Agriculture, Ecosystems and Environment 216 (2016) 344–355

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Comparative productivity of alternative cellulosic bioenergy cropping systems in the North Central USA

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ARTICLE INFO

Article history:
Received 23 June 2015
Received in revised form 15 October 2015
Accepted 16 October 2015
Available online 10 November 2015

Keywords:
Corn stover
Giant miscanthus
Harvest efficiency
Hybrid poplar
Restored prairie
Switchgrass

ABSTRACT

Biofuels from lignocellulosic feedstocks have the potential to improve a wide range of ecosystem services while simultaneously reducing dependence on fossil fuels. Here, we report on the six-year production potential (above ground net primary production, ANPP), post-frost harvested biomass (yield), and gross harvest efficiency (GHE = yield/ANPP) of seven model bioenergy cropping systems in both southcentral Wisconsin (ARL) and southwest Michigan (KBS). The cropping systems studied were continuous corn (*Zea mays* L.), switchgrass (*Panicum virgatum* L.), giant miscanthus (*Miscanthus* × *giganteus* Greef & Deuter ex Hodkinson & Renvoize), hybrid poplar (*Populus nigra* × *P. maximowiczii* A. Henry 'NM6'), a native grass mixture (5 sown species), an early successional community, and a restored prairie (18 sown species). Overall the most productive cropping systems were corn > giant miscanthus > and switchgrass, which were significantly more productive than native grasses ≈ restored prairie ≈ early successional ≈ and hybrid poplar, although some systems (e.g. hybrid poplar) differed significantly by location. Highest total ANPP was observed in giant miscanthus (35.2 ± 2.0 Mg ha^{-1} yr^{-1}) at KBS during the sixth growing season. Six-year cumulative biomass yield from hybrid poplar at KBS (55.4 ± 1.3 Mg ha^{-1}) was high but significantly lower than corn and giant miscanthus (65.5 ± 1.5, 65.2 ± 5.5 Mg ha^{-1}, respectively). Hypothesized yield advantages of diversity in perennial cropping systems were not observed during this period. Harvested biomass yields were 60, 56, and 44% of ANPP for corn, perennial grass, and restored prairie, respectively, suggesting that relatively simple changes in agronomic management (e.g. harvest timing and harvest equipment modification) may provide significant gains in bioenergy crop yields. Species composition was an important determinant of GHE in more diverse systems. Results show that well-established, dedicated bioenergy crops are capable of producing as much biomass as corn stover, but with fewer inputs.

1. Introduction

Producing biofuels from lignocellulosic feedstocks has the potential to improve social, economic, and environmental goals by increasing energy production and the supply of multiple ecosystem services (Robertson et al., 2008; Meehan et al., 2013) while avoiding the use of food/feed crops such as corn grain. With well-developed harvest, processing, and transportation infrastructure in place, agricultural crop residues such as corn stover and wheat straw are the most common feedstocks currently employed for the production of lignocellulosic ethanol in both the United States and European Union (Janssen et al., 2013). Although abundant (58.3 Tg harvestable US corn storver, Graham et al., 2007), use of annual crop residues may exacerbate the negative environmental externalities of annual grain production (e.g. soil carbon loss, erosion; Blanco-Canqui and Lal, 2007).

As an alternative to annual crops and crop residues, perennial cropping systems have the potential to provide high yields while helping to sequester soil carbon, stabilize climate, and improve water quality (Robertson et al., 2011; Gelfand et al., 2013; Sanford, 2014). Gelfand et al. (2013) for example showed that if fertilized;

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http://dx.doi.org/10.1016/j.agee.2015.10.018
0167-8809/

successional herbaceous vegetation was capable of producing more energy than annual grain crops (65 vs. 41 GJ ethanol energy ha^{-1} yr^{-1}) with a higher potential to mitigate greenhouse gas emissions (−851 vs. −397 g CO_2eq m^{-2} yr^{-2}). Moreover, diverse assemblages in perennial cropping systems should promote biodiversity in other trophic levels (Webster et al., 2010; Robertson et al., 2012; Werling et al., 2014) and may improve long-term yield stability via improved pest suppression and other important ecosystem services (Meehan et al., 2012). Candidate perennial systems include grass monocultures (e.g. switchgrass [*Panicum virgatum* L.] and giant miscanthus [*Miscanthus* × *giganteus* Greef & Deuter ex Hodkinson & Renvoize]), fast growing woody species (e.g. hybrid poplar [*Populus* spp.] and willow [*Salix* spp.]), and diverse herbaceous assemblages such as those found in restored prairies and successional plant communities (Tilman et al., 2006; Heaton et al., 2008; Vogel et al., 2011; Gelfand et al., 2013).

Switchgrass has received considerable attention in the U.S. as a promising bioenergy crop with yields ranging from of 5 to 8 Mg ha^{-1} yr^{-1} for northern-upland ecotypes (Sanderson, 2008; Heaton et al., 2008; Monono et al., 2013) to as high as 21 Mg ha^{-1} yr^{-1} reported for northern-lowland ecotypes (Casler et al., 2004). Miscanthus, a promising C_4 grass from Asia, has been grown extensively in the EU and to a lesser extent in the U.S. (Lewandowski et al., 2000; Heaton et al., 2008). Proponents of miscanthus cite its high yield potential (26–61 Mg ha^{-1} yr^{-1}), N fixing capacity, and limited potential to become invasive as key strengths for its use as a biomass crop (Lewandowski et al., 2000; Heaton et al., 2008; Cadoux et al., 2012).

