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Simulating switchgrass biomass production across ecoregions using the DAYCENT model

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Abstract

The production potential of switchgrass (*Panicum virgatum* L.) has not been estimated in a Mediterranean climate on a regional basis and its economic and environmental contribution as a biofuel crop remains unknown. The objectives of the study were to calibrate and validate a biogeochemical model, DAYCENT, and to predict the biomass yield potential of switchgrass across the Central Valley of California. Six common cultivars were calibrated using published data across the US and validated with data generated from four field trials in California (2007–2009). After calibration, the modeled range of yields across the cultivars and various management practices in the US (excluding California) was 2.4–41.2 Mg ha^{-1} yr^{-1}, generally compatible with the observed yield range of 1.3–33.7 Mg ha^{-1} yr^{-1}. Overall, the model was successfully validated in California; the model explained 66–90% of observed yield variation in 2007–2009. The range of modeled yields was 2.0–41.4 Mg ha^{-1} yr^{-1}, which corresponded to the observed range of 1.3–41.1 Mg ha^{-1} yr^{-1}. The response to N fertilizer and harvest frequency on yields were also reasonably validated. The model estimated that Alamo (21–23 Mg ha^{-1} yr^{-1}) and Kanlow (22–24 Mg ha^{-1} yr^{-1}) had greatest yield potential during the years after establishment. The effects of soil texture on modeled yields tended to be consistent for all cultivars, but there were distinct climatic (e.g., annual mean maximum temperature) controls among the cultivars. Our modeled results suggest that early stand maintenance of irrigated switchgrass is strongly dependent on available soil N; estimated yields increased by 1.6–5.5 Mg ha^{-1} yr^{-1} when residual soil mineral N was sufficient for optimal re-growth. Therefore, management options of switchgrass for regional biomass production should be ecotype-specific and ensure available soil N maintenance.

Keywords: biofuel, California, DAYCENT, irrigation, Mediterranean climate, switchgrass production

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Introduction

The current concerns over a global energy supply based on fossil fuels and the increase in atmospheric greenhouse gases have led to renewed interest in the potential for biofuels as a carbon-neutral fuel. However, there are concerns about the potential conflicts between the use of cropland and water for biofuel vs. food and the energy needed to produce biofuel vs. the energy gain (Giampietro *et al*., 1997). Recent studies add to the controversy over a potential increase in CO_2 emissions from deforestation and land-use change associated with crop-based biofuels (Fargione *et al*., 2008; Searchinger *et al*., 2008). The ecologic and economic benefits of biofuels are still uncertain, as unintended consequences have emerged by the increased use of biofuels. Thus, two main requirements should be addressed if biofuels offer a practical alternative to fossil fuels. The first requirement is that biomass production for biofuel must be economically and biophysically feasible at the regional scale without causing other environmental problems (Giampietro *et al*., 1997; Walsh, 1998). This requires the regional evaluation of biofuel ecosystem characteristics, such as yield potential, water and nutrient requirements by perennials, soil C sequestration, and emissions of major biogenic greenhouse gases. The second requirement is the economically and environmentally sound conversion of biomass into energy (Schmer *et al*., 2008).

There are five primary sources of biomass (i.e., grain or oilseed crops, crop residues, perennial grasses, fast growing trees, and sugar crops) that can be produced on prime croplands and marginal/abandoned lands (Lal, 2005; Lemus & Lal, 2005). Any combination of a biomass source with land type offers potential, but also presents challenges that need to be comprehensively evaluated. For example, cropping systems on prime croplands can provide large amounts of residues. However, limited information is available regarding the

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environmental and socio-economic sustainability of these highly extractive systems in the long-term. The production of perennial grasses on marginal cropland, on the other hand, could present a win-win situation, but questions regarding the long-term potential biomass production remain.

Switchgrass (*Panicum virgatum* L.) is a perennial C_4 grass that is native to most of North America (not California) and successfully adapted to diverse environmental conditions over large geographic regions (Lewandowski *et al.*, 2003). Once established, switchgrass is generally high yielding and characterized by high water and nutrient-use efficiency and its ability to tolerate soil disturbance (Heaton *et al.*, 2004; Barney & DiTomaso, 2008). These characteristics can meet many important selection criteria for effective biofuel crops (Lewandowski *et al.*, 2003; Wright, 2007). In the US, switchgrass was first identified as a renewable energy source by the US Department of Energy in 1985, and has been extensively evaluated for further development over the last two decades (Parrish & Fike, 2005; Wright, 2007). However, switchgrass has not been grown commercially or experimentally tested in California. In 2007, switchgrass cultivar trials were established at four California sites (Tulelake, Davis, Five Points, and El Centro). These sites represent diverse ecoregions under different environmental conditions. Switchgrass production systems at these sites have been evaluated with respect to various management options such as N fertilization rate, irrigation rate, or harvest times and frequency (Pedroso *et al.*, 2011).

It is practically difficult to evaluate the potential biomass production of switchgrass cultivars across the wide range of management practices, soils, and microclimates in California. Therefore, process-based ecosystem models provide an option to account for all possible permutations in the region. The performance of these ecosystem models strongly depends on how well they are calibrated and validated for the specific environmental conditions being evaluated (Smith *et al.*, 1997). Therefore, the model of choice should be calibrated and then validated for California conditions to address the first requirement of switchgrass production systems at the regional scale. De Gryze *et al.* (2010, 2011) calibrated DAYCENT for several crops, but not including switchgrass, and estimated plant production and soil organic C changes associated with different management practices on California croplands. California, and specifically the Central Valley, is one of the most productive agricultural regions in the world and leads national production and sales of many crop commodities, such as almonds, cotton, grapes, hay, rice, and tomatoes (California Agricultural Statistics Service, 2008); however, an ecosystems model has not yet been validated for switchgrass in this region. Therefore, the objectives of this study were (1) to calibrate the DAYCENT model using published data on switchgrass biomass production, (2) to rigorously validate the model using data generated from the four field trials in California, and (3) to estimate the yield potential of six common cultivars for all croplands within the Central Valley of California.

Materials and methods

Model description

The DAYCENT model is the daily time step version of the CENTURY ecosystem model, a fully resolved ecosystem model simulating major ecosystem processes, such as changes in soil organic matter, plant productivity, nutrient cycling (i.e., N, P, and S), soil water, and soil temperature (Del Grosso *et al.*, 2001). The DAYCENT grass/crop submodel can simulate phenology, net primary productivity, the amount of net primary productivity allocated to grain, shoot and root compartments, and the C:N ratio of biomass in plant components. It also estimates the amount and quality of residue returned to the soil and the plant's influence on the soil environment. The growth of various crops and grasses is limited by soil and air temperature and soil-water stress that is species-specific. Soil-water availability depends on current soil water, precipitation, irrigation, and potential evapotranspiration. Nitrogen, P, and S from the soil or fertilizer can also affect plant growth depending on grass/crop requirements. Management events can be specified, including crop/grass type, tillage, fertilization, organic matter (e.g., manure) addition, harvest (with variable residue removal), drainage, irrigation, burning, and grazing intensity. Germination/beginning of growing season is a function of soil temperature, and senescence is a function of accumulated growing degree days since germination or regrowth when the growing degree day submodel is implemented. For a perennial grass, timing of harvest is not determined by phenology.

For this study, we selected the DAYCENT model, because it can simulate cultivar-specific (genetic) differences, such as the length of growth period and N and water requirements. The model can also appropriately represent a range of land use, soil, and weather conditions at diverse sites. Genetic differences among switchgrass cultivars are generally confounded by diverse management and environmental conditions (Hopkins *et al.*, 1995). The model does not explicitly account for several factors known to affect switchgrass growth, such as row spacing (Ma *et al.*, 2001; Muir *et al.*, 2001), seedling emergence, and stand survival in response to planting date and temperature (Hsu *et al.*, 1985; Hsu & Nelson, 1986), development of total leaf area (Kiniry *et al.*, 1999), and chilling injury in winter (Madakadze *et al.*, 2003). Also, field conditions, such as weed and pest problems may not be directly simulated either. Despite these limitations, DAYCENT was used for our study because the model has been extensively calibrated for California conditions (De Gryze *et al.*, 2010, 2011).

