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Will energy crop yields meet expectations?

Stephanie Y. Searle [a,*], **Christopher J. Malins** [b,1]

[a] The International Council on Clean Transportation, 1225 I St NW, Ste 900, Washington DC 20008, USA

[b] The International Council on Clean Transportation, 11 Belgrave Road, IEEP Offices 3rd Floor, London SW1V 1RB, UK

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ABSTRACT

Expectations are high for energy crops. Government policies in the United States and Europe are increasingly supporting biofuel and heat and power from cellulose, and biomass is touted as a partial solution to energy security and greenhouse gas mitigation. Here, we review the literature for yields of 5 major potential energy crops: *Miscanthus* spp., *Panicum virgatum* (switchgrass), *Populus* spp. (poplar), *Salix* spp. (willow), and *Eucalyptus* spp. Very high yields have been achieved for each of these types of energy crops, up to 40 t ha^{-1} y^{-1} in small, intensively managed trials. But yields are significantly lower in semi-commercial scale trials, due to biomass losses with drying, harvesting inefficiency under real world conditions, and edge effects in small plots. To avoid competition with food, energy crops should be grown on non-agricultural land, which also lowers yields. While there is potential for yield improvement for each of these crops through further research and breeding programs, for several reasons the rate of yield increase is likely to be slower than historically has been achieved for cereals; these include relatively low investment, long breeding periods, low yield response of perennial grasses to fertilizer, and inapplicability of manipulating the harvest index. *Miscanthus* × *giganteus* faces particular challenges as it is a sterile hybrid. Moderate and realistic expectations for the current and future performance of energy crops are vital to understanding the likely cost and the potential of large-scale production.

1. Introduction

1.1. Policy relevance

Biomass is currently seen as a potentially major part of carbon mitigation strategies in the U.S. and EU. The U.S. Renewable Fuels Standard 2 [1] mandates a high volume of cellulosic biofuel to be produced in 2022; although this mandate is unlikely to be met [2], it has led to the commercialization of several cellulosic biofuel production processes in the U.S. In the EU, the Renewable Energy Directive [3] calls for 20% of total energy to be sourced from renewables by 2020, and biomass is a major component of this plan, both in the heat and power sector and as transportation fuels. In addition, the Fuel Quality Directive [4] mandates a 6% greenhouse gas (GHG) reduction in transport fuels by 2020, further incentivizing biofuels. The European Commission has proposed introducing double and quadruple counting to the RED for biofuels from non-food sources, including agricultural and forestry residues and dedicated bioenergy crops [5].

Looking forward, the EU is currently considering providing regulatory support for biofuels beyond 2020, and cellulosic biofuel may receive continued support in the U.S. as well.

Abbreviations: SRC, short-rotation coppice; GHG, greenhouse gases; DoE, U.S. Department of Energy.

* *Corresponding author*. Tel.: +1 202 534 1612.
E-mail addresses: stephanie@theicct.org (S.Y. Searle), chris@theicct.org (C.J. Malins).
[1] Tel.: +44 7905 051 671.

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Other regions are likely to consider biomass as part of their GHG mitigation strategies that does not compete with food. Dedicated energy crops are a likely candidate to meet this increasing demand for sustainable biomass.

How much sustainable biomass can we count on to meet future targets? Energy crop yield is a critical part of the answer, and will also partially determine the GHG reduction from such biomass. It is more efficient, both in terms of resources and money, to manage and harvest more biomass from the same plot of land.

1.2. *Expectations of energy crop yields*

Expectations are high for energy crop yields. The U.S. Environmental Protection Agency has quoted the literature for expected Miscanthus yields of 10–40 t ha^{-1} y^{-1} in the U.S. [6] (for reference, today's maize yields are ~10 t ha^{-1} y^{-1} [7]), while the Department of Energy (DoE) has supported switchgrass research for over a decade based on expectations of commercially viable yields up to 33 t ha^{-1} y^{-1} [8]. Well-cited studies projecting future biomass potential have assumed energy crop yields of 18 t ha^{-1} y^{-1} (global average) [9] and 10.5–22.9 t ha^{-1} y^{-1} [10]. Additionally, expectations are high for future yield growth of energy crops; the U.S. DoE assumed yield growth of up to 5% per year (for comparison, maize yields have increased on average ~2% per year over the past 60 years [11]).

