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Chapter 2

Biofuels and Water Use: Comparison of Maize and Switchgrass and General Perspectives

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Abstract

Two of the main plants currently being considered as potential biofuel feedstocks in the U.S. are switchgrass (*Panicum virgatum* L.) and maize (*Zea mays* L.). Recent expanded production of both has raised serious questions about natural resource utilization, notably, soil carbon, soil nutrients, and water. Water is often the limiting resource for crop and grass productivity. The objective of this study was to calculate and compare water use and water use efficiency of maize with current growth characteristics, switchgrass with current growth characteristics, and switchgrass with characteristics improved by normal plant breeding selection techniques. We used the calibrated and validated ALMANAC model for five sites representing the southern Great Plains (Stephenville, TX), the northern Great Plains (Mead, NE), and two locations in the Corn Belt (Ames, IA and Columbia, MO). Ten years of historical weather data were used. Mean values for water use and water use efficiency were calculated for maize, switchgrass with currently growth characteristics, and switchgrass with anticipated improved growth characteristics. These results show the relative impact of expanded maize production, expanded switchgrass production, and use of improved switchgrass varieties, on the water balance in these regions. The water use efficiency (WUE) of four switchgrass types showed means ranging from 3 to 5 mg g^{-1}. Switchgrass WUE values were much greater than WUE of maize grain, but such was not always the case when compared to WUE of maize plants. Changes in switchgrass light extinction coefficients

(k) and in switchgrass radiation use efficiency (RUE) showed the expected trends. Increased RUE caused increases in dry matter yield and in WUE, but not usually as great as the percentage increase in RUE. Results from this simulation work will give guidance to policy planners, producers, and economists.

INTRODUCTION

Two of the plant species of of major interest for biofuel production in the U.S. are maize (*Zea mays* L.) and switchgrass (*Panicum virgatum* L.). Widespread expansion of the production area of these two species has raised concerns regarding competition of biofuel production with food and fiber production as well as concern for competition over resources needed for biofuel, food, and fiber production.

Three major resources needed for production of biomass are light, nutrients, and water. Light is virtually nonlimiting during the growing season. Nutrient requirements have become a key concern as the price of inorganic fertilizers continues to rise and concerns regarding runoff-pollution continue to grow. Finally, water is an especially important resource as the competition for limited water supply becomes more intense in this country. Decisions on water allocation have to be made regarding the production of food, fiber, and fuel.

Direct measurement of water use requires labor-intensive procedures involving soil water measurement with neutron access tubes, gravimetric measurements of soil moisture with soil cores, or use of weighing lysimeters. Likewise, measurements of WUE require plant harvesting to determine dry weight of whole plants or of grain. To adequately define WUE over a range of soils, plant species cover, and climatic conditions with such measurements would require an exorbitant amount of resources and time.

The best alternative to such extensive, expensive projects is to build a process-based simulation model, using data from field experimentation to develop the equations for water use and for plant growth. Once validated, this model could be applied to a diversity of soils, weather data, and plant species. This approach lead to the development of models such as EPIC (originally the Erosion Productivity Impact Calculator, now the Environmental Policy Integrated Climate) (Williams et al., 1984), SWAT (Soil and Water Assessment Tool) (Arnold et al., 1998), and ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria) (Kiniry et al., 1992). These models simulate the water balance using various methods of calculating potential evapotranspiration and determine plant water use while considering such variables as soils, weather, and plant species cover. Simulated plant growth is reduced when simulated soil water is depleted. The plant growth model simulates changes in leaf area as well as changes in plant biomass and grain (in the case of crops).

Water use efficiency is thereby calculated with these models as dry weight of plant biomass (or grain) produced per unit water transpired (EP) or per unit total evapotranspiration (ET). In this study, we used the ALMANAC model to calculate WUE of maize, currently available switchgrass types, and anticipated improved switchgrass types in four locations in the central U.S. These locations are representative sites in the region anticipated to be the primary production area for biofuel crops in the U.S.

