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Short communication

Simulation of biomass yield of regular and chilling tolerant *Miscanthus* cultivars and reed canary grass in different climates of Europe

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ABSTRACT

Miscanthus and reed canary grass (RCG) are C_4 and C_3 perennial grasses which are popular in Europe as energy crops. Although *Miscanthus* is relatively chilling tolerant compared to other C_4 species, its production in northern Europe is still constrained by cold temperature. A more chilling tolerant *Miscanthus* cultivar which can emerge early in the spring would utilize more solar radiation and produce higher biomass yields. In this study, using MiscanFor model, we estimated potential biomass yield of *Miscanthus* in current and future climates with the assumption that breeding would provide a chilling tolerant *Miscanthus* cultivar with a base temperature (BT) of 5 °C while currently the model applies a BT of 10 °C. Also, RCG biomass yield was simulated with the MiscanFor model parameterized for RCG. The results suggest that chilling tolerant cultivars of *Miscanthus* would produce higher biomass yield throughout Europe in the current climate but the benefit of increased chilling tolerant cultivars will be smaller in the future. Although predicted biomass yield of *Miscanthus* was considerably lower than RCG in northern Europe in the current climate, more chilling tolerant cultivars of *Miscanthus* could out-compete RCG yield in many north European regions.

1. Introduction

Perennial grasses are considered to be better crops as bioenergy feedstock because of their higher biomass yield potential and lower environmental footprint during crop cultivation compared with annual crops (Jørgensen, 2011). *Miscanthus* and reed canary grass (RCG) are popular perennial grasses cultivated as energy crops in Europe with C_4 and C_3 photosynthetic pathway, respectively (Lewandowski et al., 2003). Most of C_3-species are temperate crops and plant species, and C_4-species are mainly tropical grasses (Collatz et al., 1998). Although most C_4 crops are adapted in warmer climate, *Miscanthus* has some cold tolerance as evidenced by successful cultivation in temperate climate of northern Europe including northern Germany and Denmark (Jørgensen, 1997). However, production of *Miscanthus* in northern Europe is constrained by cold temperature and has not reached its production potential (Robson et al., 2013). *Miscanthus* emerges late in spring and senesce early in autumn in northern Europe resulting in shorter canopy period compared to C_3 grasses. Therefore, a *Miscanthus* cultivar which can emerge and survive early in the growing season and senesce in late autumn could utilize solar radiation for longer period and produce higher biomass. Studies have shown considerable variations in *Miscanthus* genotypes in cold tolerance and some attempts are being made to identify traits of *Miscanthus* varieties for higher chilling tolerance (Naidu et al., 2003; Robson et al., 2013; Głowacka et al., 2015; Jiao et al., 2016).

In northern Europe, RCG is a popular perennial energy crop because of its biomass productivity, potential to grow in water logged wetlands, tolerance to lower temperature, ease of establishment with seed and strong ability to compete with weeds (Kandel et al., 2013a,b). High yielding C_4 grasses such as *Miscanthus* are constrained by the cold climate of northern Europe but chilling tolerant C_4 crops may outcompete RCG yield in a future warmer climate in the region.

Although previous studies have reported simulated *Miscanthus* yield in Europe in present and future climate, there is no comparative study on how a regular and chilling tolerant *Miscanthus* cultivar produce biomass in the present and future climate in comparisons with C_3 perennial energy grasses. Therefore, this study aims to estimate biomass yields of *Miscanthus* (both a current cultivar and a chilling tolerant cultivar) and RCG in current and future climate in Europe. A modelling approach was used to estimate biomass yield

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Table 1
Parameters used to calculate mean annual yield of *Miscanthus* and reed canary grass (RCG) in MiscanFor model.

Parameters	*Miscanthus*	RCG
Radiation use efficiency (g/MJ)	2.35	1.25
Radiation extinction coefficient	0.680	0.597
Degree day factor (°C/days)	0.0102	0.0073
Minimum growth temperature (°C)	10.0[*]	5.0
Growth Duration (degree days)	1800	1800
Cold threshold (°C)	−3.0	−30.0

[*] For *Miscanthus*, the model was also run with 5 °C as minimum growth temperature with an assumption that breeding will provide chilling resistant cultivars in the future.

of *Miscanthus* and RCG using the MiscanFor© model (Hastings et al., 2009).

2. Methods

2.1. Biomass yield modelling using MiscanFor© model

Peak aboveground biomass yield of both *Miscanthus* and RCG was estimated using MiscanFor crop growth model (Hastings et al., 2009). MiscanFor is a process based model which follows the energy use efficiency approach of Monteith (1977) to calculate dry biomass accumulation. The model was already successfully tested for *Miscanthus* with European site data from the species *M.* x *giganteus* (Hastings et al., 2009).

The MiscanFor model uses meteorological and soil data to calculate biomass yield at 0.5° grid size. The meteorological data includes daily mean temperature, temperature range, precipitation, potential evapotranspiration and cloud cover. Data on cloud cover is used to calculate radiation by SWAT Theoretical Documentation method (Neitsch et al., 2002), including a cloud correction factor (Hastings et al., 2009). MiscanFor includes a drought stress function, temperature variable RUE and the inclusion of photoperiod in the plant physiology model which are improvements over MiscanMod model (Clifton-Brown et al., 2000).