Whether or not commercial energy crop production is likely to meet these expectations is the topic of this review. We focus on currently attainable yields of 5 major candidates for large scale energy crop production: *Miscanthus* spp., *Panicum virgatum* (switchgrass), *Salix* spp. (willow), *Populus* spp. (poplar), and *Eucalyptus* spp. In the following sections, we compare reported yields from small and large scale experiments with geographical context, discuss environmental implications of energy crop production, and the future potential for yield improvement.

2. Overview of studies

2.1. *Miscanthus*

Miscanthus is a genus of perennial grasses native to Asia and Africa that use the C4 photosynthetic pathway. The type most commonly discussed as a potential energy crop is *Miscanthus* × *giganteus* Greef et Deu, thought to be a hybrid of *Miscanthus sinensis* and *Miscanthus sacchariflorus* [12]. As *M. sinensis* natively grows in cooler, northern temperate climates and *M. sacchariflorus* is better suited to a warmer climate, *M.* × *giganteus* thrives in the temperate zone but is intolerant to both cold and hot extremes [12–15].

M. × *giganteus* is a sterile triploid [16] and at the present is propagated vegetatively by transplanting rhizomes, although producing seed from the parent species has been attempted [17].

Miscanthus yields are low in the first 1–2 years after establishment, and stabilize or slowly increase after the 3rd year [15]. Yields have been known to decline in stands after 10 years [17,18], and re-establishment of stands may be necessary after this time period.

Reported yields of *M.* × *giganteus* are shown in Table 1, and full details are shown in the supporting online material. Most research performed on *Miscanthus* spp. for biomass production has been in Europe, with some at the University of Illinois in the U.S. [19]. Yields range from 5 to 13 t ha^{-1} y^{-1} on poor soils or marginal land [15,18] and from 7 to 44 t ha^{-1} y^{-1} on arable land with either sufficient precipitation or irrigation [15,20–24] (all yield measurements quoted here are presented in dry mass). Yields are highest (13–44 t ha^{-1} y^{-1}) in warm temperate regions such as Greece [15,25–27].

Previous reviews of Miscanthus yields have reported typical yields of 12 t ha^{-1} y^{-1} [28] and ranges of 8.8–16 t ha^{-1} y^{-1} [29] and 5–44 t ha^{-1} y^{-1} [15] with the higher yields generally associated with very well-irrigated and fertilized Miscanthus on arable land in warm temperate regions. Virtually all the studies reviewed here on Miscanthus were conducted on small plots, but in a broad review of European Miscanthus trials, Scurlock [30] gave 7–9 t ha^{-1} y^{-1} as yields that can be expected at field scale, which is somewhat lower than is typically measured in small plots. In some studies, Miscanthus yield has been found not to respond to nitrogen fertilization [20,31]. Yields have been found to be somewhat higher with increased fertilization [27] (15.8 t ha^{-1} y^{-1} vs. 12.7 t ha^{-1} y^{-1}, both measured in Spring), but it is likely that the yield response of Miscanthus to fertilizer is muted at best. Still, it has been advised to add a modest amount of fertilizer to Miscanthus stands, even on good soil, to avoid nutrient depletion [20].

M. × *giganteus* does not thrive in colder climates; Jorgensen [16] experienced 15% mortality of this hybrid in its first winter in Denmark, and in later experiments, no *M.* × *giganteus* survived the first winter [22]. *M. sinensis* is more hardy in northern regions where it has been found to have higher yields than the hybrid [16].

Table 1 – Range of reported yields in the literature for energy crops by climatic zone, land quality, and plot size; all values in t ha^{-1} y^{-1}.

	Total range	Climate				Land quality		Plot size	
		Cold temperate	Temperate	Warm temperate	Subtropical/ tropical	Agricultural	Marginal	Small (<1 ha)	Large (>1 ha)
Miscanthus × *giganteus*	5 to 44	7 to 11	5 to 38	13 to 44		7 to 44	5 to 13	5 to 44	7 to 9
Switchgrass	1 to 35		1 to 15	7 to 35		8 to 13	3 to 9	4 to 35	2 to 9
Willow SRC	0 to 21	0 to 21	4 to 15			4 to 15	2 to 15	4 to 21	0 to 13
Poplar SRC	0 to 35	3 to 9	0 to 28		5	5 to 18	2 to 11	0 to 35	2 to 3
Eucalyptus	0 to 51		3 to 51		0 to 33	14 to 51	0 to 17	3 to 51	4 to 5