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Comparing predicted yield and yield stability of willow and Miscanthus across Denmark

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Abstract

To achieve the goals of energy security and climate change mitigation in Denmark and the EU, an expansion of national production of bioenergy crops is needed. Temporal and spatial variation of yields of willow and Miscanthus is not known for Denmark because of a limited number of field trial data. The semi-mechanistic crop model BioCro was used to simulate the production of both short-rotation coppice (SRC) willow and Miscanthus across Denmark. Predictions were made from high spatial resolution soil data and weather records across this area for 1990–2010. The potential average, rain-fed mean yield was 12.1 Mg DM ha^{-1} yr^{-1} for willow and 10.2 Mg DM ha^{-1} yr^{-1} for Miscanthus. Coefficient of variation as a measure for yield stability was poorest on the sandy soils of northern and western Jutland, and the year-to-year variation in yield was greatest on these soils. Willow was predicted to outyield Miscanthus on poor, sandy soils, whereas Miscanthus was higher yielding on clay-rich soils. The major driver of yield in both crops was variation in soil moisture, with radiation and precipitation exerting less influence. This is the first time these two major feedstocks for northern Europe have been compared within a single modeling framework and providing an important new tool for decision-making in selection of feedstocks for emerging bioenergy systems.

Keywords: BioCro, bioenergy, C4 photosynthesis, crop model, geospatial modeling, mechanistic model, Miscanthus, perennial grasses, short-rotation coppice, Willow, Wimovac

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Introduction

The European Union has agreed upon ambitious policies on energy supply, climate change mitigation and environmental sustainability. To meet the targets, EU countries have issued so-called National Renewable Energy Action Plans (NREAP) specifying the development of renewable energy generation till 2020 (Beurskens & Hekkenberg, 2011). Biomass is a cornerstone of the NREAPs and is stipulated to account for 56% of renewable energy generation by 2020 (Beurskens & Hekkenberg, 2011), corresponding to an increase in bioenergy generation from 2.4 EJ in 2005 to 5.7 EJ in 2020. It has been estimated that the biomass consumption will increase from 3.8 EJ in 2005 to 10.0 EJ in 2020 due to the increase in bioenergy generation during this period (Bentsen & Felby, 2012).

Bioenergy is also expected to play a significant role in the Danish efforts to secure supply and mitigate climate change. To comply with EU policy, Denmark's target for the share of renewable energy is at least 30% of the gross final energy consumption by 2020 (European Parliament and the Council, 2009).

Willow and Miscanthus cultivation in Denmark

Willow (*salix spp.*) and Miscanthus (*Miscanthus* × *giganteus*, (Greef et. Deu.)) have not yet gained momentum as energy crops in Denmark, and only a very small area is used for cultivation of these. Both are considered key opportunities for achieving an increase in sustainable national biomass production and are used more extensively the neighboring countries (Alexander *et al.*, 2014; Sevel *et al.*, 2012; The Danish AgriFish Agency, 2013). Perennials are favored because of their long growing seasons, efficient recycling of nutrients, stabilization of soil and ability to

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accumulate soil carbon (Heaton *et al.*, 2010; Jørgensen *et al.*, 2013; Voigt, 2015).

Achieving the 2020 bioenergy supply, goal of Denmark might require planting of large additional areas of these feedstocks. Many factors will determine the appropriate feedstock for a given location. However, major considerations are yield and stability of yield at each location. Without widespread trials, it is difficult to know which would have the higher yield at a given location. Mechanistically rich models provide the means to predict beyond experience. Such models have been developed for Miscanthus (Clifton-Brown *et al.*, 2000, 2004; Richter *et al.*, 2008; Hastings *et al.*, 2009a,b; Bauen *et al.*, 2010; Pogson, 2011) and for willow (Lindroth & Båth, 1999; Aylott *et al.*, 2008; Mola-Yudego & Aronsson, 2008; Mola-Yudego, 2010; Tallis *et al.*, 2013), but each within its own unique modeling framework.

We use the mechanistic model BioCro, which is a generic crop model based on the WIMOWAC model, Humphries & Long (1995), adapted for Miscanthus by Miguez *et al.* (2012, 2009) and for willow by Wang *et al.* (2015). BioCro was designed to provide a single framework for predicting growth and yield of perennial bioenergy crops to avoid confounding species differences with differences in modeling assumptions and structure. It has been successfully applied previously to compare switchgrass and Miscanthus in the USA (Miguez *et al.*, 2012). Here, it is applied to compare Miscanthus and willow in Denmark, so providing a further key tool in decision making on the choice of feedstock for different locations.

This is the first time the model has been used to model both Miscanthus and willow in Europe, and this approach allows us to model potential yields for both crops within the same modeling framework. When comparing yields simulated by different models, one often risks comparing model structures and assumptions instead of comparing model results and biological differences between crops (Nair *et al.*, 2012; Wang *et al.*, 2015). This risk is avoided using one model for the two different crops.

