



A quantitative review comparing the yield of switchgrass in monocultures and mixtures in relation to climate and management factors

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Abstract

Switchgrass (*Panicum virgatum* L.), a US Department of Energy model species, is widely considered for US biomass energy production. While previous studies have demonstrated the effect of climate and management factors on biomass yield and chemical characteristics of switchgrass monocultures, information is lacking on the yield of switchgrass grown in combination with other species for biomass energy. Therefore, the objective of this quantitative review is to compare the effect of climate and management factors on the yield of switchgrass monocultures, as well as on mixtures of switchgrass, and other species. We examined all peer-reviewed articles describing productivity of switchgrass and extracted dry matter yields, stand age, nitrogen fertilization (N), temperature (growing degree days), and precipitation/irrigation. Switchgrass yield was greater when grown in monocultures (10.9 t ha^{-1} , $n = 324$) than when grown in mixtures (4.4 t ha^{-1} , $n = 85$); yield in monocultures was also greater than the total yield of all species in the mixtures (6.9 t ha^{-1} , $n = 90$). The presence of legume species in mixtures increased switchgrass yield from 3.1 t ha^{-1} ($n = 65$) to 8.9 t ha^{-1} ($n = 20$). Total yield of switchgrass-dominated mixtures with legumes reached 9.9 t ha^{-1} ($n = 25$), which was not significantly different from the monoculture yield. The results demonstrated the potential of switchgrass for use as a biomass energy crop in both monocultures and mixtures across a wide geographic range. Monocultures, but not mixtures, showed a significant positive response to N and precipitation. The response to N for monocultures was consistent for newly established (stand age < 3 years) and mature stands (stand age ≥ 3 years) and for lowland and upland ecotypes. In conclusion, these results suggest that fertilization with N will increase yield in monocultures, but not mixtures. For monocultures, N treatment need not be changed based on ecotype and stand age; and for mixtures, legumes should be included as an alternative N source.

Keywords: mixture, monoculture, *Panicum virgatum* L., yield

Nomenclature:

CT = culture type
ET = ecotype
GDD = growing degree days
MT = mixture type
PR = precipitation
SA = stand age

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Introduction

As a warm-season perennial grass native to North America, switchgrass has been designated by the US

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Department of Energy as a model bioenergy feedstock because it can produce a high yield of biomass across a wide geographic range (McLaughlin *et al.*, 2006). Switchgrass is attractive as a biofuel crop because it is suitable for use on marginal, highly erodible, and droughty soils; it has potential for sequestering large

amounts of atmospheric carbon; and it provides nesting habitats for migratory animals (Sanderson *et al.*, 1996; Roth *et al.*, 2005; McLaughlin *et al.*, 2006). Water and nitrogen (N) are the principal resources limiting productivity in warm-season grass ecosystems (Elser *et al.*, 2007; Harpole *et al.*, 2007), thus the potential of a grassland species to become a profitable bioenergy feedstock requires efficient use of these resources.

The response of switchgrass yield to added N varies widely, ranging from no response (Christian *et al.*, 2002) to a positive response (Brejda, 2000; Muir *et al.*, 2001), which could reflect differences in N availability, climate, site history, or cultivars chosen (Parrish & Fike, 2005). However, the replacement of the removed nutrients from soils is an important issue for high-biomass producing crops such as switchgrass. For example, harvesting 11 t ha^{-1} of switchgrass dry matter with 1.2% N (equivalent to a crude protein concentration of 7.5%) will remove about $130 \text{ kg of N ha}^{-1} \text{ yr}^{-1}$ (Mitchell *et al.*, 2008). Nitrogen removed as a percentage of N applied can range from <50% to >100% (Parrish & Fike, 2005). As stands age, N can be lost through biomass harvesting and leaching. To replace this N, fertilizer use must be optimized to balance the costs of fertilizer production and application with the revenues generated from improved yield. Biofuels possess the additional constraint that they need to produce more energy than they consume, yet anthropogenic N comes with a substantial cost in terms of energy consumed and CO_2 emitted (Adler, 2007). Optimizing switchgrass biomass yields and maintaining quality stands requires proper N input based on the needs of stands of different age, ecotype, and species compositions.