METHODS

Calculation of Water Use Efficiency

Water use efficiency (WUE) has been calculated both in terms of assimilation rate per unit water transpired (Nippert et al., 2007) or as plant dry weight increase per unit water used. In the latter case, plant dry weight can be either total above-ground dry weight or grain dry weight (for crops). Water use can be the amount of water transpired by plants during the growth period or total water lost (evapotranspiration) from the area, including both plant transpiration and soil evapotranspiration. For the present study, we calculated WUE as plant dry weight increase per unit water transpired. For maize, we also calculated WUE as grain weight increase per unit water transpired.

Nippert et al. (2007) reported values of WUE of 1.0 mmol CO_2 per mol of water for big bluestem (*Andropogon gerardii* Vitman) and 2.6 for indiangrass (*Sorghastrum nutans* (L.) Nash) in the field. Taking molecular weights into account, these values are 1.7 and 4.3 mg of CH_2O per g of water transpired. In an outdoor pot experiment, WUE values of different cultivars of switchgrass ranged from 4.3 to 8.5 mg dry weight per g of water used (Byrd and May, 2000). In germplasm nurseries in Tennessee and Oklahoma, WUE of switchgrass accessions were 3.5 to 6.3 mg CH_2O per g of water transpired (McLaughlin et al., 2006).

In direct terms of crop plant mass increase per unit water transpired, values of 1 to 5 mg dry weight per g of water are common (Hatfield et al., 2001). For maize above-ground dry matter, the WUE values at Bushland, TX were 1.66 to 2.34 mg g^{-1} (Eck and Winter, 1992), 2.75 to 2.88 mg g^{-1} (Howell et al., 1998), and 2.34 to 3.06 mg g^{-1} (Tolk et al., 1998). For maize grain yield, WUE values at Bushland were 0.24 to 0.81 (Eck and Winter, 1992), 1.52 to 1.57 mg g^{-1} (Howell et al., 1998), and 1.05 to 1.63 mg g^{-1} (Tolk et al., 1998). Elsewhere, WUE values for maize grain yield were 0.58 to 1.15 mg g^{-1} in Mead, NE (Varvel, 1994), 0.61 to 1.66 in Lexington, KY (Corak et al., 1991), and 1.9 to 2.3 mg g^{-1} in Iowa (Hatfield et al., 2001).

Grass WUE values also range between 1 to 5 mg dry matter production per g of water transpired. Blue grama (*Bouteloua gracilis* (H.B.K.)) in a greenhouse had a WUE value of 4.55 mg g^{-1} (Fairbourn, 1982). In a greenhouse, grass seedlings (*Sporobolus arabicus* and *Leptochloa fusca*) had WUE values of 1.0 to 1.4 mg g^{-1} (Akhter et al., 2003). In the field in Nebraska, switchgrass WUE values were 1.0 to 5.5 mg g^{-1} (Eggemeyer et al., 2006), values similar to those demonstrated by switchgrass seedlings in a growth chamber (1.45 to 5.5 mg g^{-1}; Xu et al., 2006). In the shortgrass steppe of Colorado, a mixture of cool-season and warm-season grasses (including blue grama) had WUE values of 1.0 to 4.5 mg g^{-1} (Nelson et al., 2004).

General Model Description

The ALMANAC model has been described numerous times as it has been used to simulate crops (Kiniry et al., 1997; Kiniry and Bockholt, 1998; Yun Xie et al., 2001) and warm season grasses (Kiniry et al., 1996; Kiniry et al., 2002; Kiniry et al., 2005; Kiniry et al., 2007; McLaughlin et al., 2006). Parameters to simulate different plants continue to be refined as new research results are reported. Basically, the model simulates the soil water balance, the soil and plant nutrient balance, and the interception of solar radiation. This model includes subroutines and functions from the EPIC model (Williams et al., 1984, 1990) with added details for plant growth. The model has a daily time step. It simulates plant growth for a wide range of species and is implemented easily.

