Recommendation of the Interagency Group Establishing Agronomic Rates for Energy Crops for Utilization by Biofuels Facilities.

As required by Senate Bill 378 (Session Law 2011-198)

June 30, 2011

Submitted to:

NC Environmental Review Commission

Steve Troxler, Commissioner of Agriculture

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Executive Summary

Senate Bill 378 (Session Law 2011- 198) directed the Interagency Group to develop interim agronomic rates and guidance to ensure proper application levels of animal waste for the following energy crops: miscanthus, switchgrass, fiber sorghum, sweet sorghum, and giant reed (arundo donax) no later than July 1, 2011, and final agronomic rates no later than December 1, 2014.

The Interagency Group requested a literature review be completed by Dr. Ron Gehl, Assistant Professor and Extension Specialist in the NCSU Department of Soil Science, to provide the Interagency Group a proper, science based foundation on which to recommend interim rates. The group also requested its technical advisory subgroup, Interagency Nutrient Management Committee (INMC), to provide recommendations based on the Gehl literature review and other available scientific information. The Interagency Group considered the recommendations from the INMC to develop the interim agronomic rates.

On June 30, 2011, the Interagency Group adopted interim agronomic rates for energy crops for utilization by Biofuels facilities. The interim rates are summarized in Table 1. The Interagency Group will continue to review additional information between now and December 1, 2014 to develop the final agronomic rates for the specified energy crops.

Table 1 - Summary of Adopted Interim Agronomic Rates

Energy Crops for Biofuels Feedstock	Interim Nitrogen Agronomic Rates	Application Timing	Management Considerations
Switchgrass	120 lbs per acre regardless of soil type	March 1 - August 31	N application is not recommended in the first year.
Fiber Sorghum (Sorghum Sudan Hybrid)	45 lbs – 55 lbs of N per unit yield (tons) variable with soil type	March 15 – August 31	
Sweet Sorghum (single green harvest)	80 lbs of N per acre regardless of soil type	May 1 - July 31	Total harvestable biomass is to be removed from the field.
Sweet Sorghum (multiple green harvest)	First Harvest: 80 lbs of N per acre regardless of soil type Second Harvest: 20 lbs of N per acre regardless of soil type	First Harvest: May 1 – July 31 Second Harvest: Extend until August 31	Total harvestable biomass is to be removed from the field. Harvest dates should be documented in waste management plan records.
Miscanthus x Giganteus (Giant Miscanthus)	60 lbs of N per acre regardless of soil type	March 1 – September 30	N application is not recommended during the first 3 years after planting
Arundo Donax (Giant Reed)	Year one: 30 lbs of N per acre regardless of soil type Subsequent years: 60 lbs of N per acre regardless of soil	March 1 – September 30	

Establishment of interim agronomic nitrogen application rates and guidance on proposed biofuel feedstock grasses

The March 31, 2011, meeting of the Interagency Group heard from interested parties regarding the need of establishing agronomic rates for energy crops that could be utilized by Biofuels facilities. The Interagency Group requested the Interagency Nutrient Management Committee (INMC) to provide recommendations for establishment of interim agronomic rates for Miscanthus x Giganteus (Giant Miscanthus) and Arundo Donax (Giant Reed). Additionally, Senate Bill 378 (Session Law 2011-198) mandated that the Interagency Group develop interim agronomic rates to ensure proper application levels for the following energy crops; switchgrass, "fiber sorghum", "sweet sorghum", giant miscanthus, and giant reed (Arundo Donax) by July 1, 2011, with final agronomic rates to be established by December 1, 2014.

The INMC's charge from the Interagency Group was to focus on establishment of interim nitrogen application rates and development of interim animal waste technical specialist technical guidance for using these proposed biofuel grasses in waste utilization plans. The INMC met on June 24, 2011, and Dr. Ron Gehl, Assistant Professor and Extension Specialist in the NCSU Department of Soil Science, presented findings from a review of available literature on energy crops' (those species listed above) biomass production and nitrogen application/removal status.

Recommendations were made through INMC deliberation of and evaluative consensus on literature review findings. The INMC noted that the literature review found that 'luxury' consumption of Nitrogen by these crops is largely untested, and that the crops have typically been managed to reduce required nutrient inputs. Also, Dr. Gehl noted that there are vast managerial differences in growing these crops for production versus growing them as biofuel feedstock. The processes of how these grasses affect the removal of other nutrients, such as phosphorus, potassium, calcium and magnesium were not addressed by the INMC or Interagency Group at this time.

To further document recommendation decisions made by the INMC, Dr. Gehl's report "Literature Review of Biomass Yield and Nitrogen Status from the Production of the Energy Crops: Switchgrass, Fiber Sorghum, Sweet Sorghum, Giant Miscanthus, and Arundo Donax (Giant Reed)" is attached to this report.

The Interagency Group met on June 30, 2011 and adopted the following interim agronomic rates for energy crops for utilization by Biofuels facilities.

Switchgrass

The Interagency Group interim agronomic rate for switchgrass is 120 lbs of N per acre regardless of soil type. It was determined that nitrogen application is not recommended in the first year in order to reduce weed competition. The waste application timing is March 1 – August 31 as currently reflected in the North Carolina Nutrient Management Software. The literature review noted that some yield response to applied N can be expected with adapted Switchgrass varieties.

Fiber Sorghum

The Interagency Group defined "fiber" sorghum to be Sorghum Sudan Hybrid. The Interagency Group adopted the current North Carolina Nutrient Management Software database nitrogen rate and application timing for Sorghum Sudan Hybrid as meeting the need for fiber sorghum. The approved rates are 45lbs – 55lbs of N per unit yield (tons) variable with soil type and utilizing the established realistic yield expectations (RYE). The RYE's for fiber sorghum range from 2.4 to 6.2 tons. The waste application timing is March 15 – August 31. Dr. Gehl noted that yield responses to applied N can be expected with sorghum varieties. He further described many genetic and varietal types of sorghum being grown today, which can make specific yield and nitrogen application information difficult to establish. Therefore the Interagency Group established one interim N rate to be applied for all fiber sorghum varieties at this time.