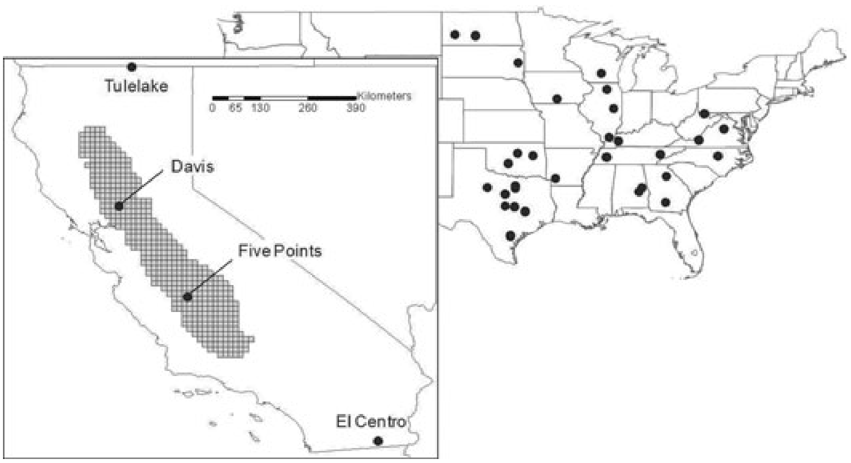

Fig. 1 Location of sites selected for calibration and validation of the DAYCENT model. For regional assessment of switchgrass biomass production, 537 grid cells (12 × 12 km) were created on all cropland within the Central Valley of California.

Input data

For the calibration of DAYCENT, we selected 37 field sites in the US that reported field data (i.e., yields, root-to-shoot ratios, C:N ratios in shoots, and roots) (Fig. 1), which cover much of the geographic distribution of switchgrass (Wullschleger *et al.*, 2010). The field experiments represent a wide range of ecotypes (upland vs. lowland), cultivars, establishment years, harvest years, N fertilization rates, and soil/weather conditions. The stands had been generally maintained for 3–10 years with different levels of N fertilization rates (0–896 kg N ha^{-1} yr^{-1}) and one to four cuts per year across the sites. For this study, we selected six cultivars: Alamo (southern lowland); Kanlow (northern lowland); Blackwell and Cave-in-Rock (southern upland); Sunburst and Trailblazer (northern upland).

For the validation of DAYCENT, we used data from switchgrass cultivar trials established at four California sites in 2007: Tulelake (41°57′N, 121°28′W), Davis (38°32′N, 121°46′W), Five Points (36°20′N, 120°6′W), and El Centro (32°48′N, 115°26′W) (Fig. 1). All the cultivar trials were fertilized at a rate of 56–336 kg N ha^{-1} yr^{-1} and irrigated as necessary. In 2008, Trailblazer switchgrass was also evaluated in response to five different N rates: 0, 37.5, 75, 112, and 150 kg N ha^{-1} yr^{-1} at Tulelake and 0, 75, 112, 224, and 300 kg N ha^{-1} yr^{-1} at the other sites. In 2007, all fields were harvested once in November. In 2008 and 2009, it was harvested once at Tulelake (November), twice at Davis and Five Points (July and November), and three times at El Centro (July, September, and November). At each site, soils were sampled to a depth of 0–0.15 m when switchgrass was established and analyzed for soil organic matter, bulk density, and texture. For further site and management descriptions, see Pedroso *et al.* (2011).

The daily maximum and minimum temperatures and precipitation data were obtained from CIMIS (http://wwwcimis.water.ca.gov) for California and from Oklahoma Mesonet (http://www.mesonet.org) for Oklahoma. For other states, we used the daily data generated by DAYMET (http://www.daymet.org). Additional weather drivers such as solar radiation, wind speed, and relative humidity were obtained only from CIMIS. Estimates of soil parameters were obtained from the Soil Survey Geographic Database (SSURGO) of the Natural Resources Conservation Service. Specifically, soil texture class, bulk density, hydraulic properties, and pH to a depth of 1.5 m were obtained. If necessary, hydraulic properties, such as field capacity and wilting point, were calculated from soil texture (Saxton *et al.*, 1986).

For regional assessments of switchgrass for biomass production, a common grid cell (12 × 12 km) was created within the Central Valley of California, resulting in 537 grid points (Fig. 1). Climate data were sampled to each grid cell from the nearest CIMIS station. Land-use survey data were obtained from the California Department of Water Resources (http://www.water.ca.gov). The SSURGO database was geographically intersected with the land-use data and area-weighted for cropland within each grid cell. Therefore, all grid cells represent typical agricultural land use, covering 2.65 million ha of cropland areas. Table 1 describes a summary of soil and climatic variables measured across the grid cells within the Central Valley of California.

Modeling procedures

Historical simulations. We simulated C_4 temperate grasses with grazing from year 0 to plow-out at the sites selected across the US for model calibration (Paruelo & Lauenroth, 1996). The plow-out date were set to as early as 1790. For the period from plow-out to 2006, historical cropping was established at the Major Land Resource Region (MLRA) level (USDA, 1997; Williams & Paustian, 2005). The crops for this period included were alfalfa, cotton, maize, sorghum, spring wheat, and winter wheat with fallow periods. For these crops, we considered different N fertilizer rates and the use of irrigation at the state scale, based on USDA data sets (http://www.ers.usda.gov/Data) and 1997 Census of Agriculture (http://www.agcensus.usda.gov). We also considered that the timing of planting and harvest varied across the sites (National Agricultural Statistics

Table 1 Summary of soil (0–0.2 m) and climatic factors measured across the Central Valley of California ($n = 537$)

	Year	Average	Maximum	Minimum
Bulk density (Mg m^{-3})		1.39	1.70	0.77
Sand (%)		0.43	0.88	0.11
Clay (%)		0.25	0.59	0.04
pH		7.15	9.02	3.24
Tmax (°C)*	2007	24.3	26.1	22.1
	2008	24.1	25.9	22.3
	2009	24.0	26.1	22.3
Tmin (°C)†	2007	8.3	10.8	5.4
	2008	8.4	11.0	5.6
	2009	8.5	11.3	5.9
Precipitation (mm)	2007	194	453	44
	2008	238	490	62
	2009	259	523	59

*Tmax, annual mean maximum temperature.
†Tmin, annual mean minimum temperature.

Service, 1997). Other management events, such as tillage and fertilization, were determined with planting.

At Davis and Five Points in the Central Valley of California, we assumed four periods of historical land use and management changes: (1) C_3 temperate grasses with low-intensity grazing for years 0–1869 (Paruelo & Lauenroth, 1996), (2) initiation of cropping for years 1870–1949, (3) introduction of irrigation and inorganic fertilizer for years 1950–1969, and (4) modern agriculture from 1970 to 2006. Major crops grown in the region were maize (*Zea mays* L.), winter wheat (*Triticum aestivum* L.), and tomatoes (*Solanum lycopersicum* L.) (after 1950). The historical runs represent the average history of land use and management in the Central Valley of California (De Gryze *et al.*, 2010). Thus, the same cropping history was used for all individual grid cells within the Central Valley of California. However, we assumed a shallow lake at Tulelake (for years 0–1910) and desert/short grass prairies at El Centro (for years 0–1948), followed by cropping. At Tulelake and El Centro, irrigated alfalfa was the major crop grown in rotation with winter wheat and fallow with an alfalfa stand that typically last for 5 years.

Parameterization. A switchgrass cultivar was assumed to have the same optimum biomass yields independent of locations or growing seasons. Exhaustive data, which are mostly not available, would be required for cultivar-specific plant parameterization in details. Thus, we made adjustments to plant parameters at both the ecotype and cultivar levels within the regional calibration. After initializing the size of soil organic matter pools in the model through historical simulations (data not shown), key plant parameters were calibrated for the 37 field sites using published data. We excluded data values if they were collected from sites experiencing unexpected events (e.g., rodent damage) or when sudden and large unexplainable changes in year-to-year yield were observed. Data values were also excluded when the amount of added N fertilizer exceeded 500 kg N ha^{-1} yr^{-1} because plant production is not sensitive to such high N rates, although other processes (e.g., nitrate leaching) may be sensitive (C. Keough, personal communication). No irrigation was considered in the calibration simulations due to lack of information in the publications.