For this study, MiscanFor was also parameterized for RCG to calculate dry aboveground biomass production. Radiation use efficiency for RCG was derived from the study of Kätterer et al. (1998). Degree day factor (°C/days) was derived using the data from a Finnish study (Sahramaa, 2004) with 75 introductions of RCG (both cultivated and wild) cultivated for 5 years in Jokioinen, Finland. Extinction coefficient was used from the study of Jing et al. (2012). Base temperature (BT) for RCG was set to 5 °C which is commonly used value for cold season grasses in plant growth modelling. Crop parameters used for *Miscanthus* and RCG in this study are shown in Table 1.

The Model was run for a baseline period (1971–2000) and a future climate model projection for 2050. The future climate model projections were based on the A2 emission scenario which represents a high end or "business as usual" scenario of moderate to high continued greenhouse gas emissions (Meehl et al., 2007), and observed climate over past years is the best match for this scenario.

The Model was also run for both baseline and the future climate scenario with 5 °C as minimum growth temperature of *Miscanthus* with an assumption that breeding would provide chilling resistant *Miscanthus* cultivars, which do not suffer in other parameters from this adaptation. The biomass yield predicted with the MiscanFor model in different runs were mapped using ArcMap (ESRI Inc., USA). Similarly, biomass yield of both crops in individual grid cells in different scenarios are compared with 1:1 comparisons. The comparisons was presented for four latitude ranges (35–45, 45–55, 55–65 and above 65° N) to understand the difference in European regions.

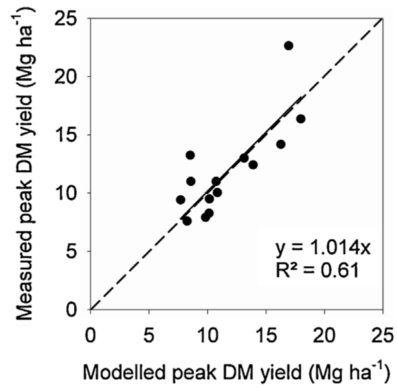

Fig. 1. Modelled and observed peak autumnal yields of reed canary grass dry matter (Mg ha^{-1}) for European sites (n = 14). Data used for model validation are taken from the studies presented in Table 2.

3. Results and discussions

Modelled and observed peak autumnal yields of RCG dry matter (Mg ha^{-1}) for European sites is presented in Fig. 1. A linear regression gives a unity relationship with an $R^2 = 0.61$ (n = 14) with a linear coefficient of 1.014. In general, the 1:1 plots showed a good agreement between the measured and modelled biomass yield.

The distribution of simulated autumnal peak yield of *Miscanthus* and RCG in baseline condition (1971–2000) and A2-scenario (2050) across Europe is shown in Fig. 2. Similarly, 1:1 comparison of the yield results for individual grid cells are presented in Fig. 3. The results suggest that a *Miscanthus* cultivar with higher chilling tolerance (base temperature, BT: 5 °C) would produce higher biomass across entire Europe compared to the current cultivars in the baseline period (Fig. 3a). On average, 50% (range 23–105%) increase in biomass yield was predicted when base temperature for growth of *Miscanthus* is changed from 10 to 5 °C. As expected, maximum increase in biomass yield of *Miscanthus* would be in the northern Europe as *Miscanthus* yield is currently constrained by cold climate in the region (Robson et al., 2013). This model output corroborates the results from previous studies that there is potential to improve yield with chilling tolerance cultivars (Clifton-Brown and Lewandowski, 2000; Robson et al., 2013). Cold tolerance traits eventually affect the length of the growing season and genetic variability in annual light interception has been shown within *Miscanthus* (Jørgensen et al., 2003). The assumption of adapting for improved chilling tolerance of C_4 photosynthesis is not unrealistic as studies of *Miscanthus* physiology have shown that there is no fundamental barrier to extending the beneficial aspects of C_4 photosynthesis into colder climates (Long and Spence, 2013), and recent studies have shown that chilling tolerant cultivars can maintain photosynthesis down to 5 °C and can survive night-time frost (Naidu et al., 2003; Głowacka et al., 2015; Jiao et al., 2016).

The future climate (A2 scenario in 2050) will have diverse effect in *Miscanthus* yield in various European regions, but northern Europe will be largely benefitted (Fig. 3b). In the future climate, chilling tolerant cultivars would produce higher biomass compared to regular cultivars, but the difference is reduced compared to the baseline period yield (Fig. 3a and c). However, chilling tolerant *Miscanthus* cultivars can be cultivated in more areas in northern Europe above 55°N in future climate (Fig. 3c).

In the baseline period, biomass yield of *Miscanthus* is considerably higher in southern Europe but RCG usually produce more biomass in the northern Europe (Fig. 3d). In the future climate, however, more chilling tolerant cultivars of *Miscanthus* could outcompete RCG yield in some north European regions (Fig. 3e) but chilling tolerant *Miscanthus* would still not be a suitable biomass