This study (a) maps potential yield and yield stability of Miscanthus and willow in Denmark, using weather data for 1990–2010 to quantify the effects of year-to-year variation in weather, combined with high resolution soil maps, (b) compares the potential yields of the two crops across the country and (c) determines which factors appear most important in determining yield and yield stability of these crops.

Materials and methods

Model description

The BioCro model is extensively described by (Humphries & Long, 1995; Miguez *et al.*, 2009, 2012; Wang *et al.*, 2015), therefore the following only provides a short overview, focusing on the set up for this study.

Miscanthus and willow in BioCro are simulated through its detailed mechanistic biochemical and biophysical multilayer canopy model that partitions assimilate between different plant organs (stem, leaf, root and storage) according to phenological development stages as determined by thermal time. Using hourly weather data, the model calculates direct and diffuse light for dynamically changing sunlit and shaded portions of the canopy layers and computes carbon and water exchange with the atmosphere by interface with leaf biochemical and biophysical submodels for each hour of the day and each day of the growing season. The canopy module is dynamically linked to a multilayer soil/hydrology module. Soil water status coupled with canopy properties is used to calculate leaf water potential which modulates stomatal conductance and which together with temperature and assimilate supply determines rates of leaf expansion and senescence.

Soil data

BioCro requires soil rooting depth, wilting point and field capacity for each location simulated. In Denmark, there is no national database that includes these properties, but instead a database has been established with soil textural properties in three layers: 0–30 cm, 30–70 cm and 70–120 cm, bulk density and rooting depth. This database is based on all available soil data (around 54 000 soil samples in total). The two topmost layers are constructed by kriging interpolation, and for the bottommost layer, median georegionalized values are used. This allows for a national map with soil textural properties in three layers with a resolution of 250 m × 250 m for the top layer and 500 m × 500 m for the two bottommost layers. All soils are ascribed to one of the 9–10 soil types most prevalent in each of Denmark's 5 georegions or one of two different wetland (which are generated separately from the minerogenic soil types) soil types (Børgesen *et al.*, 2009).

To simplify the calculations and to use the same method as previously used for BioCro, a weighted average rooting depth was calculated for each soil type and used as input to the model. The soil water content at the beginning of the growing season was set to field capacity each year which in most years is reasonable because of a precipitation surplus during the winter making the soils saturated when the growing season starts (Madsen *et al.*, 1992). The rooting depth for each soil type is taken from Børgesen *et al.* (2009) and has previously been used for crop modeling. Rooting depth varies between 50 cm and 150 cm depending on soil type. Soil hydrological parameters, field capacity and wilting point, are determined on the basis of textural properties using the equations shown in Supporting information, eq. 1 and 2.

Weather data

Daily weather data for the simulations were obtained from the Danish Meteorological Institute, Scharling (2012), for 1990–2010 for total precipitation, average temperature, accumulated potential evaporation, average wind speed and accumulated global radiation. Daily precipitation is the only data from the 10 km × 10 km grid, and the other data are from the 20 km × 20 km grid. From the Danish 40 km × 40 km climate grid, we got daily mean relative humidity and daily minimum and maximum (Plauborg & Olesen, 1991; Scharling, 1999). Daily minimum and maximum relative humidity were calculated from the recorded temperature and absolute humidity (Allen *et al.*, 1998). Day of the year, hour and latitude were used to determine the hourly solar declination and solar zenith angle. Hourly weather data were estimated from the daily data by the interpolation methods included in BioCro and described in (Humphries & Long, 1995).

Regional simulations

BioCro was parameterized as described and validated previously (Miguez *et al.*, 2009, 2012; Wang *et al.*, 2015). The full equation set and parameter tables are given in these prior publications. Simulations were performed to predict the course of growth and final yield for each year from 1990 to 2010 at the high resolution provided by the geospatial soil data available for the country (250 m × 250 m).

To perform the simulations, a climate grid was generated in ArcGIS, ESRI (2010), so that each 10 × 10 km climate cell was also filled with data from the 20 × 20 and 40 × 40 km climate data. This gives 609 unique climate cells covering Denmark and each soil cell is given climate values from the climate cell that it lies within. A very limited part of the land area was not covered by the climate grid, that is small tongues of land and small forelands. These small areas were assigned the values from the adjacent climate cell and covers <1% of the simulated area.