We verified C partitioning between shoots and roots, and C:N ratio and lignin concentration in biomass of the compartments using published values for each cultivar. Shoot growth tends to be more limited than root growth by drought stress. For example, Evers & Parsons (2003) showed that the root:shoot ratio of Alamo switchgrass was between 0.25 and 0.35 under no water stress and increased to a range of 0.25–0.45 with increasing water stress. In particular, lowland ecotypes tend to be more susceptible to drought than upland ecotypes (Stroup *et al.*, 2003). Biomass loss is also generally higher in shoot than in root with increasing N stress, and lowland ecotypes have relatively lower N requirements than upland ecotypes (Porter, 1966). Recent studies suggest that differences in total N applied may not significantly affect the accumulation of root biomass (Ma *et al.*, 2000). Consequently, an increase in root:shoot ratio of upland ecotypes tends to be greater than that of lowland ecotypes under N and water limiting conditions. Therefore, we assumed that 35–75% of net primary productivity could be allocated to root for upland ecotypes, and 30–65% for lowland ecotypes depending on water stress. In addition, 25–45% of net primary productivity was considered to be allocated to root by N stress.

Lignin concentrations in shoots ranged from 7% to 12% across the range of latitudes and tended to increase with latitude in upland ecotypes, but not in lowland ecotypes (Cassida *et al.*, 2005a). Sladden *et al.* (1991) showed little difference in lignin concentration among switchgrass cultivars (7–8%) for shoots. Johnson *et al.* (2007) reported a lignin concentration of 6.6% in shoots and 4.5% in roots for Sunburst switchgrass. However, there is a lack of data about lignin in switchgrass roots. In the model, lignin concentrations in shoots and roots were set to 7–11% and 5%, respectively. The C:N ratio in shoots and roots during the growth period were set to vary between 20 and 125 and between 25 and 55, respectively. Biomass yields were adjusted to 45.2% C content (Ma *et al.*, 2001; Liebig *et al.*, 2008) and 5% moisture content (typical for samples dried at 60 °C) for all cultivars.

It was necessary to account for differences in seasonal growth rate among cultivars (Madakadze *et al.*, 2003). The length of days to reach different development stages varies considerably due to genetic and environmental interactions (Hopkins *et al.*, 1995) as well as management practices (Hsu & Nelson, 1986). Considering the latitude of origin, base temperatures for germination or seedling growth (8–12 °C) were calibrated for each cultivar. Optimum and maximum temperatures for production were set to 31 and 46 °C for Alamo, 30 and 45 °C for Kanlow, 27 and 43 °C for Cave-in-Rock, 27 and 45 °C for Blackwell, 25 and 43 °C for Trailblazer, and 23 and 40 °C for Sunburst. The number of growing degree days to reach senescence was also calibrated using published data (Kiniry *et al.*, 1996; Mitchell *et al.*, 1997; Van Esbroeck *et al.*, 1997; Frank *et al.*, 2004). However, freeze tolerance variation among the cultivars was not calibrated due to lack of information.

After the modeled plant indices and ratios were realistic, we further adjusted the coefficient controlling biomass production potential as a function of incoming solar radiation to match net primary productivity with observed values. Net primary productivity during the establishment year was considered 50% of the full yield potential for upland ecotypes and 60% for lowland ecotypes based on published data.

Validation. DAYCENT was validated against observed data from the four field sites in California over the years 2007–2009. No model coefficients or equations were adjusted, except we minimally adjusted the coefficient that was used to calculate biomass production potential as a function of solar radiation using the data in 2007–2008. The data in 2009 were not used for any further parameterization, and are therefore pure validation data. After model validation, the model was used to predict the regional biomass yields of the selected cultivars from 2007 to 2009.

Regional simulations. For the regional yield prediction of switchgrass, we selected management practices that minimize the effects of water or N stress on biomass yield. Specifically, all cultivars were uniformly planted in July 2007 across all grid cells. The stands were irrigated and fertilized at a rate of 56 kg N ha^{-1} yr^{-1} with one cut per year in (November) 2007, and 224 kg N ha^{-1} yr^{-1} with two cuts per year in July and November 2008 and 2009. However, the growing degree day submodel was used to allow changes in planting and harvest dates by cultivar. In the simulations, automatic irrigation up to field capacity was used when soil–water content dropped below 95% of available water holding capacity in the 1.2 m depth.

For irrigated switchgrass, N losses by leaching, particularly while planting and establishing switchgrass, will potentially affect its long-term stand maintenance. Therefore, we simulated switchgrass yields with two levels of mineral N in the soil profile at the beginning of establishment year for theoretic assessments. The range of baseline soil mineral N levels was 0.0–77.8 g N m^{-2} with an average of 2.7 g N m^{-2} in the 0–0.1 m depth and 0.3–542.9 g N m^{-2} with an average of 11.1 in the soil profile (0–1.5 m). The baseline values were within the range of soil mineral N observed in several California crops (Poudel *et al*., 2001, 2002; Lee *et al*., 2006). For the selected management practices, we assumed that the optimal levels of soil mineral N were obtained by minimizing nitrate leaching risk due to irrigation: 12.2 (0.1–83.1) g N m^{-2} in the surface soil and 47.8 (0.7–516.2) g N m^{-2} in the soil profile. On average, the optimal values were somehow exceeding what was observed at times in California croplands. These high values could be expected when N inputs are greater than crop demand or the productivity is too low with reduced nitrate leaching in irrigated fields. Nitrate leaching is highly dependent on N inputs, surplus, and irrigation efficiency. In this study, however, we did not evaluate any large-level changes in management practices that may mitigate nitrate leaching (Di & Cameron, 2002), because we have no compilation of soil mineral N (nitrate and ammonium) and nitrate leaching measurements for switchgrass in California.

Uncertainty estimation and model evaluation

For the calibration simulations, model performance was assessed by computing the mean squared deviation (MSD) between modeled and observed yield values. The MSD was then partitioned into three components: squared bias (SB), nonunity slope (NU), and lack of correlation (LC) (Gauch *et al*., 2003). The SB results from two means being different, whereas the NU arises when the slope of the least-squared regression of the observed values on the modeled values is not equal to 1. The LC arises when the square of the correlation is not equal to 1. These MSD components are additive. Descriptive statistics of the modeled and observed data were collected. For assessments of region-level controls on biomass yield, correlation coefficients were calculated between yield and soil and climatic variables using PROC CORR in SAS (SAS Institute Inc., Cary, NC, USA). Normality and log-normality of the residuals of the data were checked.

Results

For the selected switchgrass cultivars, observed biomass yields across the US varied considerably across sites and by management practices (Fig. 2). For example, the yields of Alamo, Kanlow, and Cave-in-Rock ranged from 1.3 to 33.7 Mg ha^{-1} yr^{-1} over 246, 203, and124 unique combinations of site and stand age, respectively. The model was reasonably calibrated for yields across sites with little bias (Table 2). For Sunburst and Trailblazer, 68–78% of errors resulted from NU mostly due to the small sample size. The model slightly overestimated the yields toward the higher range, but the averages of modeled and observed yields were similar within the margin of error. The model explained 23–26% of observed yield variation across the sites for the lowland ecotypes (Alamo and Kanlow), and 38–71% for the upland ecotypes (Fig. 2). The model simulated

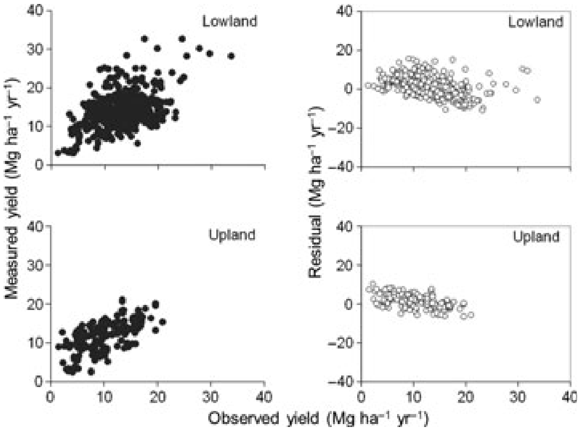

Fig. 2 Simulated vs. observed annual switchgrass yield for lowland and upland cultivars in the US (not California).