In addition to planting bioenergy crops, other grassland-based resources such as conservation, marginal, or abandoned lands could supply bioenergy feedstocks. For example, land in the CRP (Conservation Reserve Program) has been suggested as a potential resource for biomass feedstock in the United States (Jewett & Sheaffer, 1996; Lee *et al.*, 2007; Mulkey *et al.*, 2008). Tilman *et al.* (2006) suggested that a low-input high-diversity (LIHD) prairie system involving mixtures of native grassland perennials can provide more usable energy, greater environmental benefits, and less agricultural pollution per hectare than corn-ethanol or soybean-biodiesel. In particular, using a diverse mixture of native prairie species as biomass feedstocks may yield greater net energy gains than monoculture energy crops when converted into biofuels, while also providing wildlife habitat and enriching degraded soils through carbon sequestration and N fixation (Hill, 2007). The strategies for achieving higher biomass in LIHD include using N-fixing legumes as the primary source of N and a diverse range of native prairie species to gain high

efficiency in exploiting resources. Grasses have benefited from the addition of legumes when grown in mixtures, with productivity equal to N-fertilized fields (Crews & Peoples, 2004). Many of the yield benefits of mixtures may be attributed to N transfer from the legumes to the associated grasses. However, little information exists on switchgrass productivity when grown in mixtures with temperate legumes.

While the yield potential of switchgrass in monocultures has been tested by many on-farm studies and has been modeled and reviewed extensively (McLaughlin & Kszos, 2005; Sanderson *et al.*, 2006; Schmer *et al.*, 2008), to date there have been no direct comparisons of the yield of switchgrass monocultures and diverse grassland mixtures. Furthermore, there are no reports of how stand age and ecotype affect the yield of switchgrass in response to N. Will monocultures and mixtures respond to N treatment and environmental factors in the same way? This study presents a new, updated quantitative literature review of the yield of switchgrass in order to address these following questions:

- (1) How do the yields of switchgrass in monoculture and mixtures compare?
- (2) How do nitrogen addition and climate impact the yield of switchgrass in monocultures and mixtures?
- (3) How do ecotype and stand age affect the response of monocultures yield to N?

Methods

Data collection and categorization

Peer-reviewed journal articles used in building the database for this meta-analysis were obtained by searching the Science Citation Index (SCI) of the Institute of Scientific Information. The list of articles obtained was subsequently cross-checked with references cited in a large number of review articles and books with the aim of including all articles that have relevant data for this meta-analysis. Articles published in English before the end of 2008 that met all of the following criteria were included: (1) the study objective was for biomass production, as opposed to only for forage production; (2) for monoculture studies, articles contained information on stand age (years), cultivar, ecotype, site location, N fertilization level ($\text{kg ha}^{-1} \text{ yr}^{-1}$), harvest date, and dry matter yield ($\text{t ha}^{-1} \text{ yr}^{-1}$); (3) for mixture studies, articles contained information on site location, N fertilization level, harvest date and dry matter yield of switchgrass, and/or total yield of mixtures. Studies were classified as to whether they represented switchgrass monocultures or multispecies mixtures that include switchgrass. For monocultures,

based on the stand age, yield data were categorized into newly established stands (<3 years) and mature stands (≥ 3 years). For mixtures, yield data was categorized based on whether or not legume species were present in the mixtures. Switchgrass-dominated mixtures were also compared with experiments performed on restored prairies without switchgrass present based on the database compiled by LeBauer & Treseder (2008).