The highest resolution of climate data available was 10 km × 10 km. As several soil cells (250 × 250 m) within one climate cell (10 × 10 km) often would be of the same type, to avoid repeating calculations, the result from one soil cell would be applied to all other cells with the same soil type within the climate cell. This reduced the number of cells simulated from potentially about 80 000 to 4852. For each cell, BioCro calculates net carbon exchange, canopy microclimate and evapotranspiration on an hourly basis, and growth, biomass partitioning, canopy structure and soil moisture dynamics on a daily basis. As such, it is computationally intensive. To complete calculations, it was necessary to parallelize the code to allow computation on a cluster (at time of computation the cluster consisted of Dell Poweredge 1950 servers with 24 nodes each with 8 cores of 2.8 GHz CPUs).

In the simulation, willow was assumed to be grown on a 3 year coppice cycle, but annual yields are given by averaging across the 3 years. After the first year, the willow is cut back to induce coppicing. Miscanthus was simulated for an annual harvest. It was assumed that both crops would be harvested in the late winter or early spring as often done in Denmark (Larsen *et al.*, 2013, 2014a).

To determine the harvestable yield of willow, it was assumed that there was a 10% loss during harvest, and for Miscanthus, it was assumed that 67% of the peak biomass could be harvested due to losses during senescence and harvest (Beale & Long, 1995; Venendaal *et al.*, 1997; Hastings *et al.*, 2009b; Miguez *et al.*, 2012). Winter losses in willow are not well documented and leaf biomass lost due to frost is the same as in Wang *et al.* (2015). The assumption regarding harvest loss used here is based on practical experience in experimental and commercial plantations in Denmark, personal communication with L. Sevel and S. U. Larsen. The results were summarized by calculating mean annual yield for each location across the 21 years together with the coefficient of variation as a measure of yield stability, that is, year-to-year variation driven by weather conditions relative to averaged yields. Yield maps were generated at 250 m × 250 m resolution equal to that of the soil data.

Climatic and soil variable sensitivity

To determine which soil and climatic variables were most important in determining yield, we calculated a number of parameters to test with a generalized linear model (GLM). These were precipitation and radiation sum during the growing season (April–October), the available water content (AWC – difference between field capacity and wilting point for the soil profile from surface to rooting depth), and lastly, we included the Danish georegion because the soil data are generated in such a way where only the 10 most abundant soil types of each georegion are present in each (Børgesen *et al.*, 2009). The GLM procedure was performed in R (R Core Team, 2013) with the above mentioned parameters. The procedure is performed for both willow and Miscanthus.

Results

Yield predictions

Large spatial variation of harvestable yields and yield stability were found. In general, the sandy soils of western and northwestern Denmark show much lower harvestable yields than the more clay-rich soils of central and eastern Denmark (Fig. 1a,b). This holds true for both crop species. The area-weighted mean yield was 12.1 Mg DM ha^{-1} yr^{-1} for willow and 10.2 Mg DM ha^{-1} yr^{-1} for Miscanthus. The lowest annual willow yields were much higher than the lowest Miscanthus yields. This is in part because the willow yields are a mean of 3 years of production so years with weather conducive for high yield offset those causing poorer yields and *vice versa*.

Stability of yields

The coefficient of variation (CV) for annual biomass yield was calculated for Miscanthus. For willow, the results were calculated on the basis of the yield of a 3 year period corresponding to a cutting cycle. These results show that the largest coefficient of variation, and therefore lowest yield stability, was found in western