Sweet Sorghum (single green harvest)

The Interagency Group adopted an interim application rate of 80 lbs of N per acre regardless of soil type for Sweet Sorghum single green harvest. This recommendation was developed based on literature review information stating N fertilizer applications generally range from 80 to 150 lbs/acre, that the optimum N fertilizer rate to achieve maximum yields ranges from 60 to 134 lbs N/acre, and NCDA agronomic recommendations of 40-60 lbs/acre for sweet sorghum. The recommended application timing for sweet sorghum with a single green harvest is May 1 through July 31. Total harvestable biomass is to be removed from the field.

Sweet Sorghum (multiple green harvests)

The literature review resulted in limited data on multiple cuttings, as almost all available data assumed a single green harvest. The Interagency Group adopted an interim application rate of 80 lbs of N per acre regardless of soil type prior to the first harvest cut, with an additional 20 lbs of N per acre to be applied prior to the second harvest cut, for a harvest-dependent budgeted total of 100 lbs of N per acre. The recommended application timing for Sweet Sorghum for the first harvest is May 1 through July 31; the second harvest application timing would be extended to August 31. Total harvestable biomass is to be removed from the field.

Harvest dates should be a part of regular recordkeeping for producers that utilize this cropping system as part of their certified animal waste management plan.

Miscanthus x Giganteus (Giant Miscanthus)

Most of the available literature provided data for N applications and yield biomass when crop is winter harvested (post senescence). Thus, the Interagency Group chose to only provide recommendations for this type of harvest regime, as there was no substantive basis to provide recommendations for multi-harvest regimes. Dr. Gehl's report indicated that pre-senescence (green) harvest would likely remove larger amounts of nitrogen, however there are still many unknowns regarding nutrient use and continued crop sustainability due to potential root nutrient deficits when pre-senescence harvest is practiced. There is also limited data to suggest certain free-living nitrogen fixing bacteria are associated with the root system of Miscanthus x Giganteus. There is little current research available on details of how these bacterial types may interact with plant roots in the soil environment, and thus potentially affect overall crop nitrogen requirements. As additional research is completed and released, agronomic rates and guidance for green summer harvests/multiple harvests of this crop may be further evaluated.

The Interagency Group adopted an interim nitrogen rate of 60 lbs of N/acre regardless of soil type, with an application window of March 1—September 30. The literature review report noted that according to University of Illinois and Iowa State University research, nitrogen fertilizer is not needed for the first 3 years after planting. Iowa State University research indicates that typically 36-89 lbs N/acre is sufficient for maximizing crop productivity. The literature review report also found that most studies show little yield response for nitrogen applications of over 100 lbs/acre. In Miscanthus cropping systems, winter overseed of small grains will likely not be practical due to crop winter harvest, which typically occurs after the first seasonal frost. No registered herbicides for weed control in this crop are approved in NC; therefore mechanical weed control will be necessary in miscanthus cropping systems.

Arundo Donax (Giant Reed)

As with Miscanthus, most of the available literature for Arundo Donax provided data for nitrogen applications and yield biomass when crop is winter harvested (post senescence). Thus, the Interagency Group chose to only provide recommendations for this type of harvest regime, as there was no substantive basis to provide recommendations for multi-harvest regimes. There is some data that indicates pre-senescence (green) harvest would likely remove larger amounts of nitrogen, however there are still many unknowns regarding nutrient use and continued crop sustainability due to potential nutrient deficits when pre-senescence harvest is practiced. However, there was some data cited in the literature review that suggested significant amounts of N remaining in plant tissue even after senescence. As additional research is completed and released, agronomic rates and guidance for green summer harvests or multiple harvests of this crop may be further evaluated.

Due to literature review data showing little consistency in yield response to nitrogen applications for Arundo Donax, the Interagency Group recommends the same overall interim N application rate as Miscanthus beginning with year 2 after planting. It is recommended that in year one, 30 lbs N per acre may be applied regardless of soil type, and in subsequent years 60 lbs N per acre may be applied regardless of soil type. The recommended application timing is March 1—September 30. In Arundo Donax cropping systems, winter overseed of small grains will likely not be practical due to crop winter harvest, which typically occurs after the first seasonal frost. No registered herbicides for weed control in this crop are approved in NC; therefore mechanical weed control will be necessary in Arundo cropping systems.

Invasive Potential

The Interagency Group discussed the potential of some of these crops, particularly Giant Miscanthus and Arundo Donax, to have invasive tendencies. Various stakeholders including the Biofuels Center and NC Department of Agriculture and Consumer Services are developing a set of voluntary best management practices that can be utilized to reduce this potential.

Future Steps

The Interagency Group will continue to seek assistance and expertise from other entities and State agencies in order to develop additional guidance as needed for the interim agronomic rates as well as for the development of the final agronomic rates by December 1, 2014.

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Appendix

A report to the North Carolina SB 1217 Interagency Group regarding:

Literature Review of Biomass Yield and Nitrogen Status from the Production of the Energy Crops: Switchgrass, Fiber Sorghum, Sweet Sorghum, Giant Miscanthus, and Arundo Donax (Giant Reed).

10 June 2011

Ron Gehl, Ph.D.
&
Adam Heitman

NC State University
Dept. of Soil Science

Switchgrass *(Panicum virgatum* L.)

Summary	
DM yield:	optimal at 3+ years, typically 4-7 T / acre
Nitrogen removal:	0 to 493 lb N / acre
Typical N recommendation:	60 to 150 lb N / acre

Switchgrass *(Panicum virgatum* L.) is a warm-season perennial C4 grass, native to Central and North America (96). Once established, a well managed stand of switchgrass should have a productive life of 10-20 years. The US Department of Energy began investigating *P. virgatum* as a potential energy crop during the early 1990s. Switchgrass was originally selected because it is native and palatable to animals, is a forage crop that many farmers were already familiar with, and adapts well to numerous soil and climate conditions (97).