In total, 39 peer-reviewed articles on switchgrass monocultures (Appendix A), eight on mixtures dominated by switchgrass (Appendix B) and 25 on mixtures without switchgrass (Appendix C) were included in this analysis. We assumed studies conducted at different sites, yields from different treatments (e.g. fertilizer treatments), and different growing seasons were independent. Graphical data were extracted from the articles using digitizing software (GETDATA GRAPH DIGITIZER v. 2.22).

Variables

Yield of switchgrass in monocultures and mixtures was evaluated for response to growing degree days (GDD), precipitation, and N fertilizer. Above-ground biomass of mixtures dominated by nonswitchgrass species was also tested for response to N fertilizer. Daily maximum and minimum temperature information for a given site was extrapolated using LOCLIM (v. 1.0 FAO, Rome, Italy), which estimates local climate based on recorded meteorological data. Annual precipitation, along with any irrigation, was collected from articles. GDD were calculated for a growing season with a base temperature of 10 °C. The growing season was defined by the date of the last frost in the spring to the date of the first frost in the autumn or date of harvest, whichever occurred first (Heaton *et al.*, 2004). When precipitation information was not reported in an article, annual precipitation for a given site was extrapolated using the LOCLIM program. Nitrogen fertilization values were used as reported in all articles.

Data analysis

Data were sorted and tested for normality (PROC UNIVARIATE, SAS 9.1, SAS Institute, Cary, NC, USA). Square-root transformed yield data were then analyzed separately on monocultures and mixtures using mixed models analysis of variance (PROC MIXED, SAS 9.1) (Littell *et al.*, 1999). The random effects in the mixed model framework were used to account for aspects of site-to-site variability that were not accounted for by the fixed-effect covariates but which potentially caused treatments within a site to not be independent (e.g. soil types, soil micro fauna). Similarly, cultivar random

effects account for the differences within an ecotype that could not be accounted for as fixed effects due to limited and unbalanced replication. For monocultures, a mixed model taking individual studies and cultivars as random effects was conducted to test the fixed effects of ecotype (ET; upland or lowland), stand age (SA; newly established or mature stands), GDD, precipitation (PR), N and the interactions (ET \times N and SA \times N) on dry matter yield. Likewise, a mixed model taking individual studies as a random effect was performed to test the fixed effects of legume availability [mixture type MT; with or without legume species], GDD, PR, N, and the interaction of N and the presence of legumes on the yield of switchgrass in mixtures. In order to compare how yield of switchgrass in monoculture and mixtures responded to N and climate, a weighted mixed model was conducted to test the fixed effects of culture types (CT; monoculture or mixture), N, PR, GDD, and their interactions (CT \times PR, CT \times GDD, and CT \times N) on the yield of switchgrass, with individual studies as random effects. The yield data for monocultures used in this weighted model was averaged across cultivars for a given study and weighted by $1/(SD^2)$. Tests of hypotheses were considered significant at $P \leq 0.05$.

Results

Overall, switchgrass yield was twice as high in monocultures compared with mixtures (10.9 ± 5.5 vs. 4.4 ± 4.5 t ha⁻¹, $P < 0.0001$, Table 1). Among monocultures, stand age affected switchgrass yield marginally significantly ($P = 0.067$, Table 1). Among mixtures, the presence of legumes increased both total yield and switchgrass yield. Total and switchgrass yield in switchgrass-dominated mixtures was 9.9 ± 5.9 and 8.9 ± 4.7 t ha⁻¹, respectively, when legumes were present, and 5.7 ± 4.0 and 3.1 ± 3.2 t ha⁻¹, respectively, in the absence of legumes. Mixtures without switchgrass yielded 2.8 ± 2.1 t ha⁻¹ (Table 1).

For monocultures, the variance components of the random effect of individual studies and cultivars were significantly different from 0, suggesting that individual studies and cultivars did differ in their average yield scores (Table 2). ET and SA significantly affected the yield of switchgrass, with lowland ecotype and mature stands having higher yield (Figs 1 and 2; Table 2). Nitrogen and precipitation had significantly positive effects on the yield (Table 2). The response to N for monocultures was consistent for newly established (stand age <3) and mature stands (stand age ≥ 3) and for upland and lowland ecotypes (Figs 1 and 2; N \times ET and N \times SA in Table 2).