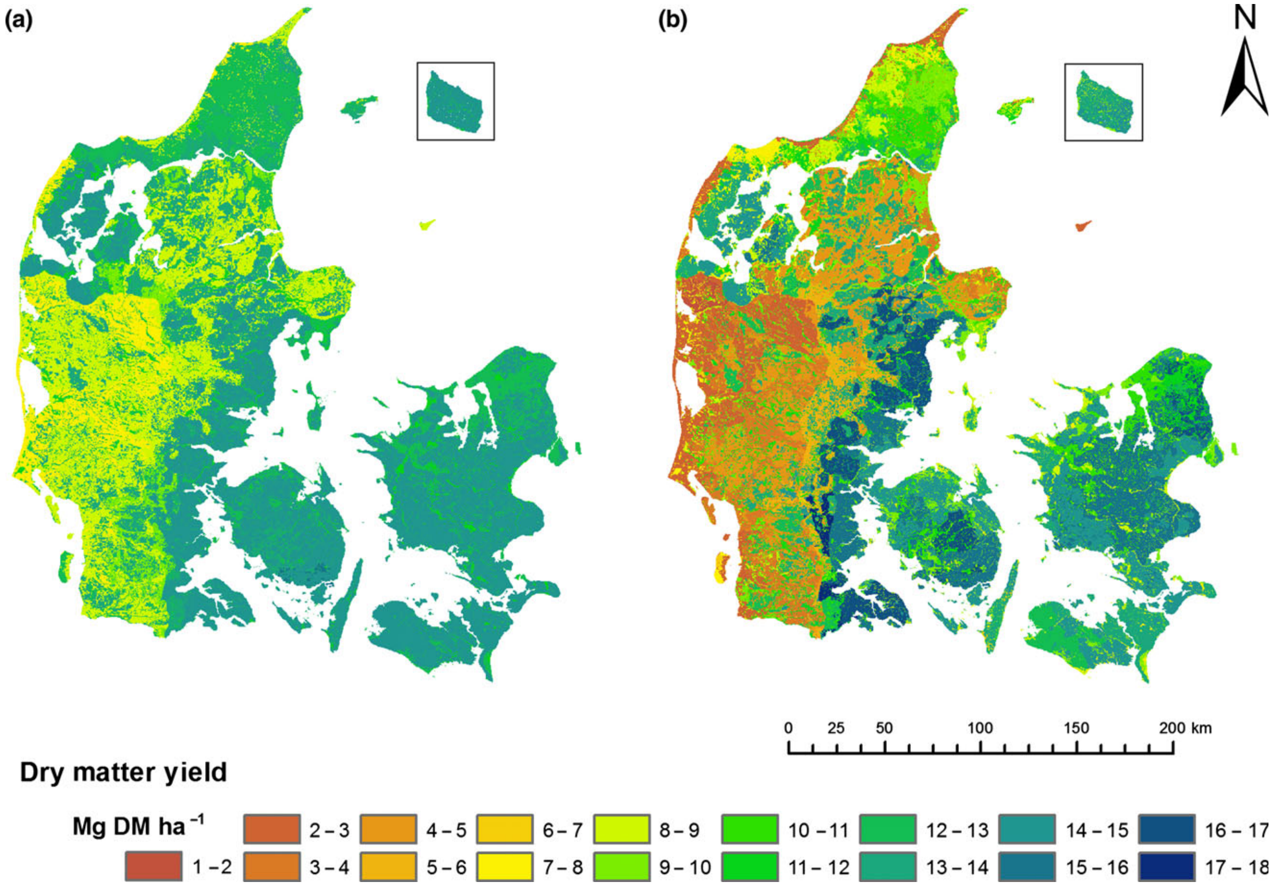

Fig. 1 Simulated mean annual harvested biomass (Mg DM ha^{-1} yr^{-1}), as dry weight, for (a) SRC willow and (b) Miscanthus over the period 1990–2010.

Denmark for both crop species, (Fig. 2a,b). However, stability was lower at all locations for Miscanthus. The poor, sandy soils are primarily found in western and northwestern Denmark (Fig. S1b).

Difference in harvestable yields

The difference in yield was calculated as a difference between the mean harvestable yields for 1990–2010 for the two species, that is, the difference between the yields illustrated in Fig. 1(a,b).

The results show that on the poor soils in western and northwestern Denmark, willow has an advantage over Miscanthus (blue shading), but on better, clay-rich soils of central and eastern Denmark, Miscanthus has a higher productivity than willow (red to green shading), Fig. 3.

Relationship between crop yield and biophysical factors

The results of the GLM procedure show that AWC is the most important factor for yield in both willow and Miscanthus. The higher the AWC, the higher the simulated yields. Precipitation, radiation sum and georegion are also significant, but exert less influence. See Fig. S1 (a) for an AWC map of Denmark.

Discussion

Model performance

The yields predicted by the model are potential yields in the sense that they are only water limited. The model assumes good agronomy with adequate fertilization and no pests, diseases or damage from extreme climatic events (Miguez *et al*., 2009). This leads to a discussion of how realistic the yields we report for the two crops are, when there is only very limited yield data available, especially for Miscanthus. Karp & Shield (2008) and Lobell *et al.* (2009) discuss the difference between theoretical, potential and actual yield. The yields simulated here are theoretical water-limited yields, and consequently, they are higher than both potential and practically achieved yields. However, predicted growth and final yield predicted with BioCro were very close to those observed in research trials, at separate sites, for both Miscanthus (Miguez *et al*., 2009) and willow (Wang

