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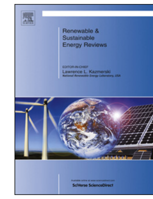

Ranking yields of energy crops: A meta-analysis using direct and indirect comparisons

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ABSTRACT

Many crops are candidate sources of renewable energy. Energy crop yields vary between species, but no global study has been carried out to rank energy crops on the basis of existing yield data. In this study, we analyzed a large set of yield data obtained for 36 energy crop species and ranked these species according to their productivity. We carried out a systematic literature review and extracted 856 yield data from 28 published papers for 36 different crop species. A statistical analysis, based on direct and indirect comparisons, was performed to compare the mean yield values of the species included in the database. For direct comparisons, the difference between crops grown at the same site was determined, whereas indirect comparisons involved estimation of the differences between crops grown at different sites (making use of a third reference crop grown at the same sites as the crops to be compared). Overall, direct and indirect comparisons generated similar crop species rankings. *Miscanthus x giganteus* was significantly more productive than most of the other energy crops included in our database. *Arundo donax* and *Pennisetum purpureum* were significantly more productive than *Miscanthus x giganteus*, but both were studied at a limited number of sites. By contrast, *Erianthus*, *Phragmites australis*, *Phalaris arundinacea*, *Miscanthus sacchariflorus* and *Miscanthus sinensis* were the least productive crop species. Our database is made freely available and could be updated with additional yield data in the future.

Contents

1. Introduction

Biomass obtained from wood, green waste, organic waste, algae and energy crops is a source of renewable energy [1]. A high number of species has been considered to produce biomass; annual crops

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such as grain or silage maize (*Zea mays*), or wheat (Triticum spp.), pluri-annual crops such as alfalfa (*Medicago sativa*) [2], perennial crops such as *Miscanthus x giganteus*, switchgrass (*Panicum virgatum*) [3] and short rotation coppice (such as poplar (*Populus*) and willow (*Salix*)) [4]. Energy crops can be converted into energy for heating or into electricity (from combustion or methanisation), and biofuels (e.g. bioethanol, biodiesel and biogas) [5,6]. Biomass produced by energy crops can be used as a substitute for fossil fuels [7], and help farmers diversifying their sources of income.

Several energy crop species are currently cultivated to produce biofuel. Bioethanol is produced by fermentation of sugar or starch extracted from crop storage organs such as grains (e.g. maize, wheat,), roots (e.g. sugar beet), or stems (e.g. sugarcane), whereas biodiesel is produced from oils extracted from grains of soybean or rapeseed, or from nuts of oil palm. The use of biofuel has become controversial due to competition for lands between energy crops and crops cultivated for food and feed. Mueller et al. [8] indeed pointed out that biofuel production from crop species used for food and feed partly contributed to the increase of major food crop prices in 2007–2008. The cultivation of crops for biofuel production has also some negative impact on the environment, especially on greenhouse gas emissions. As maize and rapeseed crops require nitrogen fertilizer, the cultivation of these species generate emissions of N_2O, a greenhouse gas with almost 300 times the global warming potential of CO_2 [9]. Biofuel production from food crops also induce changes in land use (e.g., conversion of forest or grassland to cropland) decreasing biodiversity and increasing CO_2 emissions [10,11].

In this study, we focus on a particular type of energy crops called lignocellulosic crops. The main characteristic of these crops is that their whole aerial biomass is harvested for energy production [12], not only their storage organs. This category of energy crops includes perennial crops (e.g., *Miscanthus x giganteus*), but also annual species such as triticale (*Triticosecale*). It is critical to precisely estimate the quantities of biomass that could be produced by lignocellulosic species in order to evaluate their profitability, estimate their energy balances, and assess the viability of this source of biomass for transformation industries [13]. Many published studies have reported energy crop yield data, but most of them report the results crop by crop, without estimating differences between crop species [14–16]. Lewandowski et al. [3] reviewed the range of production for the four most frequently studied perennial rhizomatous grasses used for energy production (i.e. *Panicum virgatum*, *Miscanthus x giganteus*, *Arundo donax* and *Phalaris arundinacea*). *Panicum virgatum* is native from northern America and is cultivated in central and southern Europe. *Miscanthus x giganteus* originates in southeastern Asia and is grown in central and southern Europe. *Arundo donax* is grown in Mediterranean areas. *Phalaris arundinacea* is native from northern America and is cultivated in northern Europe. These studies showed that *Panicum virgatum*, *Miscanthus x giganteus* and *Arundo donax* yields exceeded 30 ton dry matter per hectare per year ($t\,DM\,ha^{-1}\,yr^{-1}$). Other studies measured the differences in yield between two or more energy crop species [17]. These assessments were based on the results of experiments in which several crop species were grown on the same sites and in the same years. For example, Dohleman et al. [18] showed that dry biomass yield was higher for *Miscanthus x giganteus* than for *Panicum virgatum*,, based on data collected at three sites and in three years. Most of the studies [18,19] compared only two energy crop species. Only a small number of sites were considered in these studies, and no meta-analysis has ever been performed to rank a large number of energy crop species on the basis of yield data. In this study, we aim to carry out a meta-analysis

Table 1
Papers included in the database.