For mixtures, the variance component of the random effect of individual study was not significantly different

Table 1 Yield (t ha^{-1}) of switchgrass in monocultures and mixtures and total yield of switchgrass and nonswitchgrass dominated mixtures

Culture type	Estimated mean (t ha^{-1})	SD	N	P
Switchgrass yield in monocultures	10.9	5.0	324	
Switchgrass yield in mixtures	4.4	4.5	85	<0.0001
Monocultures (stand age <3)	10.1	5.5	108	
Monocultures (stand age ≥ 3)	11.2	4.8	216	0.0671
Switchgrass yield in mixtures (with legume)	8.9	5.2	20	
Switchgrass yield in mixtures (without legume)	3.1	3.3	65	<0.0001
Total yield of mixtures (with switchgrass)	6.9	5.0	90	
Total yield of mixtures (without switchgrass)	2.8	3.1	314	<0.0001
Total yield of switchgrass-dominated mixtures (with legume)	9.9	5.9	25	
Total yield of switchgrass-dominated mixtures (without legume)	5.7	4.0	65	0.0023

Differences between two means were detected by *t*-test.
SD, standard deviation; N, number of observations.

Table 2 Fixed effects from mixed model of ecotype (ET; upland or land), stand age (SA), growing degree days (GDD), precipitation (PR), nitrogen (N), and the interaction between N and SA and ET for switchgrass in monocultures on dry matter yield, taking individual studies and cultivars as random effects

Effect	F-value	Pr > F
ET	25.18	<0.0001
SA	33.51	<0.0001
GDD	2.51	0.1134
PR	27.78	<0.0001
N	5.49	0.0192
N \times SA	2.15	0.1430
N \times ET	1.99	0.1582

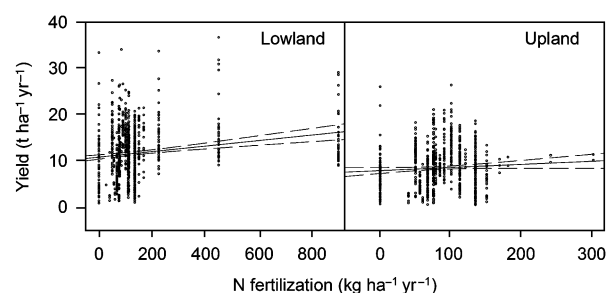
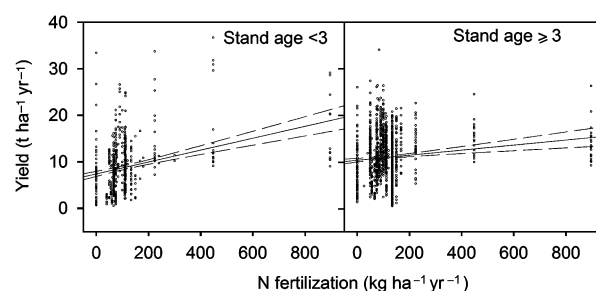
For all the effects, the df_N (numerator degrees of freedom) = 1 and the df_D (denominator degrees of freedom) = 1812.

For the random effect of individual studies: $Z = 3.38$, $P = 0.0004$.

For the random effect of cultivar: $Z = 2.92$, $P = 0.0018$.

from 0, suggesting that individual studies did not differ in their average yield scores (Table 3). Precipitation and GDD had no significant effects on the yield of switchgrass in mixtures (Table 3). Nitrogen had a marginally significant effect on yield ($P = 0.0594$ in Table 3). The response of mixtures to N was not affected by the presence or absence of legumes (Fig. 3; N \times MT in Table 3). By contrast to switchgrass-dominated mixtures, total yield in nonswitchgrass mixtures increased with the rate of N addition (right panel in Fig. 4; $r^2 = 0.12$, $P < 0.0001$, $n = 314$).