Table 2 Components (SB, squared bias; NU, nonunity slope; LC, lack of correlation) of mean squared error (MSD) between modeled and observed crop yields (Mg ha^{-1} yr^{-1})

	Lowland		Upland		
	Alamo	Kanlow	Cave-in-Rock	Sunburst	Trailblazer
N	246	203	124	15	26
Observed mean	12.3	14.4	11.1	8.4	7.7
Modeled mean	12.8	16.2	12.8	8.4	8.0
b^*	0.64	0.44	0.83	0.60	0.48
R^2	0.23	0.26	0.38	0.71	0.50
MSD	16.5	27.4	11.6	3.5	6.2
SB (%)	2	13	26	0	1
NU (%)	11	37	3	78	68
LC (%)	87	50	71	22	30

[*] The slope of the least-squared regression of measured vs. modeled yield values.

observed patterns in biomass yield reasonably well by N fertilizer, harvest frequency, and stand age (data not shown).

The model was then validated for biomass yields measured at the four field trials of California from 2007 to 2009 (Fig. 3). The model was able to account for 66–90% of the observed yield variation and temporal trends in yield for all cultivars. There was good agreement between modeled (2.0–9.9 Mg ha^{-1} yr^{-1}) and observed yield variance (1.3–12.2 Mg ha^{-1} yr^{-1}) in the 2007 establishment year. The model also simulated the yields during the years after establishment reasonably well. In 2008–2009, the observed yields were 7.8–37.4 Mg ha^{-1} yr^{-1} for Kanlow, 10.3–27.6 Mg ha^{-1} yr^{-1} for Cave-in-Rock, 11.2–30.2 Mg ha^{-1} yr^{-1} for Blackwell, 9.6–29.2 Mg ha^{-1} yr^{-1} for Sunburst, and 10.4–32.9 Mg ha^{-1} yr^{-1} for Trailblazer across the sites (Pedroso *et al.*, 2011). Alamo was killed by winter frost at Tulelake, but had yields of 20.4–41.1 Mg ha^{-1} yr^{-1} at the other sites. Overall, the model predicted that Alamo had the highest yields (10.7–41.4 Mg ha^{-1} yr^{-1}), followed by Kanlow (10.9–38.0 Mg ha^{-1} yr^{-1}), Cave-in-Rock (10.4–28.6 Mg ha^{-1} yr^{-1}), Blackwell (10.7–26.4 Mg ha^{-1} yr^{-1}), Trailblazer (5.2–29.4 Mg ha^{-1} yr^{-1}), and Sunburst (8.9–25.2 Mg ha^{-1} yr^{-1}). We found no response to N fertilization at 0–150 kg N ha ha^{-1} yr^{-1} for both modeled and observed Trailblazer yields (Fig. 4). However, the modeled and observed Trailblazer yields increased by 8.9–14.0 kg N ha^{-1} yr^{-1} and 6.9–8.9 Mg ha^{-1} yr^{-1}, respectively, when fertilized at 224–300 kg N ha^{-1} yr^{-1} compared with nonfertilized yields. The effect of N fertilizer on biomass yield was similar for the other cultivars. Depending on cultivars, two or three cuts per year produced 1.4–4.2 times higher yields than single cut per year under field conditions (Fig. 5). Similarly, the model showed 2.5–5.3 times higher yields with two or three cuts per year. At Tulelake, however, the model did not successfully simulate poor winter survival of Alamo. As a result, average modeled yield deviations were high (31%) across all cultivars.

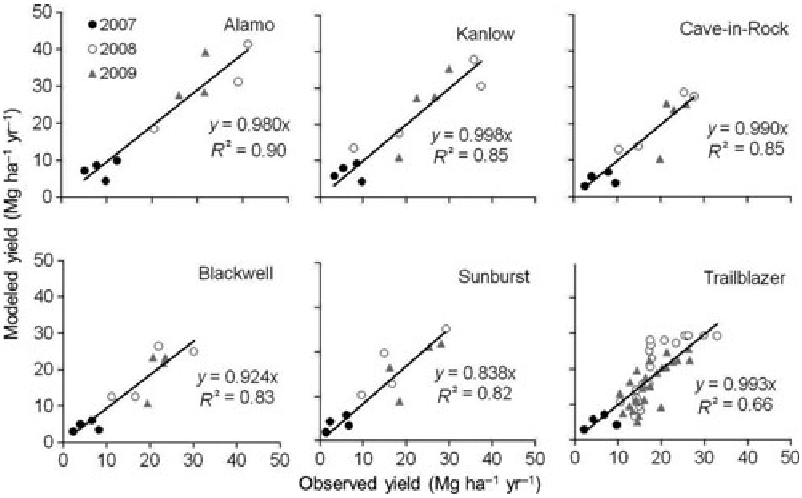

Fig. 3 Simulated vs. observed values of annual switchgrass yield by cultivar in the Central Valley of California.

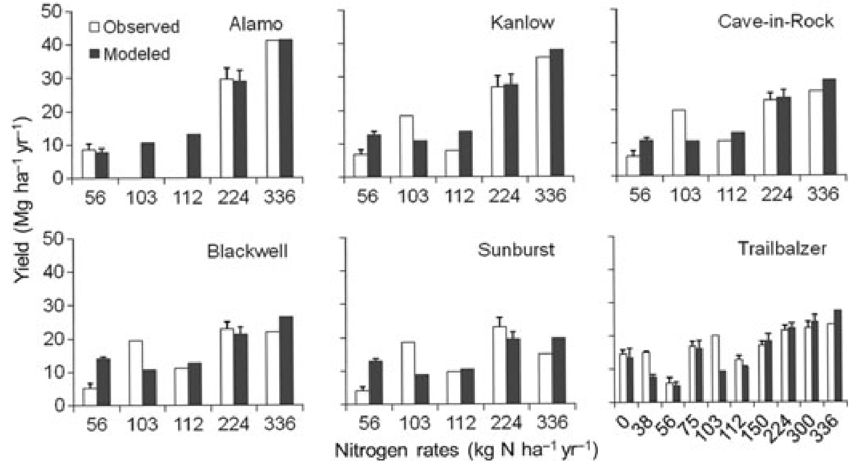

Fig. 4 Effect of applied nitrogen on annual switchgrass yields by cultivar in the Central Valley of California.

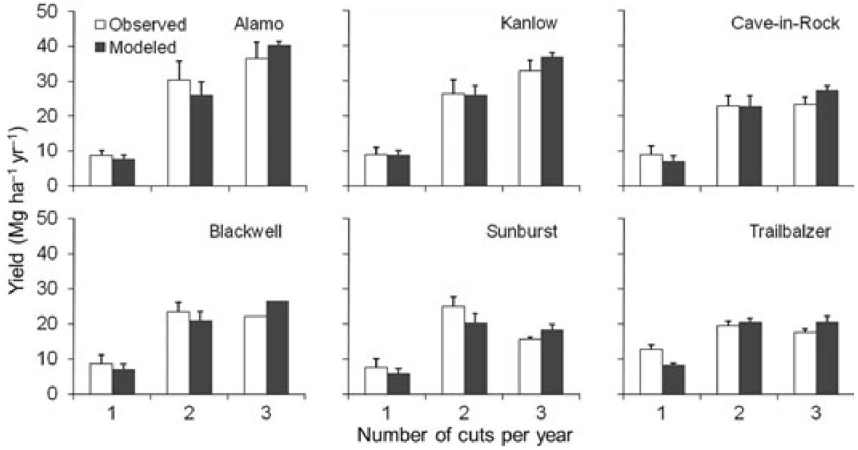

Fig. 5 Effect of number of cuts per year on annual switchgrass yield by cultivar in the Central Valley of California.