Light Interception

ALMANAC simulates light interception by the leaf canopy with Beer's law (Monsi and Saeki, 1953) and the leaf area index (LAI). The LAI is the amount of leaf area per unit ground area, a unitless variable. With greater extinction coefficient values (k), a given LAI intercepts more light.

The fraction of incoming solar radiation intercepted by the leaf canopy is

$$\text{FRACTION} = 1.0 - \exp(k \times \text{LAI}) \qquad [1]$$

Leaf Area Development

Accurate prediction of light interception depends on realistic simulation of leaf area. The model estimates leaf area production up to the point of maximum leaf area for the growing season using Eq. [2]. The sigmoid-curve function for potential LAI production takes the form:

$$F = \text{SYP}/[\text{SYP} + \exp(\text{Y1} - \text{Y2} \times \text{SYP})] \qquad [2]$$

Where F is the factor for relative LAI, SYP is the fraction of the degree days from planting to maturity, and Y1 and Y2 are the sigmoid-curve coefficients generated by ALMANAC. This curve passes through the origin and through two points, asymptotically approaching F = 1.0. The model calculates SYP each day. The sum of degree days is zero at planting in the establishment year and at tiller emergence in subsequent years, and reaches its maximum value at maturity.

The model describes the loss of leaf area late in the season with the LAI decline factor. The LAI begins to decrease after a defined fraction of the seasonal degree days have accumulated.

Biomass Production and Partitioning

The model simulates biomass with an RUE value for each plant species (Kiniry et al., 1989). Values for RUE have a wide range of crops and grasses (Kiniry et al., 1989; Kiniry et al., 1992; Kiniry et al., 1999; Kiniry et al., 2007). ALMANAC describes declining RUE in later growth stages with an identical function to the one for the decrease in LAI.

The maximum rooting depth defines the potential depth in the absence of a root-restricting soil layer. Soil cores at Temple, TX in 1994 showed that switchgrass roots extend to depths of at least 2.2 m.

Water and Nutrient Uptake

Critical for yield and biomass simulation in water-limited conditions is the simulated water demand. The ALMANAC model calculates effects of soil water on crop growth and yield with similar functions. Potential evaporation is calculated first, then potential soil water evaporation and potential plant water transpiration are derived from potential evaporation and leaf area index. Based on the soil water supply and crop water demand, the water stress factor is estimated to decrease daily crop growth and yield. However, some water balance equations differ between the two models. For this study, potential evaporation was estimated by the Penman-Monteith method (Ritchie, 1972). Potential soil evaporation and plant transpiration were estimated by:

$$E_P = E_0(\text{LAI}/3) \qquad 0 \le \text{LAI} \le 3.0 \qquad [3]$$

$$E_P = E_0 \qquad \text{LAI} > 3.0 \qquad [4]$$

$$E_S = \text{minimum of } (E_0 \exp(-0.1\text{BIO}), E_0 - E_P) \qquad [5]$$

Where E_P and E_s are potential plant transpiration and soil evaporation (mm), E_0 is potential evaporation (mm), LAI is leaf area index, and BIO is the sum of the above ground biomass and crop residue (Mg ha^{-1}).

$$E_P = E_0 \qquad \text{LAI} > 3.0 \qquad [6]$$

$$E_S = E_0(1 - 0.43\,\text{LAI}) \qquad 0 \le \text{LAI} \le 1.0 \qquad [7]$$

$$E_S = E_0 \exp(-0.4\text{LAI})/1.1 \qquad \text{LAI} > 1.0 \qquad [8]$$

Water stress factor (WSF) is the ratio of water use to water demand (potential plant transpiration) in ALMANAC, and water use (WU) is a function of plant extractable water and root depth.

The nutrient balance (N and P) also allows plants to acquire sufficient nutrients to meet the demands if adequate quantities are available in the current rooting zone. Nutrient values for switchgrass were refined with N concentration data collected at Stephenville during 5 years (Sanderson, unpublished data) and Waller et al. (1972).