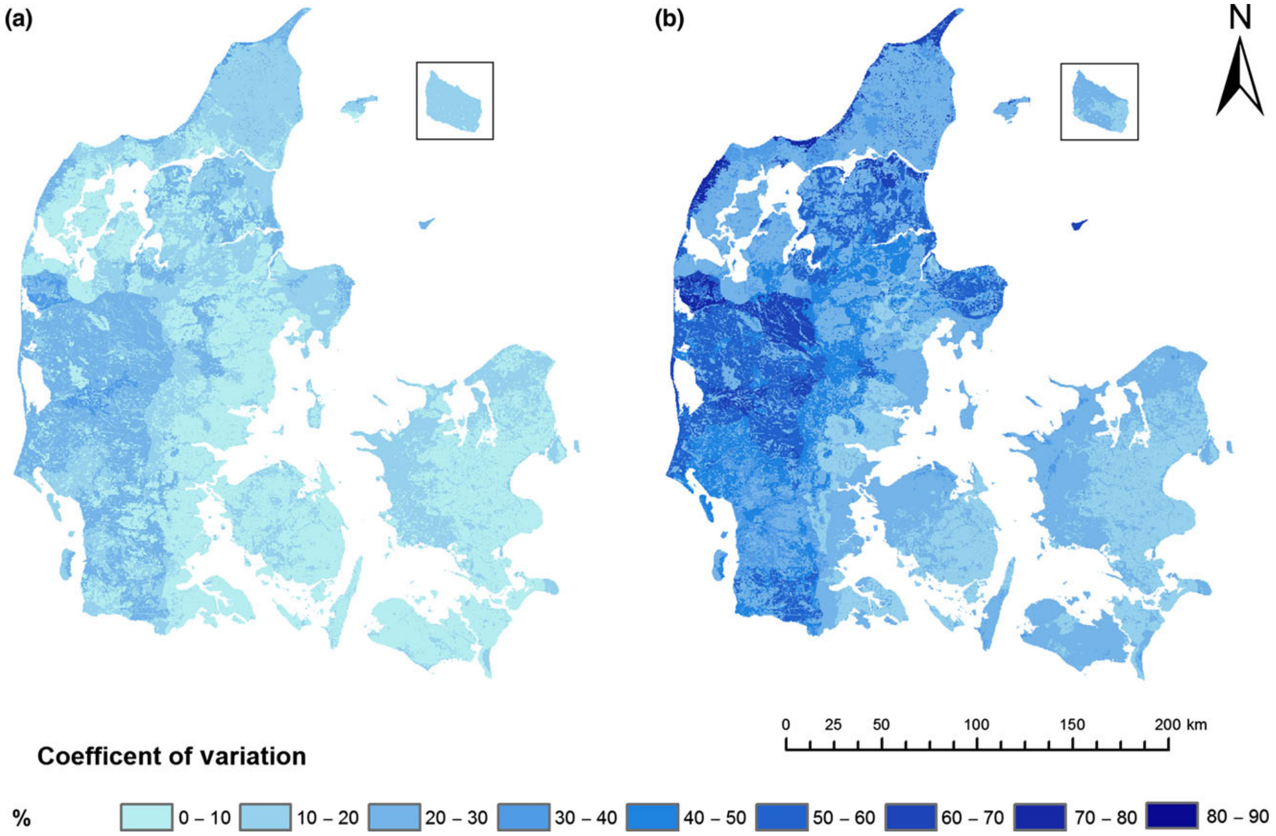

Fig. 2 Coefficient of variation in % of annual biomass productivity for the years 1990–2010 for (a) SRC willow on a 3 year coppice cycle, and (b) Miscanthus on an annual harvest cycle.

et al., 2015). Yields in research trials are commonly found to exceed those experienced in practice, but are a good representative of what may be achieved with good agronomy.

Comparison with yields in Denmark

In Denmark, a small number of experiments and trials have looked into willow productivity. Sevel *et al.* (2012) report average productivities between 5.2 and 8.8 Mg DM ha^{-1} yr^{-1} in a commercial plantation over a two-year rotation. Other willow trials in commercial plantations in Denmark have found average yields of 2–8 Mg DM ha^{-1} yr^{-1}, but with a large variation in yields indicating that the potential yield is much higher than the reported averages (Morsing & Nielsen, 1995, Venendaal *et al.*, 1997; Landbrug og Fødevarer, 2010, 2012). Other studies have found higher average yields of around 10–12 Mg DM ha^{-1} yr^{-1} for the best yielding clones and treatments (Sevel *et al.*, 2013) (Larsen *et al.*, 2014b). These trials are in line with the yields modeled with BioCro and show the potential for the best yielding clones in Denmark under close to optimal management regimes. In a general sense, the trial results show higher yields on clay-rich soil, exactly as BioCro predicts hereby showing that BioCro is well suited to take the spatial variability of Danish soils into account (Mortensen *et al.*, 1998, Landbrug Og Fødevarer, 2012).

For willow, we have compared measured and modeled yields at one location in Denmark, Fig. S2. This shows that BioCro overestimates willow yields at this location, but also shows that the best yielding treatments and years are able to produce at a level similar to that predicted by BioCro.

The only other modeling study covering Denmark predicts an average productivity of 9.5 Mg DM ha^{-1} yr^{-1} if the production is only water limited, but higher yields can be achieved when considering the best growers or 2010 production (Mola-Yudego, 2010). This model uses a completely different method to achieve its results and uses much larger spatial units, but still achieves results comparable to both the ones of BioCro and trials; especially if you compare optimally managed trials and models where optimal management is an assumption such as BioCro.