Potential biomass yields of the selected cultivars were simulated across the Central Valley of California from 2007 to 2009 (Fig. 6). In the establishment year of 2007, Alamo had the highest average yields (8.9 ± 0.6 Mg ha^{-1} yr^{-1}) across the Central Valley of California, followed by Kanlow (8.4 ± 0.5 Mg ha^{-1} yr^{-1}) and Trailblazer (6.2 ± 0.4 Mg ha^{-1} yr^{-1}). After establishment, Kanlow had the highest yields across the years: 24.0 ± 2.6 Mg ha^{-1} yr^{-1} in 2008 and 22.1 ± 2.1 Mg ha^{-1} yr^{-1} in 2009. Alamo also had relatively high yields in 2008 (23.3 ± 2.6 Mg ha^{-1} yr^{-1}) and 2009 (21.5 ± 2.1 Mg ha^{-1} yr^{-1}). In comparison, Sunburst consistently had the lowest average yields (4.8–17.0 Mg ha^{-1} yr^{-1}). Histograms showed that the majority of modeled yield data were normally distributed for these cultivars (Fig. 6). However, the Alamo and Kanlow yields were < 20 Mg ha^{-1} yr^{-1} on 7–12% and 4–8% of all grid cells in 2008–2009, respectively, which resulted in skewed yield distributions. Similarly, the Cave-in-Rock and Blackwell yields were < 15 Mg ha^{-1} yr^{-1} on 2–4% of all grid cells in the same period. The Trailblazer yields were > 20 Mg ha^{-1} yr^{-1} on 14% of all grid cells in 2008 and on 2% of the grid cells in 2009. In general, the yields were negatively related to clay content across the Central Valley of California (Table 3). However, the effect of soil texture on the yields of the northern upland ecotypes was not obvious. The yields were generally positively correlated with annual precipitation for all cultivars. The yields of the lowland ecotypes were positively related to both mean annual maximum and minimum temperatures. In comparison, the yields of the upland ecotypes were negatively correlated to temperatures. However, the model also estimated positive temperature effects on yields for Sunburst and Trailblazer. For all cultivars, the yields in the establishment year were not affected by initial soil mineral N levels

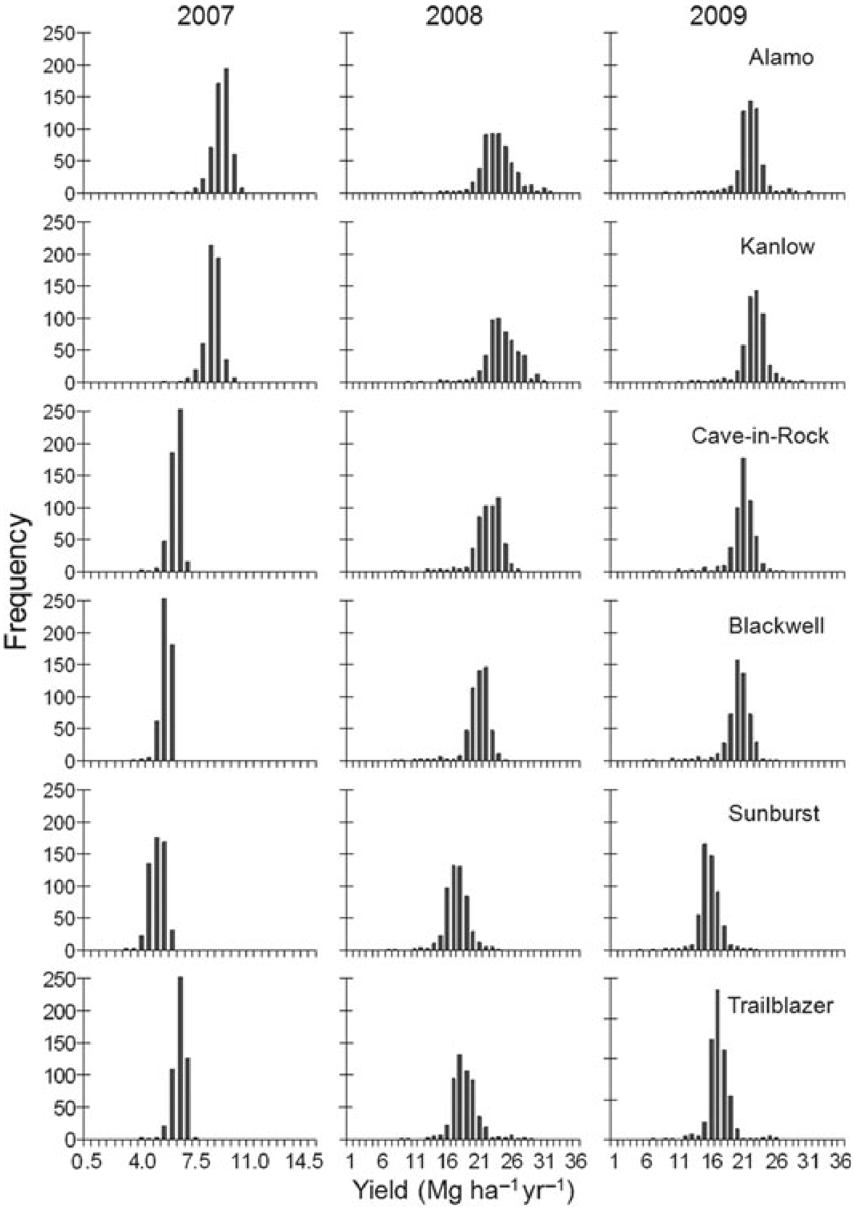

Fig. 6 Histograms of switchgrass yields across the Central Valley of California by cultivar in 2007–2009.

(Fig. 7). However, the estimated yields increased by 1.6–5.5 Mg ha^{-1} yr^{-1} when more residual soil mineral N was available for optimal re-growth with reduced nitrate leaching.

Discussion

Calibration

Cultivar-specific plant parameters were calibrated across a large geographic region in the US. Overall, the modeled biomass yields agreed very well with the observed yields, but the model appeared to underestimate the range of yield variation, particularly for high-yielding cultivars such as Alamo, Kanlow, and Cave-in-Rock. These simulation errors were probably caused by uncertainty in input parameters (Corson *et al*., 2007). As most research on switchgrass cultivars has focused on biomass production potential and how management practices affect yield, there is significantly less opportunity to obtain proper information on environmental variables for model calibration. Consequently, the model may not have sufficiently accounted for large differences in biophysical limiting factors across sites. For example, we had to ignore spatial variance in parameters controlling soil drainage conditions, nitrate

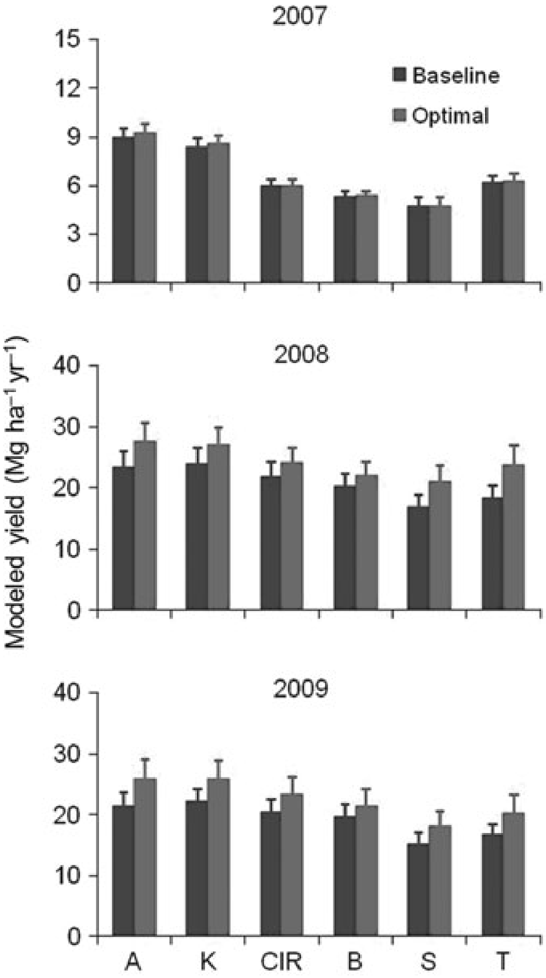

Fig. 7 Switchgrass yields across the Central Valley of California by cultivar in 2007–2009 with baseline vs. optimal levels of soil mineral N at the beginning of 2007. The optimal levels of mineral N in the soil profile were theoretically obtained with minimized nitrate leaching. See the text for details. Error bars indicate standard deviation. A, Alamo; K, Kanlow; CIR, Cave-in-Rock; B, Blackwell; S, Sunburst; and T, Trailblazer.

leaching, atmospheric N deposition, and nonsymbiotic N fixation across the sites. Parameters primarily relating to organic matter decomposition (Parton *et al.*, 1987), such as the sensitivity of potential decomposition to soil temperature and moisture, were fixed across the sites. Changes in these parameters have a significant effect on C and N dynamics (Six *et al.*, 2006) and depend on unique land use and management history (Ogle *et al.*, 2003). The maximal rate of photosynthesis is cultivar-specific, but may need to be adjusted to reflect the differences in the length of the growing season across the sites. Kiniry *et al.* (2008) adjusted the parameter for degree days to maturity to realistically simulate switchgrass yields at diverse sites by the ALMANAC (Agricultural Land Management Alternative with Numerical Assessment Criteria) model. Despite the lack of site-specific information, the performed calibration was necessary to parameterize the plant parameters independent from other biophysical controls on biomass yield.