In our review, switchgrass yields ranged from 0.4 to 15 tons per acre with an overall low-end reported average of 4 dry T/ac to an upper-end average of 7.2 dry T/ac for mature stands (3+ years) (Table 1). The range in yields is due to many factors including specific variety, soil drainage class, climate, and fertilizer rates. Switchgrass will typically reach 33 to 66% of maximum production in years one and two before reaching full productivity in year three (47). For warm-season grasses like switchgrass, nitrogen and water availability are two of the most important factors influencing yields (47).

Switchgrass varieties are often designated by morphological type – either upland or lowland. Upland varieties grow 5 to 6 feet tall, generally have reduced risk of winterkill and winter injury, and are adapted to the US Midwest, compared with lowland varieties, which may grow from 7-10 feet tall, are typically higher yielding, are more tolerant to poorly drained soils, and well-suited for the US South. The most popular lowland varieties planted in the Southeast to date include 'Alamo' and 'Kanlow', while Cave-in-Rock has become the most popular upland variety. In a study on the coastal plain of North Carolina, Alamo yielded 7.25 tons per acre while Cave-in-Rock yielded 6.25 tons per acre. In the NC Mountain region, Cave-in-Rock produced 6 tons per acre compared to 4.25 tons per acre for Alamo (8). Unpublished data by Gehl et al. reports Alamo switchgrass yields of 7.1 and 9.9 dry T/ac in the NC Coastal Plain and Mountain Regions, respectively (Table 7)

Multiple university production guides for switchgrass typically recommend that no N be applied in the seeding year, primarily to reduce weed competition. Switchgrass is a slow establishing crop and increased N availability would encourage competition from other plants. *Recommendations for fertility management during production years typically include N applications at 60-150 lb N/ac/year, depending on stand success and harvest schedules* (8; 54;

79; 81). When a two-cut management practice is used, N application may be split with 50-60 lb/ac applied early season then again just after the summer harvest (8; 19). In addition to yield differences, lowland genotypes have been reported to have higher average soil N removal rates than upland genotypes (74 vs. 37 lbs N /acre, respectively) (10). As switchgrass herbicides are improved, first-year weed competition may be reduced, allowing for successful and responsive first-year N application. Another alternative may be setting switchgrass transplants rather than seeding, which would also reduce first-season weed competition and allow for N application, though the economic feasibility of such a system remains questionable. Given the history of tobacco production in NC, the practice of transplanting switchgrass plugs rather than direct seeding may be more feasible in NC than other states due to the infrastructure already in place.

Nitrogen concentration in harvested switchgrass biomass typically ranged from 0.3-1.5% with removal ranging from 0 to 191 lbs per acre. The management practices, climate and location contribute to the wide range of values. Of these factors, a two-cut management practice consistently showed greater N removal rates (39). Even though annual yields for a two-cut system are not usually greater than a single, late season cut, harvesting during the summer when the concentration of plant tissue N is higher leads to more substantial N removal rates. For a two-cut system, as much as 64% of the total N removal results from the mid-summer cutting, and the average annual N removal of a two-cut system is nearly twice as much as one-cut (39). According to Mclaughlin and Kszos (47), nitrogen uptake efficiency for a one-cut system is 29 to 44%, which is significantly less than the 60 to 88% for a two-cut system. At rates of 45 to 89 lbs / acre, uptake can exceed applied N, suggesting additional N was supplied through mineralization or other processes (39).

A study in Oklahoma further supports increased N uptake with multiple switchgrass harvest. The objective of the experiment was to estimate N requirements for maximum production of switchgrass (90). In their study, 0 to 800 lbs of N per acre were applied to plots of 'Kanlow' switchgrass. Results indicated highest annual yields were achieved when 400 lbs of N per acre were applied in April and three cuttings were removed throughout the growing season (mean dry yield of 7.3 T/ac). This management strategy also maximized the nutrient uptake for N, P, K, and S. The study also showed relatively high (though statistically lower) yields where N was not applied, suggesting overall response to N is limited and possible luxury consumption of N was occurring. *The authors noted a trend that N uptake did not increase until N applications exceeded 200 lbs of N per acre*. Yields for multiple-cut systems always out-yielded one-cut practices (7.3, 6.6, 5.8 T/ac for 3, 2, and 1 harvest, respectively). Over the course of the 4-yr study, the multiple-cut system caused a decline in stand population. Maximizing productivity in the short-term by using multiple-cut practices may shorten the life of a switchgrass stand.

Switchgrass has been investigated as a potential spray field crop in Mississippi (46). In that study, swine effluent was applied at an approximate rate of 331 lbs per acre per year to a silty clay soil. The 3-yr study reported switchgrass yields ranging from 1.9 to 4 dry matter T/ac with N concentrations of 1.17 to 1.84% (11,700-18,400 ppm). The N concentration in dry matter equates to a removal rate of 48 to 149 lbs N / ac. The N uptake of switchgrass was 60% of the uptake observed for coastal bermudagrass (250 lbs N/ acre). Biomass yields for switchgrass were similar to coastal bermudagrass for year one of the study. However, switchgrass had a three-year average yield that was just 71% of the coastal bermudagrass yield (2.68 tons/acre vs. 3.75 tons/acre). Switchgrass did outperform all other warm season grasses that were included in the study which included johnsongrass, eastern gamagrass, and indiangrass. The authors attributed the relatively low switchgrass yields to the multiple harvest scheme of the study, where switchgrass was harvested as many as 4 times per year.

Sorghum (*Sorghum bicolor* L.)

Summary	
DM yield:	5-13 T / acre
Nitrogen removal:	8 to 180 lb N / acre
Typical N recommendation:	80 to 150 lb N / acre

Sorghums are warm-season, short-day annual grasses and are generally classified into two primary types: forage (fiber) and grain. Forage sorghums are generally further grouped into four specific types: hybrid forage sorghum, sweet sorghum, sudangrass, and sorghum x sudan hybrids (91). Forage sorghum is traditionally utilized for animal feed by either grazing or harvesting of the biomass as silage or hay (94). Sweet sorghum is a forage/fiber sorghum with relatively high sugar content (typically 12-20%). In the past, sweet sorghum was harvested for molasses but more recently has gained interest as a 1st and 2nd generation biofuel crop (91).