There have only been a few studies of Miscanthus cultivation in Denmark. Larsen *et al.* (2013) studied the long term (1993–2012) yield of Miscanthus (*M. giganteus*

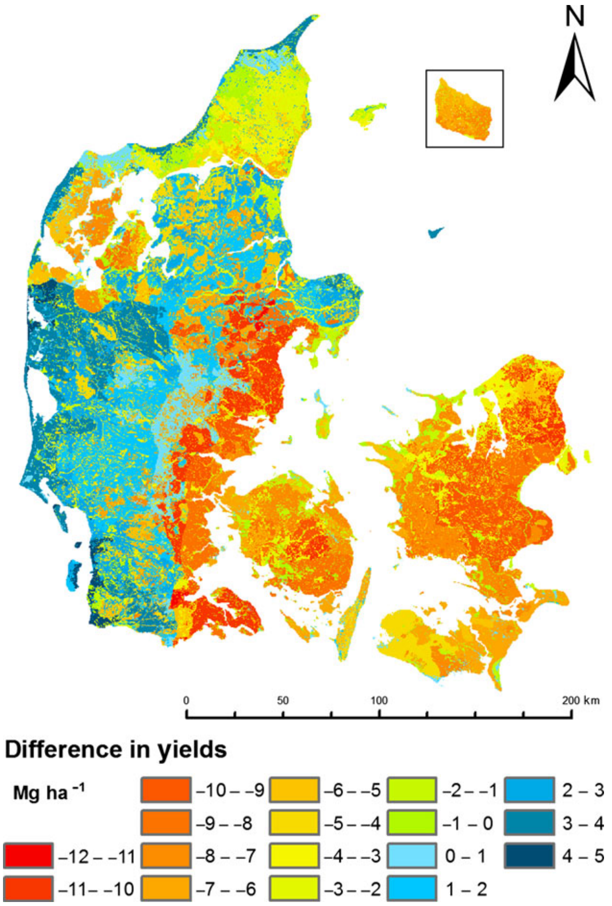

Fig. 3 Difference in mean productivity of willow and Miscanthus 1990–2010, using the data of Fig. 1. Numbers are relative to the predicted yield of willow at any one location. Therefore, a negative value is where Miscanthus is more productive than willow and *vice versa*.

and *M. goliath*) at two locations in Denmark and found that the highest yielding *M.* x *giganteus* treatment had a mean yield of 13.1 Mg DM ha^{-1} yr^{-1} with late autumn harvest. Spring harvest is shown to reduce the yield by 34–42%, which is a little higher compared to the assumption of 33% used here, but the fraction lost depends on the exact harvest dates.

Venendaal *et al.* (1997) report mean yields of 7–8 (sandy soil) and 8–9 (clay soil) Mg DM ha^{-1} yr^{-1} for spring harvested Miscanthus in Denmark under commercial conditions.

Again, we have compared measured and modeled yield for one location in Denmark, Fig. S3. BioCro overestimates the yields, except for one year. There can be a number of reasons for this, for instance nonoptimal management of the experiments, poor BioCro performance for this location and soil or a yield decline as discussed below. One should exercise great caution to conclude anything from this comparison, but it is evident that for this location BioCro vastly overestimates productivities of Miscanthus.

Larsen *et al.* (2013) also report a yield decline after 5–8 years and Arundale *et al.* (2014) similarly reports a decline. As a relatively new crop, these are the only studies to report beyond 5 years of experience and so it is difficult at this point to understand whether this should be expected wherever the crop is grown or if this is specific to given climates, soils or agronomy. Given the limited information, this effect cannot be simulated in BioCro so it would be more appropriate to compare BioCro simulations with the yields achieved in the maturity phase in Larsen *et al.* (2013), which are 8–12 Mg DM ha^{-1} yr^{-1} for spring harvested *M.* x *giganteus* in a location in the central western part of Denmark (Foulum) and thus more comparable to the yields simulated by BioCro.

Crop yield and biophysical factors

As shown in other studies, climate parameters are important for determining yield (Hastings *et al.*, 2009b; Miguez *et al.*, 2012; Wang *et al.*, 2015).

The GLM procedure shows that precipitation has a negative influence on yields. This might seem strange, but the reason for this should be that the regions in Denmark with the highest precipitation (the western and central parts of the peninsula Jutland) are also regions where sandy soils dominate. So even if there is high precipitation, the sandy soils dictate that the plant available water storage capacity is low.

Miscanthus and willow harvest losses

We assume that 10% of the stem biomass is lost for willow and 33% for Miscanthus between the time of peak biomass and harvest, due to stubble and translocation during senescence and shoot fragmentation in the case of Miscanthus. For Miscanthus, the assumption is corroborated by experimental trials in Denmark and abroad (Lewandowski & Heinz, 2003; Heaton *et al.*, 2009; Larsen *et al.*, 2013). Our assumption of 10% harvest loss is based on practical experience as mentioned above. However, it is reasonable to anticipate smaller losses in willow. The stem serves as the key perennation organ, so less material is translocated below ground in the autumn while the woody and living stems will be far less vulnerable to fragmentation losses in high winds.