The effect of N fertilizer on biomass yield was highly variable and uncertain across the sites, although a significant site-level N effect on biomass yield has been reported (Heaton *et al.*, 2004). Nevertheless, our results showed that the yields were positively related to N fertilizer across the US (data not shown). Similarly, Brown *et al.* (2000) showed that switchgrass yields simulated by Erosion Productivity Impact Calculator (EPIC) increased with increasing N fertilization rates at two sites (Ames, Iowa and Mead, Nebraska), but the effect of N fertilizer on observed yield was inconsistent between the sites. The changes in yield with harvest frequency were also reasonably well simulated. In general, yields of common cultivars are probably higher with two or three cuts than a single cut per year (Fike *et al.*, 2006a). Specifically, Alamo, Kanlow, and Cave-in-Rock had 25–37% more modeled yields with two cuts than single cut per year (data not shown).

Validation

The model was able to account for most of the differences in observed biomass yield among the cultivars and across ecoregions in California over the years 2007–2009. Our results showed that lowland ecotypes generally had higher yields than the upland ecotypes (Fig. 3). For each cultivar, both modeled and observed yields generally decreased from northern to southern sites in the establishment year (data not shown). Our results also suggest that it is relatively slow to reach full yield potential for all cultivars at Tulelake and Davis compared with the other sites. However, there was yield decline in the third year after establishment at Five Points and El Centro. This suggests that differences in yield potential related to establishment may exist at an early stand age across the sites.

It is still uncertain how genetic characteristics interact with a group of elements (e.g., soil taxonomy, climate, historical land use) from each ecoregion in California. For example, there were differences in the length of frost-free day between Tulelake (164 days) and the other sites (307–365 days). This suggests that the selected cultivars possibly have different growth responses to temperature across ecoregions (Medlyn *et al.*, 2002). In particular, Alamo did not survive the winters at Tulelake in 2008 and 2009. Typically, Alamo continues to grow late in the fall, hence decreasing winter hardness and survival (Lewandowski *et al.*, 2003; Casler *et al.*, 2004). This suggests that Alamo is not a promising cultivar for biomass production in mountainous areas in

Table 3 Significant ($P < 0.05$) Pearson's correlation coefficients between yields and environmental factors by cultivar ($n = 537$). Blank indicates that a correlation is not significant ($P < 0.05$) or it is significant, but explains less than 5% of yield variation. All variables are log-transformed

Cultivar	Year	Sand	Clay	Maximum temperature	Minimum temperature	Precipitation
Alamo	2007		−0.28	0.25	0.30	0.29
	2008			0.42		
	2009		−0.31			
Kanlow	2007		−0.33			0.34
	2008			0.40		
	2009		−0.38			
Cave-in-Rock	2007		−0.35	−0.44		0.47
	2008		−0.23	0.27		
	2009		−0.41			0.39
Blackwell	2007		−0.36	−0.42		0.46
	2008		−0.27			
	2009		−0.39	−0.29		0.55
Sunburst	2007			−0.77	−0.55	0.39
	2008	−0.24		0.30		
	2009			−0.31		0.50
Trailblazer	2007		−0.23	−0.48	−0.28	0.45
	2008	−0.30		0.30		
	2009					0.36

northern California. The model failed to simulate winter survival for Alamo at Tulelake because the initiation of switchgrass growth was not strictly controlled by temperature. Similarly, the yields were underestimated for all cultivars at Tulelake in 2007 and 2009. In contrast, the yields were slightly overestimated in 2008 presumably due to a buildup of mineral N (nitrate and ammonium) in the soil profile when the model underestimated the observed yields in the establishment year.

There was general agreement between modeled and observed yields by N fertilizer. For Trailblazer, we found no significant yield responses to added N over the years after establishment at each site (Pedroso *et al.*, 2011). However, the yields can potentially increase with increasing N addition at the site scale. The model tended to overestimate the Trailblazer yields across the sites when fertilized at 224–336 kg N ha^{-1} yr^{-1}. There were probably other primary factor(s) limiting switchgrass yields that were not simulated when plant N stress was removed by N fertilization. This trend was not obvious at Tulelake, where the production potential was low, probably due to cold temperatures year around. Presumably, there was a similar effect of N fertilizer on biomass yield for the other cultivars, but this requires further validation. Regrowth potential of switchgrass is greatly affected by harvest frequency (Parrish & Fike, 2005) and further differs by ecotype (Fike *et al.*, 2006a). The effect of harvest frequency on biomass yield was not fully evaluated within each site and across the sites because the management effect was confounded by location and stand age.

Regional estimation

Wullschleger *et al.* (2010) showed a lower yield potential of switchgrass across the Central Valley of California compared with the Midwest. However, our results suggest similar or higher yield potentials for the selected cultivars when cultivated in California compared with other regions. Wullschleger *et al.* (2010) did not consider irrigation, which may explain the discrepancy; switchgrass biomass yield was a function of ecotype, temperature, precipitation, and N fertilizer only. Across the Central Valley of California, Alamo had the highest modeled yields (8.9 ± 0.6 Mg ha^{-1} yr^{-1}) in the establishment year, but Kanlow had the highest yields (24.0 ± 2.6 Mg ha^{-1} yr^{-1} in 2008 and 22.1 ± 2.1 Mg ha^{-1} yr^{-1} in 2009) during the years after establishment. Differences in yield between Kanlow and Alamo were small: 0.7 ± 0.6 Mg ha^{-1} yr^{-1} in 2008 and 0.6 ± 0.4 Mg ha^{-1} yr^{-1} in 2009. Thus, Kanlow or Alamo has optimum potential as a biofuel crop in the Central Valley of California under the selected management practices once established. Sunburst showed the least yield potential among the cultivars.

The effects of soil texture on modeled yields were similar among the cultivars. For the lowland and southern upland ecotypes, high clay content (i.e.,

> 30%) had limited yield potentials. No major N stress was expected for the growth of switchgrass with N fertilization, but clayey soils would be N-limited due to typically low decomposability of soil organic matter. The irrigation requirements of the cultivars were also extremely high in the areas as field capacity increased linearly, but saturated hydraulic conductivity decreased exponentially with increasing clay content (Saxton *et al.*, 1986). As a result, there was more runoff or leaching of water and nutrients below the root zone with irrigation, possibly increasing nutrient stress. In part, this explained why the modeled yields in 2008 and 2009 were more sensitive to soil mineral N dynamics. Our model results suggest that it is possible to obtain 8–30% more yields if there is a sufficient amount of soil mineral N before the initiation of re-growth after establishment. Decreasing yields with time at a fixed N fertilization rates also suggests that yield potential would substantially depend on soil N availability. Therefore, managing soil N pools is potentially important with time for optimum biomass production of established switchgrass (Lemus *et al.*, 2008). In California, N removal by biomass harvest can decrease switchgrass biomass production over time on clayey soils particularly for high-yielding cultivars.

Phenologic development patterns and spatial distribution of switchgrass are closely related to temperature (Sanderson, 1992; Casler *et al.*, 2004). Jager *et al.* (2010) and Wullschleger *et al.* (2010) found a quadratic relationship between yield and annual temperature over larger geographic regions across the US. In California, the modeled yield responses to maximum or minimum temperature were generally linear. The Alamo yields in the establishment year were affected by both annual mean maximum and minimum temperatures due to relatively slow germination. In the years after the establishment year, the yields of Alamo and Kanlow tended to increase with increasing maximum temperatures only. In contrast, the successful establishment of the stands for the upland ecotypes was negatively affected by maximum/minimum temperatures. Consequently, our model results suggest that the upland ecotypes are more sensitive to temperature than the lowland ecotypes. As implied by contrasting temperature effects on yields by ecotype, optimum maximum temperatures for biomass production potential appear to be more important for the upland than lowland ecotypes in the Central Valley of California. In contrast, Jager *et al.* (2010) reported a significant response of the yields of lowland ecotypes to winter minimum temperature.