For fast growing woody species such as hybrid poplar and willow, high planting densities and short harvest intervals are often employed to maximize biomass. In a review of short rotation cultural practices for hybrid poplar, Ceulemans and Deraedt (1999) reported planting densities from 15 studies ranging from 1142 to 111,100 plants ha^{-1} with a median density of 5500 plants ha^{-1}. Similarly, harvest intervals from one year to eight years, with a median interval of four years were reported. Poplar yields were higher in coppiced stands than in stands grown from cuttings (20–25 Mg ha^{-1} yr^{-1}).

Native polycultures and successional plant communities may also be viable options for the production of lignocellulosic biofuels. Gelfand et al. (2013) report biomass yields of 3.3–5.4 Mg ha yr^{-1} for unfertilized successional plant communities and 4.8–7.9 Mg ha^{-1} yr^{-1} for the same system receiving 124 kg N ha^{-1} yr^{-1}, which exceed yields reported for corn stover in the same region (4.8 Mg ha^{-1}). Jarchow et al. (2012) reported biomass yields from central Iowa of >10 Mg ha^{-1} for a three species native grass mixture of switchgrass, big bluestem (*Andropogon gerardi* Vitman), and indiangrass (*Sorghastrum nutans* (L.) Nash).

Published productivity data for mono- and poly-culture perennial bioenergy crops vary considerably (Vogel et al., 2002; Adler et al., 2009; Jarchow et al., 2012). While this stems in part from regional climate and soil differences, variation in production estimates may also reflect the scale, method, and timing of biomass collection. Therefore, to forecast available regional biomass supplies and make informed decisions on the potential tradeoffs between important ecosystem services and biomass production, it is critical to understand the aboveground net primary production (ANPP) potential of candidate bioenergy crops, as well as their realized harvested yields using agricultural equipment likely to be available to producers. Differences between ANPP and yield occur as a result of combined biomass losses through harvest timing (crop senescence and herbivory) and harvest efficiency (cutting height, incomplete collection, transport).

The seven model cropping systems we studied span gradients of perenniality (annual and perennial crops) and diversity (mono- and polycultures). We provide estimates of ANPP, harvestable yield, and gross harvest efficiency (GHE) for a diverse array of cropping systems grown together on agronomically-relevant plots

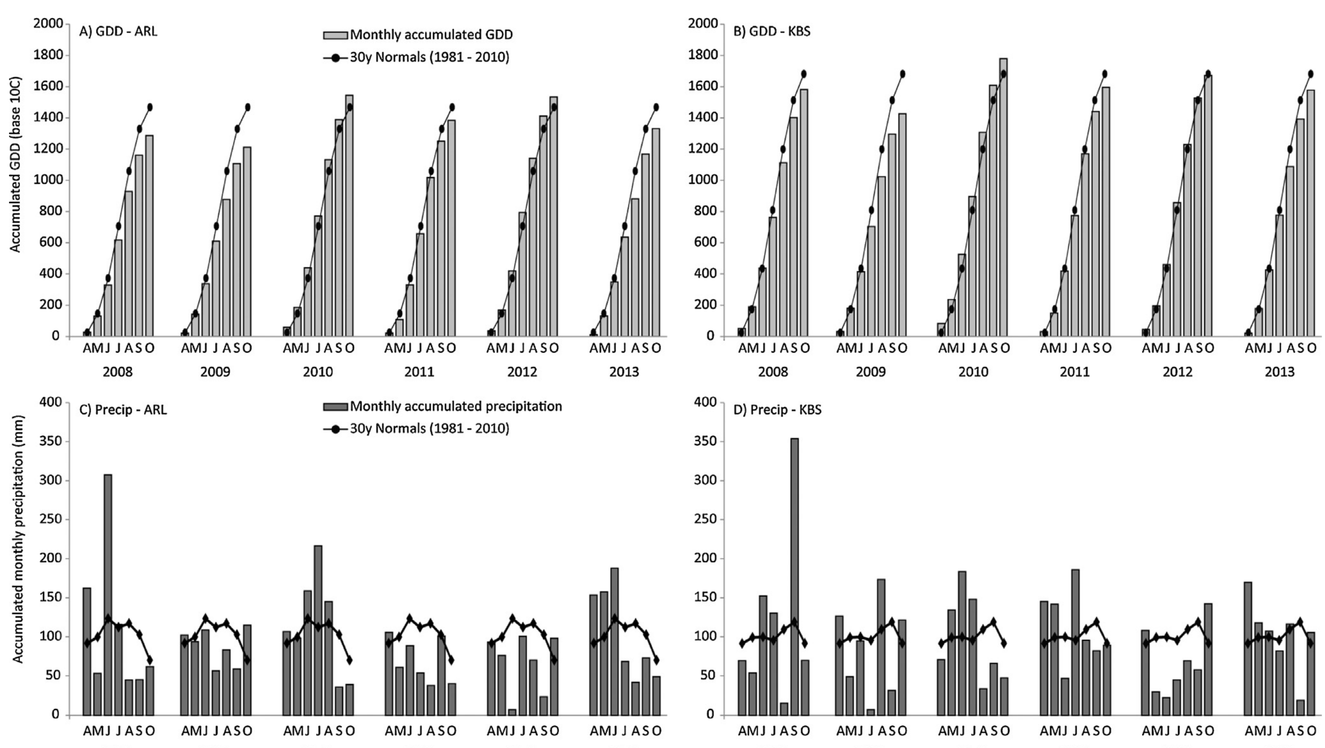

Fig. 1. Monthly accumulated growing degree days (GDD) at (A) ARL and (B) KBS and precipitation (precip) at (C) ARL and (D) KBS between 2008 and 2013 (1 April to 31 October), as well as 30-year climate normals (1981–2010) for each location. Growing degree units calculated between 10 (base) and 30 (max) °C. Climate normals are from the Wisconsin and Michigan state climatology offices respectively. Growing season weather data logged daily at both ARL and KBS.