Sorghum is well-adapted to warm regions, and has higher temperature requirements than other annual, warm-season crops such as corn. Low temperature during the growing season can lead to decreased yields for sorghum. For this reason, sorghum is planted later than most annual, warm-season grasses. Due to its drought tolerance, increased precipitation or irrigation frequency has little effect on biomass yield. Multiple studies have documented marginal to no effect of irrigation on sorghum yield. Miller and Ottman (49) reported that although irrigation increased biomass in early vegetative stages, there was no indication of the increased growth at fall harvest. In Texas, Thompson et al. (69) showed that dry land yields actually exceeded those under a gravity irrigation system.

Fall harvest yields for sorghum ranged from 3.4 to 16 tons per acre for the studies included in our review. The low-end average yield for forage sorghum and sweet sorghum was 5 and 8 tons per acre, respectively (Tables 2 and 3). The high-end average yield for forage and sweet sorghums was 8 and 13 tons per acre, respectively. Nitrogen removal for sweet sorghum was 43 to 180 lbs N per acre. Forage sorghum nitrogen removal rates were slightly less (56 to 167 lbs N per acre). In Kansas, studies of multiple sorghum types at the same study site showed a low-end sweet sorghum yield that was greater than the high-end forage sorghum yield (55; 56). The sweet sorghum removal rates in that study were greater (153 to 180 lbs N / acre) than that of forage sorghum (121 to 167 lbs N / acre).

Nitrogen requirement and uptake for sorghums are seemingly quite dependent on specific variety, type, and/or hybrid, and can be much greater than reported for traditional forage sorghum. Sorghum-sudan N recommendations are typically the greatest of the sorghum family at 100 to 240 lbs per acre (19; 93; 94; 95). Sudangrass is similar to forage sorghum hybrids with N recommendations of 80 to 140+ depending on the number of cuttings (93; 94).

Nitrogen fertilizer recommendations for sorghum generally range from 80 to 150 lbs per acre (19; 91; 92; 93; 94; 95). The studies in our review indicate that the optimum N rate to achieve maximum yields ranges from 60 to 134 lbs per acre. The optimum N fertilizer rate for ethanol and total matter production for sorghum was reported to be 96 lbs. per acre (68). At this rate, yield is maximized without exceeding the critical level for ash content (for ethanol production).

Row spacing and multiple-cut systems can have an effect on sorghum biomass yields and nutrient removal. A multiple-cut system resulted in greater dry yields and N removal than that of the single-cut system (69). Measured N removal in summer harvest biomass has been reported to range from 54 to 104 lbs N per acre (69). The increase in N removal is a result of harvest before senescence and loss of leaf tissue. Row spacing has also been shown to affect dry matter yields, with greater yields resulting as row spacing narrows (70). Based on the limited information currently available, the expected summer yields in June and July may range from 2.2 to 4.6 tons per acre in the southern US where the growing season is longer due to high temperatures in the spring and fall compared with the US northern latitudes (49; 58; 69).

Giant Reed (*Arundo donax* L.)

Summary	
DM yield:	5-12 T / acre
Nitrogen removal:	11-497 lb N / acre

Arundo donax L. (Adx) is a large, rapidly-growing C3 grass native to South Asia and is one of the fastest growing grasses in the world (96). It is a densely culmed, emergent aquatic cane grass that forms densely packed monotypic stands with an extensive and vigorous root system and is capable of creating rapidly spreading rhizomes (98). Culms are thick and persistent with reported heights of 2 to 9 meters (96). While Adx readily propagates vegetatively, with small stem and rhizome fragments producing shoots at nodes, there were no published reports (in our review) of native Adx propagating via seed production anywhere in the world. Generally, seeds are produced but are sterile. Strong competition for water and fast growth have made Adx an aggressive invasive in some riparian environments in Texas and California (43). In these locations, Adx often acts as a transformer species, changing the ecosystem from one regulated by floods to ecosystems regulated by fire. Studies have shown that Adx prefers well-drained soils with good water supply. However, Adx will grow in heavy clays to loose sands and gravelly soils, as well as saline soils (42). Arundo donax prefers temperate climates similar to those experienced in southern Europe (3). The growth potential of Adx makes it a potentially attractive biomass feedstock option in non-riparian, managed agricultural systems.

Arundo donax biomass yields vary substantially as the crop establishes during the first few growing seasons. Typically, a large increase in yield is reported from year one to year two (18), and maximum yields are often not achieved until year three or four (44; 84). Following year three, yields tend to remain consistent or decrease slightly. The low-end average yield for the studies reported here was 4.6 T/ac and the high-end average yield was 12.4 T/ac (Table 4).

Multiple sources report that giant reed is quite adaptable to many growing environments. In South Carolina and Australia, Adx was supplied saline winery effluent as irrigation water (74; 75). The high salt content of the effluent had little effect on the productivity of the plants suggesting Adx is tolerant to water logging and salinity. In these studies, Adx also demonstrated drought tolerance and the production capability in soils ranging from pH 3to 9.

A study in Alabama had a long term average yield of 15.2 tons per acre (32). Fertilizer was applied at two rates, 0 and 100 lbs per acre. In year one, the fertilizer was applied as ammonium nitrate. In the subsequent years, fertilizer was applied as broiler litter. The yield for the 0 lbs per acre rate was 12.9 to 14.6 tons per acre, which was higher than yields for the 100 lbs per acre rate (10.5 to 13.5 tons per acre). Mid-growing season yields ranged from 5.4 to 12.9 tons per acre. Anderson et al. (84) are currently investigating Adx as a bioenergy feedstock in Tifton, GA. Since planting in 2005, they have reported erratic and relatively low yields, ranging from ~2.24-5.35 T/acre. They also calculated nitrogen use efficiency (NUE), based on the actual amount of N taken up by the winter-harvested crop, to be approximately 300 lb dry matter per lb N, or an equivalent of ~6.7 lb N per ton DM.

