Miscanthus. The lower biomass had a greater impact on the RUE than the reduced

Table 4 Final dry weight v alues (g m^{-2}; mean ± SD) of switchgrass and Miscanthus at the two sites

	2008	2009	2010	Mean
Elsberry, MO				
Switchgrass				
Cave-in-Rock	1,230±601	1,032±139		1,131
Kanlow	1,684±936	1,310±208		1,497
Alamo	2,044±956	1,412±197		1,738
Miscanthus				
M. × *giganteus*	2,945±1,476	2,549±922		2,747
Gustine, TX				
Alamo switchgrass				
Irrigated	1,028±413	2,949±219	1,900±625	1,959
Non-irrigated	517±289	1,729±543	481±139	909
Miscanthus				
Irrigated	1,080±409	2,386±243	1,430±625	1,632
Non-irrigated	197±78	1,003±259	155±88	452

At Gustine, the irrigated treatment received dairy waste water through a center pivot irrigation system while the non-irrigated treatment only received rain, with no applied fertilizers

Table 5 Radiation use efficiency (RUE; g per MJ IPAR) values for switchgrass cultivars and *Miscanthus* × *giganteus* at two locations

Elsberry, MO	2008	2009		Mean
Switchgrass				
Cave-in-Rock	3.15±0.79	3.19±0.41		3.17
Kanlow	3.78±1.58	3.62±0.55		3.70
Alamo	5.05±0.90	3.56±0.56		4.30
Miscanthus				
M. x giganteus	3.76±0.91	3.66±1.53		3.71
Min. Sign. Diff.	2.44	1.95		
Gustine, TX	2008	2009	2010	Means (2009 and 2010)
Alamo switchgrass				
Irrigated	1.96±0.42	3.04±0.24	3.35±0.54	3.20
Non-irrigated	1.97±0.28	2.07±0.79	2.26±0.26[a]	2.16
M. x giganteus				
Irrigated	1.14±0.20[a]	2.39±0.24	2.09±0.24[a]	2.24
Non-irrigated	0.48±0.22[a]	1.42±0.47	1.07±0.16[a]	1.25
Min. Sign. Diff.		0.93		

Values are the mean±SD, except for Gustine 2008, which is slope ± SE. Minimum significant differences are from *t* tests. Results for Gustine, TX in 2008 and 2010 regressions are shown for which slopes (RUE values) are significantly different from the irrigated treatment of switchgrass

[a] RUE values significantly different from the RUE for irrigated treatment of switchgrass that year

FIPAR, causing Miscanthus RUE to be less than the RUE for Alamo.

Discussion

The comparative productivity of switchgrass and Miscanthus is of critical importance to perennial grass feedstock production for the biofuel industry. Two values from the literature, the Miscanthus RUE value of 4.1 g per MJ of Heaton et al. (2007) and the Alamo switchgrass RUE value of 4.7 g per MJ of Kiniry et al. [15] implies that Miscanthus is 87% less productive than Alamo switchgrass based on RUE. The results of this study indicate similar relative RUE values, with the Miscanthus mean RUE being 86% of Alamo switchgrass RUE in MO and 70% in TX. The mean RUE for the more northern lowland switchgrass cultivar Kanlow was 99.7% of the Miscanthus mean RUE in MO. Cave-in-Rock switchgrass, a northern upland cultivar, had the lowest mean RUE, which was 85% of the mean for Miscanthus, 86% of the mean for Kanlow, and 74% of the mean for Alamo. Consequently, in areas where Miscanthus produces greater biomass than lowland switchgrass cultivars such as Alamo (as it did in MO, but not in the last 2 years in TX), it is due to longer growth duration and not greater RUE. This has implications for simulation of these important grasses as well as implications for resource utilization and plant breeding. Longer growth duration and similar leaf area cover (and thus greater evapotranspiration) for Miscanthus suggests it will need more water to produce its maximum potential yields. Likewise, as indicated by the non-irrigated treatment in TX, Miscanthus will grow less biomass with a lower RUE than

Table 6 Intervals of growth for calculation of radiation use efficiency (RUE)

	2008	2009	2010
Elsberry, MO			
Switchgrass			
Cave-in-Rock	29 Apr–2 July (0.963)	29 May–30 June (0.956)	
Kanlow	29 Apr–14 Aug (0.991)	29 May–30 June (0.993)	
Alamo	29 Apr–14 July (0.989)	29 May–30 June (0.989)	
Miscanthus			
M. x giganteus	29 Apr–8 Aug (0.995)	29 May–20 July (0.989)	
Gustine, TX			
Alamo switchgrass			
Irrigated	24 Apr–3 June (0.871)	14 Apr–4 July (0.951)	22 Apr–30 June (0.981)
Non-irrigated	24 Apr–3 June (0.469)	14 Apr–4 July (0.578)	22 Apr–30 June (0.922)
Miscanthus			
Irrigated	24 Apr–7 July (0.832)	14 Apr–4 July (0.836)	22 Apr–30 June (0.927)
Non-irrigated	24 Apr–3 June (0.330)	14 Apr–4July (0.420)	22 Apr–30 June (0.371)

Values in parentheses are the final measured values for fraction of PAR intercepted. The ending date was considered to be when maximum dry weight occurred switchgrass when water and nutrients are more limiting. These results reiterate the importance of directly comparing biomass and RUE for candidate feedstocks in multiple divergent environments to develop accurate input parameters for plant-growth models.

Q3

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