Base Temperature, Optimum Temperature, and Total Degree Days

Base temperature in ALMANAC is constant for all growth stages. Base temperature constrains the initiation of leaf area growth and thus dry matter accumulation. Higher optimum temperature can allow increased plant development rate later in the season when temperatures are greater. The sum of degree days to maturity controls the duration of growth. Heat units are reset to zero after maturity each year. Heat units are calculated from daily maximum and minimum temperatures, assuming the maximum equals the optimum if it exceeds the optimum.

Parameters Used to Simulate Four Switchgrass Types

We used an extensive, published data set (Casler et al., 2004) with two years of measured data at five sites of varying latitude to derive and verify switchgrass parameters. The four switchgrass types were Northern Upland (NU), Northern Lowland (NL), Southern Upland (SU), and Southern Lowland (SL). The locations were Spooner, WI (42° 49′ N 91° 54′ W), Arlington, WI (43° 20′ N 89° 23′ W), Mead, NE (41° 13′ N 96° 29′ W), Manhattan, KS (39°12′ N 96° 15′ W) and Stillwater, OK (36° 07′ N 96° 05′ W). The soil type at Spooner was Omega loamy sand (soil depth=1.52 m, plant available water=6.7 cm). The soil type at Arlington was Plano silt loam (soil depth=1.83 m, plant available water=37.0 cm). The soil type at Mead was Sharpsburg silt loam (soil depth=1.52 m, plant available water=29.3 cm). The soil type at Manhattan was Plano silt loam (soil depth=1.52 m, plant available water=30.6 cm). The soil type at Stillwater was Kirkland silt loam (soil depth=2.03 m, plant available water=27.0 cm). Runoff curve number was set to 71 for all the locations. Plots were planted in spring, 1998. Plots were fertilized with 112 kg N ha^{-1} in spring each year. Plots were harvested and biomass was quantified in late summer 1999 and 2000.

Parameters were adjusted to get reasonable simulated yields of each switchgrass type, as compared to the mean of the two years of measured yields. Using parameters developed for Alamo switchgrass in Texas (Kiniry et al., 1996; Kiniry et al., 1999; and Kiniry et al., 2007), the only two parameters adjusted were the degree days to maturity (base 12 C) and the potential leaf area index (PotLAI). The light extinction coefficient for Beer's Law (Monsi and Saeki, 1953) was set to -0.51, the average of the two means from Kiniry et al. (1999) and Kiniry et al., (2007).

The values of PotLAI and degree days varied with latitude and switchgrass types (Table 1). Other parameters used for all the locations and switchgrass types were:

1. 3.9 g per MJ intercepted photosynthetically active radiation for the radiation use efficiency (RUE) at low vapor pressure deficits (VPD)
2. 0.65 unit decrease in RUE for each 1 kPa increase in VPD above 1 kPa
3. Base temperature of 12 C and optimum temperature of 25 C
4. Linear decreases in LAI and in RUE from 70% of total degree day accumulation until maturity
5. Maximum potential rooting depth of 2.2 m
6. Optimum nitrogen concentrations of 2.57% for plants early in the spring, 1.1% for plants near mid season, and 0.28% for plants near maturity each year
7. Optimum phosphorus concentrations of 0.14% for plants early in the spring, 0.10% for plants near mid season, and 0.07% for plants near maturity each year.