Regardless of cultivar, annual precipitation significantly affected the yields in the establishment year. Once established, growth in the lowland ecotypes was not sensitive to precipitation, but the upland ecotypes showed inconsistent responses. In California, growth in either ecotype was probably not limited by water stress during the growing season due to frequent irrigation. Specifically, the modeled yields of the lowland and southern upland ecotypes were unusually low with annual precipitation of less than 200 mm (data not shown). Wullschleger *et al.* (2010) showed that switchgrass biomass yields increased with an increase in growing season (April to September) precipitation up to approximately 600 mm, but did not above 600 mm. Overall, yields did not significantly respond to growing season precipitation (Heaton *et al.*, 2004; Wullschleger *et al.*, 2010). In contrast, Wang *et al.* (2010) showed that annual precipitation can limit yields across the US. Lee & Boe (2005) found that April and May precipitation was a key factor limiting the yields of Dacotah and Cave-in-Rock in North Dakota. Therefore, the yield potential of irrigated switchgrass can be a function of precipitation as it probably affects the regrowth potential of switchgrass in the spring before irrigation starts.

Conclusion

Although there was large data uncertainty, cultivar-specific plant parameterization was able to account for biomass production potential across the US. Biomass production of irrigated switchgrass differs by N fertilizer and harvest frequency across ecoregions in California, which was reasonably validated. Once established, Alamo and Kanlow (21–24 Mg $\mathrm{ha^{-1}\ yr^{-1}}$) produce higher yields than the other cultivars in fertilized (224 kg N $\mathrm{ha^{-1}\ yr^{-1}}$) two-cut systems. Consequently, Alamo and Kanlow have a potential to facilitate biomass production within the Central Valley of California under the selected management practices. Our model results suggest that there are distinct controls by annual mean maximum/minimum temperature on the yields of the different ecotypes. Thus, management options of switchgrass for biomass should differ by cultivar depending on the temperature regime. In this study, we focused on switchgrass biomass production over the first 3 years after establishment, but the model can be used to evaluate longer-term biomass production potential of switchgrass and its implications on other ecologic processes in California. However, we need to further understand tolerance of switchgrass to temperature and precipitation extremes and system N dynamics for California.

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References

Barney JN, DiTomaso JM (2008) Nonnative species and bioenergy: are we cultivating the next invader? *BioScience*, **58**, 64–70.

Brown RA, Rosenberg NJ, Hays CJ *et al.* (2000) Potential production and environmental effects of switchgrass and traditional crops under current and greenhouse-altered climate in the central United States: a simulation study. *Agriculture, Ecosystems & Environment*, **78**, 31–47.

California Agricultural Statistics Service (2008) Agricultural overviews. In: *California Agricultural Statistics 2007 Crop Year* (eds Tolomeo V, Rutz J, Hoffman S), pp. 1–10. USDA-NASS, Sacramento, CA.

Casler MD, Vogel KP, Taliaferro CM *et al.* (2004) Latitudinal adaptation of switchgrass populations. *Crop Science*, **44**, 293–303.

Cassida KA, Muir JP, Hussey MA *et al.* (2005a) Biofuel component concentrations and yields of switchgrass in south central US environments. *Crop Science*, **45**, 682–692.

Corson MS, Rotz CA, Skinner RH (2007) Evaluating warm-season grass production in temperate-region pastures: a simulation approach. *Agricultural Systems*, **93**, 252–268.

De Gryze S, Wolf A, Kaffka SR *et al.* (2010) Simulating greenhouse gas budgets of four California cropping systems under conventional and alternative management. *Ecological Applications*, **20**, 1805–1819.

De Gryze S, Lee J, Ogle S *et al.* (2011) Assessing the potential for greenhouse gas mitigation in intensively managed annual cropping systems at the regional scale. *Agriculture, Ecosystems & Environment*, **144**, 150–158.

Del Grosso SJ, Parton WJ, Mosier AR *et al.* (2001) Simulated interaction of carbon dynamics and nitrogen trace gas fluxes using the DAYCENT model. In: *Modeling Carbon and Nitrogen Dynamics for Soil Management* (eds Schaffer M, Ma L, Hansen S), pp. 303–332. CRC Press, Boca Raton, FL.

Di HJ, Cameron KC (2002) Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies. *Nutrient Cycling in Agroecosystems*, **64**, 237–256.

Evers GW, Parsons MJ (2003) Soil type and moisture level influence on Alamo switchgrass emergence and seedling growth. *Crop Science*, **43**, 288–294.

Fargione J, Hill J, Tilman D *et al.* (2008) Land clearing and the biofuel carbon debt. *Science*, **319**, 235–1238.

Fike JH, Parrish DJ, Wolf DD *et al.* (2006a) Switchgrass production for the upper southeastern USA: influence of cultivar and cutting frequency on biomass yields. *Biomass and Bioenergy*, **30**, 207–213.

Frank AB, Berdahl JD, Hanson JD *et al.* (2004) Biomass and carbon partitioning in switchgrass. *Crop Science*, **44**, 1391–1396.

Gauch HG Jr, Hwang JTG, Fick GW (2003) Model evaluation by comparison of model-based predictions and measured values. *Agronomy Journal*, **95**, 1442–1446.

Giampietro M, Ulgiati S, Pimentel D (1997) Feasibility of large-scale biofuel production. *BioScience*, **47**, 587–600.

Heaton E, Voigt T, Long SP (2004) A quantitative review comparing the yields of two candidate C_4 perennial biomass crops in relation to nitrogen, temperature and water. *Biomass and Bioenergy*, **27**, 21–30.

Hopkins AA, Vogel KP, Moore KJ *et al.* (1995) Genotypic variability and genotype × environment interactions among switchgrass accessions from the Midwestern USA. *Crop Science*, **35**, 565–571.

Hsu FH, Nelson CJ (1986) Planting date effects on seedling development of perennial warm-season forage grasses. I. Field emergence. *Agronomy Journal*, **78**, 33–38.

Hsu FH, Nelson CJ, Matches AG (1985) Temperature effects on germination of perennial warm-season forage grasses. *Crop Science*, **25**, 215–220.

Jager HI, Baskaran LM, Brandt CC *et al.* (2010) Empirical geographic modeling of switchgrass yields in the United States. *Global Change Biology Bioenergy*, **2**, 248–257.

Johnson JMF, Barbour NW, Weyers SL (2007) Chemical composition of crop biomass impacts its decomposition. *Soil Science Society of America Journal*, **71**, 155–162.

Kiniry JR, Sanderson MA, Williams JR *et al.* (1996) Simulating Alamo switchgrass with the ALMANAC model. *Agronomy Journal*, **88**, 602–606.

Kiniry JR, Tischler CR, Van Esbroeck GA (1999) Radiation use efficiency and leaf CO_2 exchange for diverse C4 grasses. *Biomass and Bioenergy*, **17**, 95–112.

Kiniry JR, Schmer MR, Vogel KP *et al.* (2008) Switchgrass biomass simulation at diverse sites in the northern Great Plains of the U.S. *Bioenergy Research*, **1**, 259–264.

Lal R (2005) World crop residues production and implications of its use as a biofuel. *Environment International*, **31**, 575–584.

Lee DK, Boe A (2005) Biomass production of switchgrass in central South Dakota. *Crop Science*, **45**, 2583–2590.

Lee J, Six J, King AP *et al.* (2006) Tillage and field scale controls on greenhouse gas emissions. *Journal of Environmental Quality*, **35**, 714–725.

Lemus R, Lal R (2005) Bioenergy crops and carbon sequestration. *Critical Reviews in Plant Sciences*, **24**, 1–21.

Lemus R, Parrish DJ, Abaye O (2008) Nitrogen-use dynamics in switchgrass grown for biomass. *Bioenergy Research*, **1**, 1939–1234.

Lewandowski I, Scurlock JMO, Lindvall E *et al.* (2003) The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. *Biomass and Bioenergy*, **25**, 335–361.

Liebig MA, Schmer MR, Vogel KP *et al.* (2008) Soil carbon storage by switchgrass grown for bioenergy. *Bioenergy Research*, **1**, 215–222.