For the averaged yield across different cultivars for a given study, the variance components of the random effect of individual studies were significantly different from 0, suggesting that individual studies did differ in their average yield scores (Table 4). Monocultures had a

**Fig. 1** Response of the annual yield of upland and lowland switchgrass in monocultures to nitrogen fertilizer. Solid lines indicate least-squares linear regression; dashed lines represent 95% confidence limits.**Fig. 2** Response of the annual yield of newly established stands (stand age <3) and mature stands (stand age ≥ 3) of switchgrass monocultures to nitrogen fertilizer. Solid lines indicate least-squares linear regression; dashed lines represent 95% confidence limits.

significantly higher yield than mixtures; precipitation and N had significant positive effects on the weighted yield of switchgrass in monocultures and mixtures (Table 4). GDD had no significant effect on the yield of switchgrass (Table 4). There was a significant difference for the yield of switchgrass in monocultures and

Table 3 Fixed effects from mixed model of mixture type (MT; with or without legume species), growing degree days (GDD), precipitation (PR), nitrogen (N), and the interaction of N × MT on the yield of switchgrass in mixtures, taking individual studies as random effects

Effect	F-value	Pr > F
MT	25.07	<0.0001
GDD	1.64	0.2182
PR	1.79	0.1844
N	3.67	0.0594
N × MT	0.61	0.4382

For all the effects, the $df_N = 1$ and the $df_D = 73$.

For the random effect of individual studies: $Z = 1.31$, $P = 0.0952$.

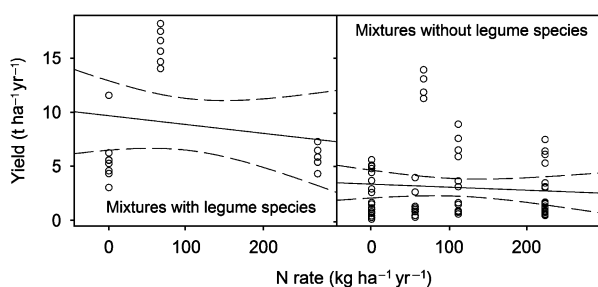


Fig. 3 Response of the annual yield of switchgrass in mixtures with or without legume species, to nitrogen fertilizer. Solid lines indicate least-squares linear regression; dashed lines represent 95% confidence limits.

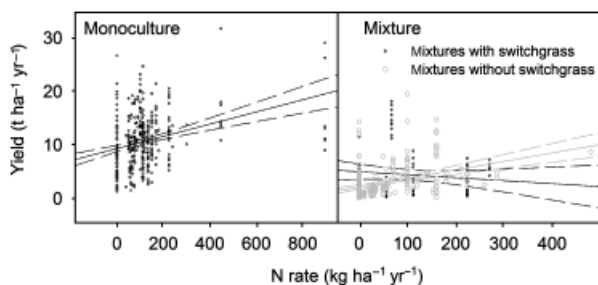


Fig. 4 Response of the annual yield of switchgrass in monocultures, mixtures with switchgrass (black dots), and mixtures without switchgrass (gray dots) to nitrogen fertilizer. Solid lines indicate least-squares linear regression; dashed lines represent 95% confidence limits.

mixtures to response to GDD (Fig. 6; GDD × CT in Table 4), but not to precipitation and N (Figs 4 and 5; PR × CT and N × CT in Table 4).

Discussion

Switchgrass produced 6.4 t ha^{-1} more biomass in monocultures than in mixtures (Table 1) over a range of

Table 4 Fixed effects from weighted-mixed model of culture types (CT; monoculture or mixture), nitrogen, precipitation (PR), growing degree days (GDD), and their interactions on the yield of switchgrass, taking individual studies as random effects

Effect	F value	Pr > F
CT	11.07	0.0010
PR	15.69	<0.0001
N	22.39	<0.0001
GDD	2.06	0.1520
N × CT	0.54	0.4623
PR × CT	0.73	0.3922
GDD × CT	4.83	0.0286

For all the effects, the $df_N = 1$ and the $df_D = 402$.