Table 1. Data sets (Casler, et al., 2004) to develop parameters for and validate the ALMANAC model for four switchgrass types

Switchgrass Type:	SL	NL	SU	NU
Stillwater, OK (36° N)				
Degree days	1200	1100	1050	950
Pot LAI	3.0	3.0	2.5	1.8
Msrd Yield	15.13	14.81	12.62	10.45
Sim. Yield	15.12	15.45	13.65	11.31
Sim./Msrd.	1.00	1.04	1.08	1.08
Overall mean Sim./Msrd=1.05				
Manhattan, KS (39° N)				
Degree days	1200	1100	1050	950
Pot LAI	3.0	3.0	2.5	2.0
Msrd Yield	9.26	10.28	7.96	7.05
Sim. Yield	9.14	8.62	8.17	6.86
Sim./Msrd.	0.99	0.84	1.03	0.97
Overall mean Sim./Msrd=0.96				
Mead, NE (41° N)				
Degree days	1100	1100	900	800
Pot LAI	3.0	3.0	2.5	2.0
Msrd Yield	17.46	20.93	14.99	12.71
Sim. Yield	16.84	17.75	15.30	12.92
Sim./Msrd.	0.96	0.85	1.03	1.03
Overall mean Sim./Msrd=0.97				
Arlington, WI (43° N)				
Degree days	800	1100	800	800
Pot LAI	1.8	2.4	2.5	2.0
Msrd Yield	6.46	10.61	11.44	10.25
Sim. Yield	7.07	10.70	11.56	9.88
Sim./Msrd.	1.09	1.01	1.01	1.02
Overall mean Sim./Msrd=1.02				
Spooner, WI (46 ° N)				
Degree days	540	630	900	800
Pot LAI	1.8	1.8	2.5	2.0
Msrd Yield	3.81	4.60	7.39	7.33
Sim. Yield	4.07	4.76	7.96	6.73
Sim./Msrd.	1.07	1.04	1.08	0.95
Overall mean Sim./Msrd=1.03				

The four types were Southern Lowland (SL), Northern Lowland (NL), Southern Upland (SU), and Northern Upland (NU). Degree days are the values (base 12 C) to maturity each growing season. Pot LAI is the input potential leaf area index. Msrd. Yield is the published yield (Mg ha^{-1}). Sim Yield is the yield (Mg ha^{-1}) simulated by ALMANAC. Sim/Msrd is the ratio of simulated divided by measured yields

We showed good overall agreement between simulated and measured yields following the adjustment of degree days and potential LAI (Table 1). For Stillwater, OK, simulated yields were within 8% of measured yields, with the mean simulated/measured ratio being 1.05. For Manhattan, KS, simulated yields were within 3% of measured for three of the four switchgrass types. The mean overall ratio of simulated/measured was 0.96. For Mead, NE, simulated yields were within 4% of measured for three of the four switchgrass types. The mean simulated/measured ratio was 0.97. For the two sites in WI, the simulated yields were always within 9% of the measured yields, with the two mean simulated/measured ratios being 1.02 and 1.03. Thus, overall, we were able to realistically simulate the measured yields of the four switchgrass types at these diverse latitudes by adjusting only two plant parameters.

Locations Simulated to Compare WUE of Four Switchgrass Types to WUE of Maize

Four sites were chosen to represent a major portion of the area in the U.S. potentially useful for biofuel production: Stephenville, TX (32° 13′ N 98° 13′ W), representative of the Southern Great Plains; Mead, NE (41° 13′ N 96° 29′ W), representative of the Northern Great Plains; and Columbia, MO (38° 57′ N 92° 19′ W) and Ames, IA (42° 1′ N 93° 42′ W), which represent the Corn Belt. We used 10 years of measured weather data and three representative soils for each of the pertinent counties (Table 2).

Table 2. Soils used for switchgrass and maize simulations

Soil Type	Depth m	PAW m	CN
Mead, NE			
Yutan silty clay loam	2.03	0.292	71
Tomek silt loam	1.83	0.256	71
Nodaway silt loam	1.52	0.222	71
Ames, IA			
Clarion loam	1.52	0.187	69
Nicollet loam	1.52	0.225	69
Webster clay loam	1.52	0.192	69
Columbia, MO			
Keswick silt loam	1.52	0.172	78
Mexico silt loam	1.52	0.167	78
Weller silt loam	1.52	0.205	78
Stephenville, TX			
Brackett clay loam	1.52	0.166	89
Altoga clay loam	1.68	0.215	89
Houston Black clay	2.00	0.284	89

Plant available water (PAW) is the difference between field capacity and wilting point. CN is the runoff curve number. The first soil listed for each site is the most common for the county and was used for the simulations with improved switchgrass types.