Ma Z, Wood CW, Bransby DI (2000) Impacts of soil management on root characteristics of switchgrass. *Biomass and Bioenergy*, **18**, 105–112.

Ma Z, Wood CW, Bransby DI (2001) Impact of row spacing, nitrogen rate, and time on carbon partitioning of switchgrass. *Biomass and Bioenergy*, **20**, 413–419.

Madakadze IC, Stewart KA, Madakadze RM *et al.* (2003) Base temperatures for seedling growth and their correlation with chilling sensitivity for warm-season grasses. *Crop Science*, **43**, 874–878.

Medlyn BE, Dreyer E, Ellsworth D *et al.* (2002) Temperature response of parameters of a biochemically based model of photosynthesis. II. A review of experimental data. *Plant Cell and Environment*, **25**, 1167–1179.

Mitchell RB, Moore KJ, Moser LE *et al.* (1997) Predicting developmental morphology in switchgrass and big bluestem. *Agronomy Journal*, **89**, 827–832.

Muir JP, Sanderson MA, Ocumpaugh WR *et al.* (2001) Biomass production of ‘Alamo’ switchgrass in response to nitrogen, phosphorus, and row spacing. *Agronomy Journal*, **93**, 896–901.

National Agricultural Statistics Service (1997) *Usual Planting and Harvesting Dates for U.S. Field Crops*. United States Department of Agriculture, Sacramento, CA.

Ogle S, Breidt FJ, Eve MD *et al.* (2003) Uncertainty in estimating land use and management impacts on soil organic carbon storage for US agricultural lands between 1982 and 1997. *Global Change Biology*, **9**, 1521–1542.

Parrish DJ, Fike JH (2005) The biology and agronomy of switchgrass for biofuels. *Critical Reviews in Plant Sciences*, **24**, 423–459.

Parton WJ, Schimel DS, Cole CV *et al.* (1987) Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Science Society of America Journal*, **51**, 1173–1179.

Paruelo JM, Lauenroth WK (1996) Relative abundance of plant functional types in grasslands and shrublands of North America. *Ecological Applications*, **6**, 1212–1224.

Pedroso G, De Ben C, Hutmacher RB *et al.* (2011) Establishment and productivity of irrigated switchgrass across ecozones in California. *California Agriculture*, **65**, 168–173.

Porter CL Jr (1966) An analysis of variation between upland and lowland switchgrass, *Panicum virgatum* L., in central Oklahoma. *Ecology*, **47**, 980–992.

Poudel DD, Horwarth WR, Mitchell JP *et al.* (2001) Impacts of cropping systems on soil nitrogen storage and loss. *Agricultural Systems*, **68**, 253–268.

Poudel DD, Horwath WR, Lanini WT *et al.* (2002) Comparison of soil N availability and leaching potential, crop yields and weeds in organic, low-input and conventional farming systems in northern California. *Agriculture Ecosystems & Environment*, **90**, 125–137.

Sanderson MA (1992) Morphological development of switchgrass and kleingrass. *Agronomy Journal*, **84**, 415–419.

Saxton KE, Rawls WJ, Romberger JS *et al.* (1986) Estimating generalized soil-water characteristics from texture. *Soil Science Society of America Journal*, **50**, 1031–1036.

Schmer MR, Vogel KP, Mitchell RB *et al.* (2008) Net energy of cellulosic ethanol from switchgrass. *Proceedings of the National Academy of Sciences*, **105**, 464–469.

Searchinger T, Heimlich R, Houghton RA *et al.* (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, **319**, 238–1240.

Six J, Frey SD, Thiet RK *et al.* (2006) Bacterial and fungal contributions to carbon sequestration in agroecosystems. *Soil Science Society of America Journal*, **70**, 555–569.

Sladden SE, Bransby DI, Aiken GE (1991) Biomass yield, composition and production costs for 8 switchgrass cultivars in Alabama. *Biomass and Bioenergy*, **1**, 119–122.

Smith P, Smith JU, Powlson DS *et al.* (1997) A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. *Geoderma*, **81**, 153–225.

Stroup JA, Sanderson MA, Muir JP *et al.* (2003) Comparison of growth and performance in upland and lowland switchgrass types to water and nitrogen stress. *Bioresource Technology*, **86**, 65–72.

USDA (1997) *1997 National Resource Inventory*. Natural Resources Conservation Service, Washington, DC, and Statistical Laboratory, Iowa State University, Ames, Iowa. Available at: http://www.nrcs.usda.gov/technical/NRI (accessed 27 October 2011).

Van Esbroeck GA, Hussey MA, Sanderson MA (1997) Leaf appearance rate and final leaf number of switchgrass cultivars. *Crop Science*, **37**, 864–870.

Walsh ME (1998) U.S. bioenergy crop economic analyses: status and needs. *Biomass and Bioenergy*, **14**, 341–350.

Wang D, Lebauer DS, Dietze MC (2010) A quantitative review comparing the yield of switchgrass in monocultures and mixtures in relation to climate and management factors. *Global Change Biology Bioenergy*, **2**, 16–25.

Williams SA, Paustian K (2005) *Developing Regional Cropping Histories for Century Model U.S. National Level Simulations*. A White Paper Submitted to the Environmental Protection Agency for Agricultural Soil Carbon Inventory Documentation.

Wright L (2007) *Historical Perspective on How and Why Switchgrass was Selected as a "Model" High-Potential Energy Crop*. ORNL/TM-2007/109. Oak Ridge National Laboratory, Oak Ridge, TN.

Wullschleger SD, Davis EB, Borsuk ME *et al.* (2010) Biomass production in switchgrass across the United States: database description and determinants of yield. *Agronomy Journal*, **102**, 1158–1168.

Database References

Berdahl JD, Frank AB, Krupinsky JM *et al.* (2005) Biomass yield, phenology, and survival of diverse switchgrass cultivars and experimental strains in western North Dakota. *Agronomy Journal*, **97**, 549–555.

Bouton JH (2002) *Bioenergy Crop Breeding and Production Research in the Southeast*. Final report for 1996 to 2001. ORNL/SUB-02-19XSV810C/01. Oak Ridge National Laboratory, Oak Ridge, TN.

Casler MD, Boe AR (2003) Cultivar × environment interactions in switchgrass. *Crop Science*, **43**, 2226–2233.

Cassida KA, Muir JP, Hussey MA *et al.* (2005b) Biomass yield and stand characteristics of switchgrass in south central US environments. *Crop Science*, **45**, 673–681.

Fike JH, Parrish DJ, Wolf DD *et al.* (2006b) Long-term yield potential of switchgrass-for-biofuel systems. *Biomass and Bioenergy*, **30**, 198–206.

Fuentes RG, Taliaferro CM (2002) Biomass yield stability of switchgrass cultivars. In: *Trends in New Crops and New Uses* (eds Janick J, Whipkey A), pp. 276–282. ASHS Press, Alexandria, VA.

Heaton EA, Dohleman FG, Long SP (2008) Meeting US biofuel goals with less land: the potential of Miscanthus. *Global Change Biology*, **14**, 2000–2014.

Lemus RW (2004) *Switchgrass as an Energy Crop: Fertilization, Cultivar, and Cutting Management*. PhD thesis, The Virginia Polytechnic Institute and State University, Blacksburg, VA.

Lemus R, Brummer EC, Moore KJ *et al.* (2002) Biomass yield and quality of 20 switchgrass populations in southern Iowa, USA. *Biomass and Bioenergy*, **23**, 433–442.

Reynolds JH, Walker CL, Kirchner MJ (2000) Nitrogen removal in switchgrass biomass under two harvest systems. *Biomass and Bioenergy*, **19**, 281–286.

Sanderson MA, Read JC, Reed RL (1999) Harvest management of switchgrass for biomass feedstock and forage production. *Agronomy Journal*, **91**, 5–10.

Sanderson MA, Reed RL, Ocumpaugh WR *et al.* (1999) Switchgrass cultivars and germplasm for biomass feedstock production in Texas. *Bioresource Technology*, **67**, 209–219.

Thomason WE, Raun WR, Johnson GV *et al.* (2004) Switchgrass response to harvest frequency and time and rate of applied nitrogen. *Journal of Plant Nutrition*, **27**, 1199–1226.