Overall in our review, N concentration in Adx plant tissue ranged widely from 2000 to 20,900 ppm. In Italy, N concentration in the stems was found to be three times that of the leaves (50). This would suggest a high concentration of N remaining in the plant tissue even after senescence. From the concentration data, the N removal rate was estimated by calculation to range from 5 to 497 lbs per acre (32; 42). However, Mavrogianopoulos et al. (45) found that the N concentration in the plant tissue was only 25% of the soil depletion suggesting that there was significant N fixation and N loss to volatilization. Likewise, soil solution nitrate concentrations increased throughout the year which indicates N applications of 1065 lbs N per acre exceeded the removal capacity of the plant-soil system (plant uptake and denitrification) (71). Unpublished data by Gehl shows that winter-harvested Adx grown in NC yielded 9-13 T/ac and removed 66-241 lb N/ac in years 2-3 after planting (Table 7).

Miscanthus (*Miscanthus* x *giganteus* L.)

Summary	
DM yield:	5-12 T / acre
Nitrogen removal:	8-268 lb N / acre

Miscanthus × giganteus (Mxg) is a rhizomatous perennial C-4 grass and is a naturally occurring **sterile** triploid hybrid generally accepted to be the progeny of diploid M. sinensis and tetraploid M. sacchariflorus (85). While Mxg is the primary choice for biomass production in Europe, costs associated with vegetative propagation, a greater sensitivity to colder temperatures during establishment, and difficulty in improvement as a result of sterility have restricted widespread adoption of Mxg (86; 87; 88; 89).

Dry matter yields ranged from 1 to 20 tons per acre for all included studies. For these studies, the low-end average yield was 5 tons per acre and the high-end average yield was 12 tons per acre (Table 5). Miscanthus yield potential varies significantly due to climatic conditions and, to a lesser degree, nitrogen fertilizer rate. Also, the timing of harvest factors into potential yield. Dry matter yield has been shown to increase throughout the growing season until August or September (67). Giant miscanthus can produce more biomass per unit area and input than switchgrass (30). Also, Miscanthus appeared as favorable for carbon sequestration as C3 perennial grasslands for carbon sequestration (23).

Miscanthus dry matter yields typically increase substantially for years one through three until reaching a plateau, or maximum yield at about year 4 (15; 22; 44; 60; 61). The number of years until yield maximizes seems to be largely influenced by climate, and Mxg is seemingly well adapted to the southern- and mid-latitudes of the US. Zub and Brancourt-Hulmel (78) found that peak yields were achieved more rapidly in warmer climates. In other climates, the maximum yields were not achieved until year six (14). Unpublished data by Gehl from studies conducted on the NC Coastal Plain and Mountain regions have shown increased Mxg winter-harvested biomass for 3 consecutive years, with year 3 yields of 9.2 dry T/ac (Table X). After reaching a plateau, yields can remain consistent for over 10 years.

Miscanthus has a high NUE and water-use efficiency (29). In one study, Mxg showed a more significant response to water than to temperature and N rates (30). In times of water stress, leaf area will be lost be senescence (16). However, Mxg is not tolerant to prolonged drought, stagnant water, or soil compaction. Yields of 13 tons per acre were observed on sites with high annual incident global radiation (6200MJ/m^2) and high average temperatures (60° F) (42). Cosentino et al. (17) showed that max yields were achieved under good soil water conditions, or 100% ET restoration (17). In Illinois, a yield projection of 12.0 to 19.6 tons per acre was made based on climatic conditions and soil factors (27).

Estimated fertilizer demands varied among the included studies from 36 to 167 lb N per acre (6; 22). According to Heaton et al. (29), N fertilizer is not needed until year three and typically 36 to 89 lb N per acre is sufficient for maximum productivity (29). Most studies found increases in nitrogen application beyond 100 lbs per acre had little effect on yield (14; 15; 30; 61; 78). However, one study found that maximum yields in year three occurred when 167 lbs of nitrogen per acre were applied (22). Zub et al. (78) found that nitrogen availability had varying effects on plant biomass. When no fertilizer application was made the previous year, Mxg yields responded to nitrogen application (15). More established stands (3 years and beyond) of Mxg are more efficient at intercepting nitrogen. A study was conducted where labeled N was applied to quantify N uptake (12). In that study, thirty-eight to sixty-four percent of labeled nitrogen was recovered for plants ranging from one to three years of growth, respectively (12). An important point to note is that few of the reported literature manage Mxg with summer harvest or multi-harvest regimes, which will certainly impact nutrient use and crop sustainability.

Nitrogen removal rates ranged from 8 to 268 lbs per acre for post-senescence harvest. The summer nitrogen removal rates observed were 104 to 207 lbs per acre (31; 67). Additionally, Gehl (unpublished, Table 6) reports N removal of 111 and 151 lb N/ac from June and July harvested 2-year in field Mxg, respectively. The anticipated greater N removal from summer harvests compared with winter can be attributed to senescence and remobilization of nitrogen to below-ground tissue (67). When the crop is harvested after senescence, a significant portion of the plant N has already moved to the root system. Removing plant biomass prior to senescence, then, will likely remove much greater quantitates of N, but the question remains whether the plant can withstand the root nutrient deficit in subsequent years.

Table 1. Site information, dry matter biomass yield, and nitrogen status for switchgrass. Additional comments for each citation can be found in the file "Sprayfield Bioenergy Grass N Data.xls".