The reason for reporting the harvestable yield instead of total aboveground biomass is to make it easier to compare the amounts of biomass that would be available for bioenergy processing for the two crops. In particular, for Miscanthus, there is a difference concerning mass and quality of the biomass depending on harvest time. Autumn harvest results in higher yields of wetter biomass, whereas delaying harvest until late winter or spring results in a smaller but drier biomass yield (Heaton *et al.*, 2010). Winter harvest is better for thermal conversion of the biomass, whereas autumn harvest can be better suited for fermentation of sugars in the biomass (Lewandowski *et al.*, 2003; Le Ngoc Huyen *et al.*, 2010; Hodgson *et al.*, 2011).

Difference in yields

In the case of willow, Sevel *et al.* (2012) showed a higher production on organic soil compared to sandy soil in southern Sweden. These results support the findings of this study that willow biomass production is higher on clayey soils compared to sandy soils and that willow productivity is positively correlated with available water content. Miscanthus is considered more water use efficient, because of its use of C4 photosynthesis. These biochemical differences and their effects on leaf level water use efficiency are described fully in BioCro (Miguez *et al.*, 2009; Wang *et al.*, 2015). On the other hand with a longer growing season, willow can take advantage of a longer period of precipitation, which will have particular benefit in the early spring when potential evapotranspiration is low. This may explain the superior yields predicted for willow on the lighter soils of western Denmark (Fig. 3). Average growing season temperatures are also lower on the western part of Denmark, and this would also favor willow over Miscanthus (cf. (Miguez *et al.*, 2009; Wang *et al.*, 2015)).

Water availability is important to the yields of both crops. Although Denmark may be considered an area of high precipitation relative to potential evapotranspiration, the stochastic nature of precipitation events means that transient periods of water shortage occurs. These are ameliorated on deep and clay or organic matter rich soils by better water storage capacity. This is offset on the most clay-rich soils, by the fact that clay particles bind water generating a low matric potential and causing less of the water present to be available to the plant. Water availability is therefore a combination of soil type, precipitation and evapotranspiration. These transient effects are captured by BioCro, which dynamically simulates water transfer between ten soil layers in the rooting zone. Effects of soil composition on the availability of water are accounted for by calculating water potential from volumetric soil water content in each layer from first principles (Miguez *et al.*, 2009).

Yield stability

The coefficient of variation (CV) in annual yields is a measure of yield stability, or the year-to-year variation in yield. This is an important property with respect to biomass facilities, because it affects the security of supply. For both crops, yield stability was lowest on the poor, sandy soils. In this situation, willow has a major advantage, since on a 3-year cycle, it will tend to average poor with good years. This is an artifact of how yields are calculated. In addition, willow biomass can in effect be stored live until sufficient yield is obtained. However, Miscanthus has to be harvested each year. The higher variability is driven by the poorer ability of these soils to store water, making them more vulnerable to transient droughts. Arundale *et al.*, 2014 showed larger year-to-year variation in yields in Illinois on the sandy soil of Havana compared to the deep loam soil of Urbana over a 7-year study.

In previous applications, BioCro has shown the lowest CV on the soils giving the highest yields of both willow and Miscanthus within a region (Miguez *et al.*, 2012; Wang *et al.*, 2015).

Limitations of BioCro

If there had been a large body of field data for these crops across Denmark, an empirical model interpolating between this data may have been more appropriate. Inevitably, it does leave the question of what faith can be placed in largely untested predictions. However, parameterization of the model based on data from one site in south England allowed a remarkably close prediction of the measured growth and production of Miscanthus across sites from Portugal and Greece to Ireland and south Sweden, capturing the experienced year-to-year variation at individual sites (Miguez *et al.*, 2009). As in the present study, the model was run with soil and weather data for the individual sites. The BioCro model has not been validated for Denmark as a part of this analysis because of limitations in field trial data, but data from temperate regions all over the world have been used to develop and validate the model as described in (Miguez *et al.*, 2009; Wang *et al.*, 2015).

Another limitation of BioCro is that it does not take frost kills of Miscanthus into account when simulating yields and establishment. Several studies and reviews indicate that Miscanthus has problems with frost during establishment in Europe and Denmark (Venendaal *et al.*, 1997; Heaton *et al.*, 2004; Larsen *et al.*, 2013). Miscanthus has, however, been able to survive very low temperatures and there should be breeding resources available to improve the cold tolerance of several Miscanthus species by different techniques (Heaton *et al.*, 2008, 2010; Głowacka *et al.*, 2014). So although the cold tolerance aspect is a limitation of the model, there is scope for improvement of the cold tolerance of Miscanthus. Other modeling studies show that frost kill is taking place in

Denmark and Europe, but new hybrids and a changing climate may limit these impacts in the future (Hastings *et al.*, 2009a,b).