For the random effect of individual studies: $Z = 3.92$, $P < 0.0001$.

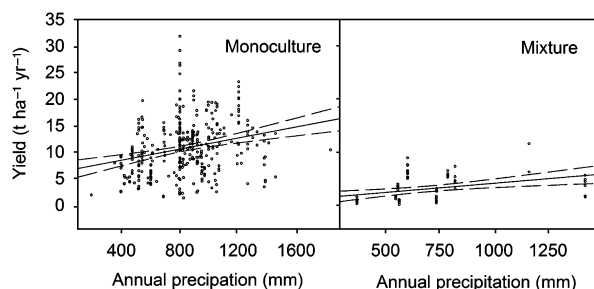


Fig. 5 Response of the annual yield of switchgrass in monocultures and mixtures to annual precipitation. Solid lines indicate least-squares linear regression; dashed lines represent 95% confidence limits.

growing conditions. Switchgrass in monocultures yielded 10.9 t ha^{-1} and no significant difference was found across stand ages. This result is close to 10.3 t ha^{-1} reported by Heaton *et al.* (2004), even though Heaton's study only included mature stands. Mixtures had an annual yield of 6.9 t ha^{-1} , of which switchgrass accounted for 4.4 t ha^{-1} on average. These results are consistent with the study of Adler *et al.* (2005) in which above-ground biomass averaged 6.6 t ha^{-1} at 34 sites surveyed across the northeast United States that included Conservation Reserve Program (CRP; a land set-aside program established by the USA Food Security Act of 1985), wildlife habitat improvement program (WHIP), mine reclamation, and other conservation lands as a resource assessment for biomass production. The results in this study were also comparable with the 4.4 t ha^{-1} yield of mixtures grown with low inputs on agriculturally degraded land (Tilman *et al.*, 2006). Monocultures had higher yield than mixtures, which supports the view that changes in resource availability

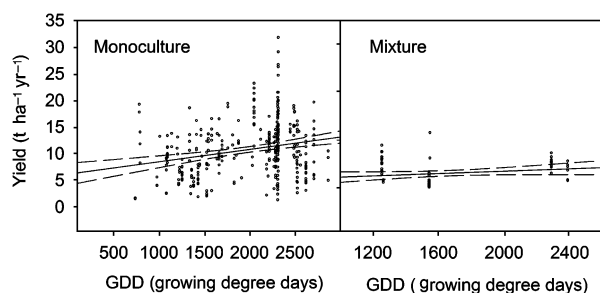


Fig. 6 Response of the annual yield of switchgrass in monocultures and mixtures to growing degree days (GDD). Solid lines indicate least-squares linear regression, dashed lines represent 95% confidence limits.

are more important for productivity than changes in diversity (Hooper *et al.*, 2005; Spehn *et al.*, 2005) (Fig 6).

Switchgrass yield was significantly higher in the mixtures with legumes present compared with mixtures without legumes (Table 1). This supports the findings of Blanchet *et al.* (1995) and Berdahl *et al.* (2001) that legumes benefit the grass in a grass-legume mixture if the legumes achieve an adequate stand density. Total yield of the mixtures was significantly higher when legumes were present (Table 1) and was not significantly different from monoculture yield, suggesting legumes can be incorporated into established switchgrass without negatively impacting total dry matter yields. Commercial fertilizer savings for biomass systems using legumes deserves further study, because legumes offer a more environmentally sound and sustainable source of N to ecosystems (Crews & Peoples, 2004; Pretty, 2008). On average, about 72 kg N ha⁻¹ was added to the soil by several winter legumes (Hargrove, 1986). The N₂ fixation rate has also been reported for red clover (*Trifolium pratense* L.) (373 kg N ha⁻¹), white clover (*Trifolium repens* L.) (545 kg N ha⁻¹), and alfalfa (*Medicago sativa* L.) (350 kg N ha⁻¹) (Carlsson & Huss-Danell, 2003). Further research on the potential role of legumes in sustainable biomass production is urgently needed. Unresolved issues include when to harvest the mixtures to get the highest yield while minimizing N removal while promoting the establishment of the temperate legumes in subsequent years and which management strategies reduce competition between warm-season grasses and temperate legumes.