Citation	Location	Soil type	Climate† Temp	Climate† Precip	N applied	Yield range Lower	Yield range Upper	Harvest timing	DM Nitrogen§	N removal
			°F	in	lb/ac	T/ac			%	lb/ac
8	Plymouth, NC	nr‡	62ab	52ac	128	6.2	7.9	May, July, Oct.	nr	nr
8	Laurel Springs, NC	nr	51ab	49ac	128	4.2	6	May, July, Oct.	nr	nr
8	Raleigh, NC	clay loam	60ab	46ac	56	4.2	7	Oct.	nr	nr
8	Raleigh, NC	clay loam	60ab	46ac	112	5.3	7	Mid-summer, Oct.	nr	nr
90	Oklahoma	silt loam, sandy loam	nr	nr	0-800	2.3	16.4	one-, two-, three-cut	0.74-1.50*	34-493
10	AR, TX, LA	multiple	63-92d	12-21d	nr	3.2	3.2	Sept.-Nov.	0-2.98*	0-191
7	Booneville, AR	silt loam	59-81d	27d	80	5.4	5.4	Aug.-Oct.	0.12-0.15	13-16*
39	8 SE states	silt loam to clay	nr	nr	45-89	7.1	7.1	Mid-summer, Nov.	0.13-0.23	34-113
46	Mississippi	silty clay	32-91	12	331	4	4	May-Sept.	1.17-1.84	48-149
51	Milan, TN	silt loam	nr	nr	0-179	3.8	8	Oct.-Nov.	nr	nr
59	TX, VA, AL	sandy loam, loam	nr	nr	0-73	2.4	12	June-Oct.	nr	nr
63	east central AL	fine-loam	50-95f	53c	75	3	15	June-Nov.	0.70-1.37	42-411*
66	TX	nr	58-88e	22d	9.0-89	nr	nr	Aug.-Oct.	nr	nr
54	multi-state	nr	nr	nr	nr	nr	nr	nr	nr	nr
47	multi-state	multiple	nr	nr	nr	4.2	10	nr	nr	nr
30	worldwide review	multiple	nr	nr	nr	5	5	nr	nr	nr
27	North Illinois	fine-silty	48c	40a	22	3.6	3.6	June-Feb.	nr	nr
27	Central Illinois	fine-silty	52c	40a	22	8.8	8.8	June-Feb.	nr	nr
27	South Illinois	fine-silty	59c	50a	22	3.9	3.9	June-Feb.	nr	nr
52	NE Kansas	nr	nr	nr	0-218	2.5	6	nr	nr	nr
57	IL, WI, MN	nr	nr	nr	nr	3.4	5	nr	nr	nr
77	Iowa	nr	nr	nr	0-250	3.8	6	nr	nr	nr
72	Ithaca, NE	silty clay loam	nr	nr	nr	nr	nr	nr	nr	nr
55-56	NE Kansas	silt loam	nr	33-36d	40	1.6	5	Nov.	4.40-0.79	19-42
42	NR	nr	nr	nr	nr	0.4	15	nr	0.71-1.37	6-411*
50	Bologna, Italy	clay loam	nr	nr	89	nr	nr	winter	0.79, 0.32	nr
6	SW Germany	silty clay	59d	19d	71	6.3	6.3	Oct., Jan.-Feb.	0.23-0.46*	29-58
19	Georgia	nr	nr	nr	nr	nr	nr	nr	nr	nr

† Climate info as reported, where a=long-term (30y) average, b=annual normal monthly mean, c=mean annual, d=growing season average, e=growing season range, f=yearly range

‡ nr, not reported

§ DM, dry matter; values calculated using reported N removal or concentration are indicated with *

Table 2. Site information, dry matter biomass yield, and nitrogen status for forage sorghum varieties, not including sweet sorghums. Additional comments for each citation can be found in the file "Sprayfield Bioenergy Grass N Data.xls".

Citation	Location	Soil type	Climate†		Irrigation	N applied	Yield range		Harvest timing	DM Nitrogen§	N removal
			Temp	Precip			Lower	Upper			
			°F	in	in	lb/ac	T/ac			%	lb/ac
25	Jonesboro, AR	nr	nr	nr		nr	7.7	10.9	nr	0.36-0.63	56-137
76	Bell, FL	sand	43-91f	52-57c		402-804	3.4	5	Nov.	1.13-1.33	90-122
53	TX	clay	nr	39c	1.5	0-200	4	9	nr	0.60-1.25*	100-107
68	Lubbock, TX	sandy clay loam	nr	14d		0-150	5	7	Sept.	0.59-1.19*	59-166
69	College Station, TX	silty clay loam	32-104f	nr		nr	4	6	nr	0.64-1.98	60-154
9	central and southern IA	silty clay loam	49-74e	32a		0-250	6.3	9	Sept.	1.05	7.9-10.3
9	central and southern IA	silty clay loam	49-74e	32a		0-250	4.4	8	Sept.	1.05	7.9-10.3
55-56	NE Kansas	silt loam	nr	33-36d		149-161	7	9.2	Sept.-Oct.	0.86-0.91*	121-167
50	Bologna, Italy	clay loam	nr	nr		89	nr	nr	Sept.	0.26, 1.34	nr
58	Sudan	nr	nr	6-8c	20-22	36	4.5	8	Summer	nr	nr
19	Georgia		N Rec: 150 lbs/acre (increase by 30% if irrigated); sorghum-sudan N rec= 180-240 lbs/acre								
91	Florida		N Rec: 120-150 lb/ac								
92	Penn State		N Rec: 120 lb/ac								
93	Kansas State		N Rec: 30-50 lb/ac/T of expected yield; sudangrass N rec= 30-50 lb/ac/T yield; sorghum-sudan N rec= 30-50 lb/ac/T yield								
94	Virginia Tech		N Rec: 100-140 lb/ac; sudangrass N rec= 60-80 lb/ac at establishment, 40-60 lb/ac after each cutting; sorghum-sudan N rec= 60-80 lb/ac at establishment, 40-60 lb/acre after each cutting								
95	Iowa State		N Rec: 100-150 lb/ac; sorghum-sudan N rec= 80 lb/ac pre-plant and 40-60 lb/ac after each cutting								

† Climate info as reported, where a=long-term (30 y) average, b=annual normal monthly mean, c=mean annual, d=growing season average, e=growing season range, f=yearly range

‡ nr, not reported

§ DM, dry matter; values calculated using reported N removal or concentration are indicated with *

Table 3. Site information, dry matter biomass yield, and nitrogen status for sweet sorghum varieties. Additional comments for each citation can be found in the file "Sprayfield Bioenergy Grass N Data.xls".