Willow does not have the same problems with frost because cold tolerant hybrids have been developed and willow has also been grown for many years in climates far colder than Denmark (Ledin, 1996; Larsson, 1998). Some Danish experiments have, however, shown problems with frost damage in Denmark (Sevel *et al.*, 2012).

Model uncertainties

The BioCro model has some uncertainties on top of those limitations reported above. Some of these uncertainties are mentioned in (Miguez *et al.*, 2009, 2012; Wang *et al.*, 2015).

There is a specific uncertainty connected with the low-lying, organic soil types. The hydrological properties of these soils are not well simulated because they are groundwater fed and available water is very important for yield. This leads to added uncertainty for the 16.2% of the area occupied by these soil types (Madsen *et al.*, 1992; Børgesen *et al.*, 2009). But, low-lying, organic soils with high ground water tables can be productive in Denmark, at least for willow (Sevel *et al.*, 2012).

Similarly, other aspects of soil properties are uncertain: Soil hydrological parameters are established using equations based on a limited dataset and the rooting depth is established as a general value for crops, not specifically for perennial bioenergy crops (Madsen *et al.*, 1992; Børgesen *et al.*, 2009). We have, however, used the same data for both crops, so any uncertainties are the same for both crops.

Yield improvements and scope of Miscanthus and willow cultivation in Denmark

As discussed above, there is a gap between the model simulations and achieved yields for both crops. Agronomy of both crops is in its infancy and yields will increase from increased experience. Further breeding for improved yield and climatic tolerance has only just begun for Miscanthus. Therefore, there is considerable potential for closing the yield gap. The mechanistic basis of BioCro allows reparameterization to include new developments in genetics and agronomy, and allow recasting of the projected yields presented as innovations emerge.

For willow, there is a clear trend of increasing yields in Sweden caused by both improved genetic material and management. The historic yield increase has been shown to be 0.34 Mg DM ha^{-1} yr^{-1} for Swedish growers from 1986 to 2000 (Mola-Yudego, 2011). Similar results are seen in the UK where breeding efforts have improved the yield with 2 Mg DM ha^{-1} yr^{-1} from 1974 to 2005 (Karp *et al.*, 2011).

There is much less experience with growing Miscanthus in Denmark and Europe. But it is often stated that there is a large potential for Miscanthus to improve its productivity (Heaton *et al.*, 2008, 2010). This is partly due to Miscanthus being genetically unimproved, so a breeding and selection effort is likely to improve its productivity or other key traits (Heaton *et al.*, 2010). For example, germplasm with greater freezing and chilling tolerance has recently been identified in tests within Denmark (Głowacka *et al.*, 2014).

In 2013, there was only a small area in Denmark grown with willow (5633 ha) and Miscanthus (66 ha), but it is expected that perennial biomass crops can play a vital role in the future agriculture of Denmark where biomass crops are used in a biorefinery concept and can be used for both feed and fuels (Alexander *et al.*, 2014; Gylling *et al.*, 2013; Jørgensen *et al.*, 2013). This study shows what yields can be expected if willow and Miscanthus areas are expanded to areas where there currently is no production. Furthermore, Denmark has a high proportion of CHP and district heating plants that are able to use wood chips and straw as a feedstock for energy production and even more is expected in the future (Danish Energy Agency, 2012, Energistyrelsen, 2012). These aspects make it very important to be able to accurately estimate the feedstock production of biomass crops. A crop model is very useful in this regard because it offers opportunities to investigate how much feedstock that can be produced, but also offers information on the yield variation and spatial patterns exhibited by these crops. This aspect will be very important for making decisions on where and which feedstock to grow in Denmark. It is obvious that perennial biomass crops such as willow and Miscanthus can help to achieve the ambitious climate change mitigation policies of Denmark. The most recent analysis of bioenergy in Denmark suggests increasing use of biomass in the Danish energy system in both near- and medium-term future. Similarly, there will be an increase in area available for biomass production, so there are ample opportunities to increase production (Dalgaard *et al.*, 2011; The Danish Energy Agency, 2014).

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Available water content (in m of plant available water from soil surface to rooting depth) and (b) simplified soil map of Denmark.
Figure S2. Measured and modeled yield of willow at one location in Denmark for the years 1998, 2001, 2004, 2007 and 2009. A 1 : 1-line is added to represent the 'perfect' fit.
Figure S3. Measured and modeled yield of Miscanthus at one location in Denmark for the years 1995–2000, 2003, 2005 and 2008. A 1 : 1-line is included to represent the 'perfect' fit.