Nitrogen limits net primary production (NPP) in terrestrial ecosystems (Vitousek & Howarth, 1991; LeBauer & Treseder, 2008), and our study specifically demonstrates that N limits switchgrass production. Use of N fertilizer must be optimized in biomass feedstock production to balance the economics, energy, and environmental costs of fertilizer use with the resulting gains in yield. This study shows that N addition

increases switchgrass yield in monocultures (Fig. 4). Contrary to our expectation that N demand might increase as stands age due to N removal from biomass harvesting and leaching out of root zone, the response of switchgrass yield in monocultures to N treatment did not change as stands age (Fig. 2). However, switchgrass yield in mixtures was not impacted by N addition, even when legumes were absent (Figs 3 and 4). In contrast, nonswitchgrass dominated mixtures responded to N addition significantly (Fig. 4), which is consistent with the study of LeBauer & Treseder (2008) in which temperate grasslands NPP increased 53% after N addition. The different response of switchgrass-dominated and nonswitchgrass-dominated mixtures to N addition might be due to the effect of end-of-season harvest for biomass studies. As reported in Heaton *et al.* (2009), switchgrass would have potentially removed 187 kg N ha⁻¹ if harvested green, and as little as 5 kg N ha⁻¹ if harvested in late winter. Warm-season grasses internally recycle N from the above-ground shoots to below-ground, reducing N removal from the system, thereby increasing the N-use efficiency (Parrish & Fike, 2005). About 18% of the annual N demand of native prairie species is supplied by internal reserves (McKendrick *et al.*, 1975). If the dead dry shoots are harvested after N is reallocated belowground, internal cycling and storage of N within switchgrass plant may contribute to its conservative N use and reduce the need for additional fertilizer (Beale & Long, 1997; Dubeux *et al.*, 2007).

This analysis indicates switchgrass yield in monocultures but not in mixtures was affected significantly by water availability [Power >0.99 by power analysis (Zar, 1999) for both monoculture and mixture; Fig. 5, Table 2]. Lee & Boe (2005) found that April and May precipitation was a key indicator of biomass production for two switchgrass cultivars in central South Dakota United States. With mixed stands, however, individual species within a mixture may respond differentially to moisture received during different times in the growing season. The lack of the response of the yield of switchgrass in monocultures and mixtures to GDD was consistent with the results reported in Heaton *et al.* (2004). The response pattern suggests a broad optimal temperature range for the yield of switchgrass. Though the yield of switchgrass was not significantly affected by GDD, the phenology of flowering time and nutrient translocation might be affected (Sanderson, 1992). This phenology change could also affect the yield.

In conclusion, this analysis demonstrates the potential of switchgrass for use as a biomass energy crop across a wide geographic range. Nitrogen addition is required for switchgrass growth in monocultures, and N demand does not increase as switchgrass stands age. Switchgrass and total yield in mixtures is comparable

with other studies (Adler *et al.*, 2005; Tilman *et al.*, 2006), which also confirmed the possibility of growing switchgrass in mixtures as a biofuel feedstock in marginal lands (Gonzalez-Hernandez *et al.*, 2009). Switchgrass yields significantly higher when legumes are present in the mixtures, supporting the possibility of using legumes as the N source. Legume-based agro-ecosystems could maintain greater ecological integrity than that of fertilizer-based systems (Crews & Peoples, 2004), avoiding the competition for fertile soils with food production and the possibility of ecosystem destruction.

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