Citation	Location	Soil type	Climate†		Irrigation	N applied	Yield range		Harvest timing	DM Nitrogen§	N removal
			Temp	Precip			Lower	Upper			
			°F	in	in	lb/ac	T/ac			%	lb/ac
73	Weslaco, TX	clay loam	nr	14d	12	0-200	4	9	July, Oct.	0.54-0.69*	43-125
55-56	NE Kansas	silt loam	nr	33-36d		149-161	12.6	14.5	Sept.-Oct.	0.61-0.62*	153-180
49	Tucson, AZ	fine sandy loam	64-95e	9d	45-51	176-222	9	13	Sept.	nr	nr
64	Ames, IA	silty clay loam	nr	21d		0-150	25 (net stock)		Sept.	nr	nr
64	Fort Collins, CO	clay loam	nr	nr	6	0-150	33 (net stock)		Sept.	nr	nr
70	Bursa, Turkey	clay loam	58a	12a		0-179	11	14	Sept	nr	nr
77	Beijing, China	silt loam	53a	22a		86	6	16	Aug.-Sept	nr	nr
50	Bologna, Italy	clay loam	nr	nr		89	nr	nr	Sept.	0.44, 1.35	nr
35	Karachi, Pakistan	nr	nr	nr		15	nr	nr	nr	nr	nr
21	Central Greece	clay loam	nr	nr	14-20	36	nr	nr	Oct.	nr	nr
19	Georgia		N Rec: sweet sorghum=80 lb/acre								

† Climate info as reported, where a=long-term (30 y) average, b=annual normal monthly mean, c=mean annual, d=growing season average, e=growing season range, f=yearly range

‡ nr, not reported

§ DM, dry matter; values calculated using reported N removal or concentration are indicated with *

Table 4. Site information, dry matter biomass yield, and nitrogen status for arundo donax (giant reed). Additional comments for each citation can be found in the file "Sprayfield Bioenergy Grass N Data.xls".

			Climate†				Yield range				
Citation	Location	Soil type	Temp	Precip	Irrigation	N applied	Lower	Upper	Harvest timing	DM Nitrogen§	N removal
			°F	in	in	lb/ac	T/ac			%	lb/ac
32	south central AL	nr	nr	nr	nr	0-100	10.5	14.6	summer & winter	1.20-1.70	253-497*
83	Georgia	loamy sand	nr	46c	0	0	1.3	5.4	Dec.-Feb.	0.29-0.69	122.5
74-75	Australia and SC	nr	nr	nr	nr	nr	nr	20	May, Aug.	0.13-1.17	471
37	FL (everglades)	sand	46-91f	45.3c	nr	277	2.4	2.7	Dec., Mar.	nr	nr
84	Tifton, GA	loamy sand	66a	48a	nr	0	2.24	5.35	winter	300 lb DM/lb N	nr
24	Belle Glade, FL	muck soils	nr	nr	nr	nr	20gw	40gw	Aug.-Oct.	nr	nr
44	Sicily, Italy	sandy	86-104d max	<8d	25-75% ET	44-89	3	17	Feb.-Mar.	0.19-0.61	11-207*
82	Greece	nr	nr	nr	nr	nr	nr	13.4	June	0.84	493
2	Pisa, Italy	silt loam	36-84a	37c	nr	0-179	6	14	Oct.-Mar.	nr	nr
3	central Italy	loam	49-68b	34c	nr	89	nr	17	Oct.-Nov.	nr	nr
11	N. Italy	loam	nr	nr	nr	nr	4.5	20.2	July-Nov.	nr	nr
18	Southern Italy	nr	41-95e	nr	5.9-11.8	71	7	15	Feb.	nr	nr
18	Southern Greece	nr	41-95e	nr	5.9-11.8	71	6	6	Feb.	nr	nr
18	Spain	nr	41-95e	nr	5.9-11.8	71	7	15	Feb.	nr	nr
42	worldwide review	nr	nr	nr	nr	nr	1	17	nr	1.20-1.40	24-476*
45	central Greece	gravel	nr	nr	nr	nr	5 (stems)	10 (stems)	winter	1.87-2.06	nr
50	Bologna, Italy	clay loam	nr	nr	nr	89	nr	nr	winter	0.52, 1.43, 1.57	nr
65	England	England	nr	nr	nr	0-372	15g/pot	96g/pot	Dec.-Jan.	0.37-1.94	nr
71	Greece	clay loam	nr	nr	49.8	1065	nr	3.6	Oct.	nr	nr

† Climate info as reported, where a=long-term (30 y) average, b=annual normal monthly mean, c=mean annual, d=growing season average, e=growing season range, f=yearly range
‡ nr, not reported
§ DM, dry matter; values calculated using reported N removal or concentration are indicated with *

Table 5. Site information, dry matter biomass yield, and nitrogen status for Miscanthus x giganteus (giant miscanthus reed). Additional comments for each citation can be found in the file "Sprayfield Bioenergy Grass N Data.xls".