Authors	Year of publication	Country	Location(s)	Crop species
Angelini et al. [44]	2009	Italy	Pisa	*Arundo donax*, *Miscanthus x giganteus*
Aravindhakshan et al. [45]	2011	USA	Oklahoma	*Panicum virgatum*, *Cynodon dactylon*, *Pennisetum flaccidum*, *Eragrostis curvula*
Beale and Long [46]	1997	UK	Essex	*Miscanthus x giganteus*, *Spartina cynosuroides*
Beale et al. [47]	1999	UK	Essex	*Miscanthus x giganteus*, *Spartina cynosuroides*
Boehmel et al. [27]	2008	Germany	Ihinger Hof	*Miscanthus x giganteus*, *Panicum virgatum*, *Salix*, *Triticosecale*
Borkowska and Molas [48]	2012	Poland	Lublin	*Salix*, *Sida hermaphrodita*
Borkowska and Molas [49]	2013	Poland	Lublin	*Miscanthus x giganteus*, *Miscanthus sacchariflorus*, *Salix*, *Sida hermaphrodita*
Buxton et al. [50]	1998	USA	Ames, Chariton	*Medicago sativa*, *Phalaris arundinacea*, *Sorghum bicolor*
Cadoux et al. [17]	2014	France	Estrees Mons	*Festuca arundinacea, Medicago sativa*, *Miscanthus x giganteus*, *Panicum virgatum*, *Sorghum bicolor*, *Triticosecale*
Chaichi et al. [51]	2007	Iran	Tehran	*Medicago sativa*, *Sorghum bicolor*
Christian et al. [52]	2002	UK	Rothamsted	*Panicum amarum*, *Panicum virgatum*
Dohleman et al. [53]	2009	USA	Champaign	*Miscanthus x giganteus*, *Zea mays*
Dohleman et al. [18]	2012	USA	Urbana	*Miscanthus x giganteus*, *Panicum virgatum*
Erickson et al. [39]	2012	USA	Gainesville	*Arundo donax*, *Pennisetum purpureum*, *Saccharum spp*
Fedenko et al. [40]	2013	USA	Citra, Ona, Belle Glade	*Arundo donax*, *Miscanthus x giganteus*, *Pennisetum purpureum*, *Saccharum arundinaceum*, *Saccharum spp*
Hakala et al. [54]	2012	Finland	Jokioinen	*Festuca arundinacea*, *Phleum pratense*, *Trifolium pratense*
Hulle et al. [55]	2012	Belgium	Merelbeke	*Miscanthus x giganteus*, *Miscanthus sinensis*, *Panicum virgatum*, *Phalaris arundinacea*, *Phragmites australis*,*Salix*
Lewandowski and Kauter [56]	2003	Germany	Gutenzel, Ihinger Hof, Hohenheim	*Triticosecale*, *Triticum aestivum*, *Secale cereale*
Mantineo et al. [36]	2009	Italy	Enna	*Arundo donax*, *Cynara cardunculus*, *Miscanthus x giganteus*
Nassi o Di Nasso et al. [57]	2011	Italy	Pisa	*Arundo donax*, *Miscanthus x giganteus*
Niemeläinen et al. [58]	2004	Finland	Jokioinen	*Festuca arundinacea*, *Phleum pratense*, *Trifolium pratense*
Ra et al. [38]	2012	Japan	Nishitokyo	*Erianthus*, *Panicum virgatum*, *Pennisetum purpureum*, *Saccharum officinarum*, *Sorghum bicolor*, *Sorghum halepense*, *Zea mays*
Scholz et al. [59,60]	2002,2010	Germany	Potsdam	*Cannabis sativa*, *Dactylis glomerata*, *Helianthus tuberosus*, *Populus*, *Salix*, *Secale cereale*, *Secale montanum*
Smith and Slater. [19]	2010	UK	Newbridge-on-Wye	*Miscanthus x giganteus*, *Phalaris arundinacea*
Stout et al. [61]	1988	UK	Bedford-Leck Hill, Calvin, Klinesville	*Festuca arundinacea*, *Panicum virgatum*
Zema et al. [62]	2012	Italy	San Lorenzo	*Arundo donax*, *Phragmites australis*, *Typha latifolia*
Zhang et al. [63]	2011	China	Huang-Huai-Hai	*Medicago sativa*, *Zea mays*