Parameters Adjusted to Simulate Improved Switchgrass Types

Two key plant characteristics that may be manipulated in efforts to improve switchgrass yields are 1. the mean leaf angle and 2. photosynthetic rate. We simulated different leaf angles by changing the light extinction coefficient from -0.25 (upright leaf types), to -0.50 (intermediate leaf angles), and to -0.75 (relatively flat leaf types). We simulated possible increases in photosynthetic rate by increasing the RUE by 5%, 10% and 20%.

Only one switchgrass type was used at each site for these simulations. The type was the Southern Lowland for Stephenville, TX and was the Northern Upland for the other three sites. Only the most common soil of the three for each site was used for these simulations.

RESULTS

The WUE values for switchgrass and maize were similar to those reported in the literature. Comparisons between switchgrass types and maize, for WUE resulted in differing results depending on the location and the switchgrass type. Likewise, yields and WUE of improved switchgrass types showed interesting variations among locations.

Table 3. Mean water use efficiency values (mg of biomass per g of water transpired) simulated by ALMANAC for 10 years

Ames, Iowa	SL	NL	SU	NU	Mplant	Mgrain
soil 1	4.1	4.0	4.5	3.3	3.7	2.2
soil 2	4.1	4.6	3.2	2.8	3.5	2.2
soil 3	4.5	4.3	3.6	2.8	3.5	2.2
Mead, Nebraska						
soil 1	5.3	5.4	3.9	3.6	4.3	2.0
soil 2	5.0	4.9	3.4	3.0	4.2	2.1
soil 3	5.0	4.9	3.4	3.0	4.4	2.0
Columbia, Missouri						
soil 1	4.5	4.6	4.1	3.9	5.6	2.5
soil 2	4.3	4.5	3.7	3.2	4.2	1.8
soil 3	4.2	4.3	3.7	3.2	4.2	1.9
Stephenville, Texas						
soil 1	3.5	3.3	3.2	3.2	4.2	1.4
soil 2	3.5	3.2	3.1	3.1	4.0	1.4
soil 3	3.5	3.2	3.2	3.1	3.9	1.6

There are four switchgrass types, Southern Lowland (SL), Northern Lowland (NL), Southern Upland (SU), and Northern Upland (NU) (Casler et al., 2004). Maize whole plant (Mplant) and maize grain (Mgrain) WUE values are included for comparison. Soils are in the same order as in Table 2.

Water Use Efficiency of Four Switchgrass Types

The WUE of all four switchgrass types showed means ranging from 3 to 5 mg g^{-1} (Table 3). The greatest WUE values were nearly always for the lowland types. The one exception was for the first soil in Ames. The northern lowland type had the highest WUE in more than half the cases in the three northern locations. In Texas, the southern lowland type had the highest WUE for all three soils. For comparison, the maize types had WUE values of 3.5 to 5.6 for plant WUE and 1.4 to 2.5 for grain WUE, similar to reported values in the literature.

Comparing Water Use Efficiency of Switchgrass to WUE of Maize

Switchgrass WUE values were much greater than WUE of maize grain, but such was not always the case when compared to WUE of maize plants (Table 4). When compared to WUE of maize grain, switchgrass WUE was 1.8 to 5.0 times as great. Thus switchgrass produces more biomass per unit water transpired than does maize grain, currently the most common source for ethanol in the U.S. When compared to maize plant biomass, switchgrass WUE was greater in all the northern three sites except for the second soil at Columbia. However, for the Stephenville site, maize biomass WUE was always greater than switchgrass WUE. Thus for a given amount of soil water, we simulated greater biomass yields for switchgrass than for maize biomass at the first three sites, but lower yields for switchgrass than for maize at the southernmost site, Stephenville, Texas.