Citation	Location	Soil type	Climate†		Irrigation	N applied	Yield range		Harvest timing	DM Nitrogen§	N removal
			Temp	Precip			Lower	Upper			
			°F	in	in	lb/ac	T/ac			%	lb/ac
7	Booneville, AR	silt loam	59-81d	27.2d		80	nr	3	Aug.-Oct.	0.13-0.15	7.8-9.0*
55-56	NE Kansas	silt loam	nr	32.7-35.8d		nr	1	6	Nov.	0.40-0.11	23-54
22	Pisa, Italy	clay	nr	13.0d	9.1	0-179	7	12	Oct.	0.48-0.75	128-141
6	SW Germany	silty clay	59d	19.1d		36	nr	8	Oct., Jan.-Feb.	0.16-0.17	25-27
31	W. Germany	loamy sand	49c	28.1c		0-161	nr	13	Feb.-Mar.	0.17-0.24	45-63
67	N. France	silt loam	51c	24.6c		0-107	9	12	Oct., Feb.	0.16-0.56	29-135
60	Austria	nr	47-50c	19.7-39.7c		nr	8	11	Jan.-Feb.	0.34-0.61	54-134
61	Austria	nr	55d	22.6d		0-161	nr	13	Jan.-Feb.	nr	nr
14	Hertfordshire, UK	silty clay loam	56d	15.6d		0-107	nr	6	winter	0.23-0.74	27-89
15	southern Ireland	loam to sandy loam	50c	39.5c		0-214	8	9	Dec.-Mar.	0.40-0.70	45-125
12	SE England	silty clay loam	nr	24.6c		54	6	8	Mar.	0.79-0.87	104-124
42	worldwide review	nr	nr	nr		nr	2	20	nr	0.19-0.67	7.6-268*
44	Sicily, Italy	sandy	86-104d	<7.8d	25-75% ET	45-89	1	12	Feb.-Mar.	nr	nr
3	central Italy	loam	49-68b	33.7c		89	nr	13	Sept.-Oct.	nr	nr
4	Essex, UK	nr	32-86e	5.9d	7.9	107	nr	13	June-Sept.	nr	nr
4	Essex, UK	nr	32-86e	5.9d		107	nr	11	June-Sept.	nr	nr
41	Germany	loamy sand, silty clay	46-50c	27.2-33.5c		0-125	4	17	Feb.	nr	nr
17	Sicily, Italy	sandy clay loam	37-95f	4.4d		nr	nr	12	Feb.-Mar.	nr	nr
20	Ireland	silty clay loam	nr	nr		0-161	nr	nr	nr	nr	nr
27	North Illinois	fine-silty	48c	37a		22	nr	14	June-Feb.	nr	nr
27	Central Illinois	fine-silty	52c	41a		22	nr	20	June-Feb.	nr	nr
27	South Illinois	fine-silty	59c	48a		22	nr	19	June-Feb.	nr	nr
29	Illinois	nr	nr	nr		nr	12	20	nr	nr	nr
33	Jutland, Denmark	coarse sandy loam	nr	29.4c		0-67	nr	nr	Aug.	nr	nr
50	Bologna, Italy	clay loam				89	nr	nr	winter	0.16, 0.63	nr
65	England	nr	nr	nr		0-78	0.7	1.7	Mar.	0.57-1.27	nr
62	Japan	volcanic ash	57c	44-48.2f		nr	30-1117g/m2/m		nr	0.80-0.90	nr

† Climate info as reported, where a=long-term (30 y) average, b=annual normal monthly mean, c=mean annual, d=growing season average, e=growing season range, f=yearly range

‡ nr, not reported

§ DM, dry matter; values calculated using reported N removal or concentration are indicated with *

Table 6. Harvest timing and frequency effect on biomass yield and nutrient removal of Miscanthus x giganteus grown at the Mountain Horticultural Crops Research and Extension Center near Mills River, NC. Miscanthus was planted 29 April 2009 in Hayesville loam soil and has never received fertilizer additions. Source: R.J. Gehl (unpublished data).

				Nutrient removal summer harvest						
Date	Harvest 1	Harvest 2	Total	N	P	K	Ca	Mg	S	Fe
		dry T ac^{-1}					lb ac^{-1}			
16 Jun 2010	2.81			111	14	216	28	14	11	3
16 Jul 2010	8.44			151	17	221	44	18	12	3
4 Jan 2011	-			-	-	-	-	-	-	-
							Mean % nutrient			
16 Jun 2010				0.97	0.12	1.89	0.24	0.12	0.09	0.02
16 Jul 2010				0.88	0.10	1.32	0.26	0.11	0.07	0.02

				Nutrient removal winter harvest (4 Jan 11)						
	Harvest 1	Harvest 2	Total	N	P	K	Ca	Mg	S	Fe
		dry T ac^{-1}					lb ac^{-1}			
June		1.14		6.7	0.5	4.8	7.2	1.8	0.9	0.1
July		0.75		6.8	0.4	2.9	5.8	1.3	0.7	0.1
4 Jan 2011		3.98		9.6	1.3	23.3	10.9	2.9	1.5	0.2
							Mean % nutrient			
June				0.29	0.02	0.21	0.31	0.08	0.04	0.00
July				0.46	0.03	0.20	0.38	0.09	0.05	0.01
4 Jan 2011				0.12	0.02	0.29	0.14	0.04	0.02	0.00

				Total nutrient removal						
	Harvest 1	Harvest 2	Total	N	P	K	Ca	Mg	S	Fe
		dry T ac^{-1}					lb ac^{-1}			
June	2.81	1.14	3.95	118	14	221	35	16	12	3
July	8.44	0.75	9.19	158	18	224	50	19	13	3
January	-	3.98	3.98	10	1	23	11	3	1	0

Table 7. Dry biomass yield and nutrient removal for winter-harvested biomass crops Miscanthus x giganteus, Switchgrass (v. Alamo), and Arundo donax. All crops were planted in spring 2008. The soil type at Mills River is Bradson gravelly loam and at Wallace is Goldsboro loamy sand.

			Nutrient removal		
Location	Harvest date	Dry yield	N	P	K
		T ac^{-1}	lb ac^{-1}		
M. x giganteus					
Wallace	7 Jan 2009	0.72	10	1	5
	6 Jan 2010	5.23	92	3	26
	20 Dec 2010	9.30	34	4	56
Mills River	6 Feb 2009	2.24	24	1	10
	11 Jan 2010	8.12	116	2	53
	4 Jan 2011	9.02	32	4	91
Switchgrass (Alamo)					
Wallace	7 Jan 2009	2.92	40	4	34
	6 Jan 2010	4.00	91	5	50
	20 Dec 2010	7.10	66	6	72
Mills River	6 Feb 2009	0.65	18	1	3
	11 Jan 2010	6.80	135	6	82
	4 Jan 2011	9.86	74	8	109
Arundo donax					
Wallace	7 Jan 2009	0.26	10	1	3
	6 Jan 2010	9.26	241	13	177
	20 Dec 2010	13.17	157	14	227
Mills River	6 Feb 2009	1.31	29	4	27
	11 Jan 2010	10.89	231	12	176
	4 Jan 2011	9.53	66	12	207

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