Table 4. Ratios of water use efficiency values of lowland switchgrass (WUEsw) to water use efficiency of maize, both simulated by ALMANAC for 10 years. Comparison with WUE of maize grain (WUEgrain) and maize total above-ground biomass (WUEbiomass) are included. Soils are in the same order as in Table 2.

	soil 1	soil 2	soil 3
Ames, Iowa			
WUEsw/WUEgrain	2.08	1.85	1.90
WUEsw/WUEbiomass	1.28	1.10	1.17
Mead, Nebraska			
WUEsw/WUEgrain	2.70	5.00	2.43
WUEsw/WUEbiomass	1.24	1.17	1.14
Columbia, Missouri			
WUEsw/WUEgrain	2.42	1.84	2.18
WUEsw/WUEbiomass	1.02	0.80	1.01
Stephenville, Texas			
WUEsw/WUEgrain	2.42	2.57	3.50
WUEsw/WUEbiomass	0.87	0.85	0.90

Water Use Efficiency of Improved Switchgrass Types

Changes in switchgrass light extinction coefficients (k) and in switchgrass RUE showed the expected trends, but not necessarily the magnitude of responsiveness that we hypothesized (Table 5). Biomass yields consistently increased as the k increased from -0.25 to -0.50 and to -0.75. The increase was expected due to the greater light interception prior to leaf canopy closure, with increased k values. The largest increase, however, caused only a 2 to 5% increase in yield, relative to the original switchgrass parameters. Correspondingly, WUE

increased as k increased, with highest values 2 to 7% greater than the WUE of the original switchgrass.

Table 5. For potentially improved switchgrass types, mean biomass yields (yield), mean transpiration (EP), mean evapotranspiration (ET), water use efficiency (WUE, mg of biomass per g of water transpired), WUE of the improved type as compared to the original switchgrass type (WUE/WUEorig), and ratio of biomass yield of improved type to biomass yield of original type (YIELD/YIELDorig)

	original	Ext25	Ext50	Ext75	RUE1.05	RUE1.1	RUE1.2
Ames, Iowa							
yield (Mg/ha)	17.23	11.68	17.19	18.09	17.46	17.68	18.08
EP (mm)	399	457	399	397	399	398	397
ET (mm)	669	728	670	665	669	667	666
WUE (mg per g)	4.32	2.56	4.31	4.56	4.38	4.44	4.55
WUE/WUEorig	1.00	0.59	1.00	1.06	1.01	1.03	1.05
YIELD/YIELDorig	1.00	0.68	1.00	1.05	1.01	1.03	1.05
Mead, Nebraska							
yield (Mg/ha)	15.65	9.2	15.58	16.03	15.83	15.9	16.03
EP (mm)	290	292	291	293	292	283	292
ET (mm)	623	652	623	619	622	621	619
WUE (mg per g)	5.39	3.15	5.36	5.47	5.42	5.62	5.48
WUE/WUEorig	1.00	0.59	0.99	1.02	1.01	1.04	1.02
YIELD/YIELDorig	1.00	0.59	1.00	1.02	1.01	1.02	1.02
Columbia, Missouri							
yield (Mg/ha)	15.85	10.63	15.81	16.29	16.02	16.12	16.27
EP (mm)	356	472	360	356	356	356	356
ET (mm)	681	759	686	668	677	675	675
WUE (mg per g)	4.46	2.25	4.39	4.58	4.50	4.53	4.57
WUE/WUEorig	1.00	0.50	0.98	1.03	1.01	1.02	1.02
YIELD/YIELDorig	1.00	0.67	1.00	1.03	1.01	1.02	1.03
Stephenville, Texas							
yield (Mg/ha)	13.91	9.27	13.84	14.64	15.28	15.58	16.08
EP (mm)	393	370	393	385	425	422	412
ET (mm)	656	674	656	652	663	611	651
WUE (mg per g)	3.54	2.51	3.52	3.80	3.59	3.69	3.90
WUE/WUEorig	1.00	0.71	0.99	1.07	1.01	1.04	1.10
YIELD/YIELDorig	1.00	0.67	0.99	1.05	1.10	1.12	1.16

These are the results of 10 years of simulation by the ALMANAC model on the most common soil for each site. Columns represent potential improvements to switchgrass. Ext25 assumes a light extinction coefficient value of -0.25. Ext50 assumes a light extinction value of -0.50. Ext75 assumes a light extinction coefficient value of -0.75. RUE1.05 assumes a 5% increase in RUE. RUE1.10 assumes a 10% increase in RUE. RUE 1.2 assumes a 20% increase in RUE

Increased RUE caused increases in dry matter yield and in WUE, but not usually as great as the percentage increase in RUE. Increases in RUE of 5% caused yields to increase 1% in the northern three locations, and by 12% in the southern location. Increases in RUE of 10% caused yields to increase by 2 to 3% in the northern three locations and by 12% in the southern location. However, there was a diminishing return; when RUE was doubled from 10% to 20%, yields only increased by 2-5% at the northern locations and by 16% in Texas. Correspondingly, WUE values increased by greater percentages at the southern location than at the northern three sites as RUE was increased.

Discussion

As the U.S. and other countries continue to expand the use of alternative energy sources, bioenergy in the form of maize grain, maize biomass, and switchgrass biomass are being investigated. Their use raises numerous questions, not the least of which are how will widespread expansion of their production affect natural resources through changes in soil erosion, through changes in soil carbon, and through changes in water use. The latter becomes especially important as this county defines strategies to allocate its limited water to feed and clothe its population, as well as supply energy needs.

The results presented in this paper are useful guides for how efficiently maize and switchgrass use water to produce biomass or grain (for maize). Switchgrass is very efficient when compared with the commonly used source of ethanol, maize grain.

Likewise, these results give some guidance for best selection strategies for future breeding programs on improving switchgrass biomass and switchgrass WUE. The ALMANAC simulation model can be extremely valuable as a research tool to define where breeding efforts can best be applied for improving switchgrass for biofuel.

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Chapter 3

BIOTECHNOLOGICAL IMPROVEMENT OF A BIOFUEL CROP: *JATROPHA CURCAS* LINN.

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ABSTRACT

Energy remains the mainstay for the entire civilized world. The concept dates back to 1885 when Rudolf Diesel built the first diesel engine with the full intention of running it on vegetative source. The Kyoto protocol has prompted resurgence in the use of biodiesel throughout the world. There is a growing interest in *Jatropha curcas* as a biodiesel 'miracle tree' to help alleviate the energy crisis, reduce the countries dependence on foreign oil imports and generate income in rural areas of developing countries. It is becoming a poster child amongst some proponents of renewable energy. *J.curcas* also called the physic nut is used to produce the non-edible *Jatropha* oil and the estimates of the oil content in seeds range from 35-40% and in the kernels 55-60%. India is the 5th largest energy consumer in the world. The country imported 90MT of crude oil by 2003-04 that was only 70 % of the requirement. By 2030 the estimated consumption is to scale up to 5.6 m barrels/day of which 95% is to be met by import. The ever-increasing demand can only be met by an alternative source as biofuel. Normal conventional propagation of *Jatropha curcas* has several drawbacks like poor seed viability, low germination, scanty and delayed rooting of seedlings etc. The yield of nuts is unsure and unsustainable, coupled with unknown genetic potential. The plants propagated by cuttings show a lower longevity and possess a lower drought and disease resistance. Therefore the need of the hour is to shake hands with biotechnological processes to overcome the hindrances. This chapter is just a hand forward to uniform, genetically stable, quality planting material yield, intricately interwoven with sustainability in energy. Plant biotechnology serves as a powerful tool for fast and quality plant production and we have been successful to apply it to regenerate plants in *J.curcas*. Protocol development is the prerequisite for creating genetically improved crops and we

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