Modeling long-term yield trends of *Miscanthus × giganteus* using experimental data from across Europe

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ARTICLE INFO

ABSTRACT

Miscanthus × giganteus is a perennial grass that is considered to have a high feedstock potential for bioenergy production. Assessment of that potential is however highly related to the crop yields and to their change through the crop lifetime, which is expected to be longer than 20 years. *M. giganteus* is known to have an establishment phase during which annual yields increased as a function of crop age, followed by a ceiling phase, the duration of which is unknown. We built a database including 16 European long-term experiments (i) to describe the yield evolution during the establishment and the ceiling phases and (ii) to determine whether *M. giganteus* ceiling phase is followed by a decline phase where yields decrease across years. Data were analyzed through comparisons between a set of statistical growth models. The model that best fitted the experimental data included a decline phase. The decline intensity and the value of several other model parameters, such as the maximum yield reached during the ceiling phase or the duration of the establishment phase, were highly variable. The highest maximum yields were obtained in the experiments located in the southern part of the studied area and the duration of the establishment phase was strongly related to the establishment method. Since energetic viability and profitability of *M. giganteus* hinge critically on yields, these results could be integrated in further assessment works.

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1. Introduction

Miscanthus × giganteus is a perennial C4 rhizomatous energy crop originating from Southeast Asia (Lewandowski et al., 2000). It is known for its high yield potential and low input requirement (Lewandowski et al., 2000, 2003). *M. giganteus* has been studied as an energy crop since the mid-1980s, mostly in the European Union (Lewandowski et al., 2003). According to Lewandowski et al. (2000), the crop is characterized by a yield increase during an establishment phase, lasting three to five years, followed by a ceiling phase with stable yields. Miguez et al. (2008) quantified those two phases using a meta-analysis: they described the growth of *M. giganteus* over years with a logistic function and estimated

that it takes between three and five years to attain mature yields. Once mature yields are reached, *M. giganteus* is expected to have a plantation lifetime of 20–25 years (Lewandowski et al., 2000). However, Clifton-Brown et al. (2007), Christian et al. (2008) and Angelini et al. (2009) studied the evolution of *M. giganteus* yields for 16, 14 and 12 years respectively, and observed a third growth phase characterized by a yield decline beginning after 10, 11 and 3 years of growth respectively. Such a decline has already been reported for other perennial crops such as sugarcane (*Saccharum* spp.), a C4 tropical grass from the same tribe of the genus *Miscanthus* (*Andropogoneae*) (Hoy and Schneider, 1988; Keerthipala and Dharmawardene, 2000; Ferraro et al., 2009). At the same time, *M. giganteus* ceiling yields varied between trials: Lewandowski et al. (2000), Heaton et al. (2004) and Miguez et al. (2008) reported yields ranging from less than 10 to more than 40 t of dry matter (DM) per hectare across Europe. The knowledge of *M. giganteus* yield and of its evolution over time is essential in estimating the economic and carbon mitigation potential of the crop. As *M. giganteus* incurs a
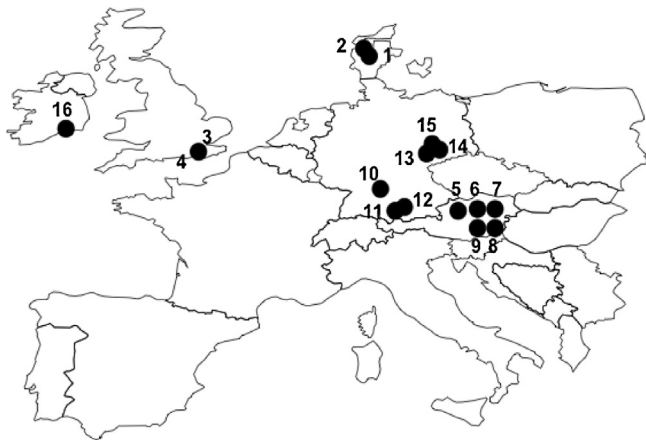
Fig. 1. Location of the experimental sites included in the *M. giganteus* long-term yield database (a site can include several experimental units, *cf.* Table S1).

Fig. 2. Yield evolution of *M. giganteus* as a function of crop age. Points represent the data, the solid line shows the mean prediction from model (4g), dashed lines represent the 2.5 and 97.5% percentiles describing the between site-year variability.

high establishment cost (*e.g.* more than 3000 € per hectare in the UK (Lewandowski et al., 2000)), yields determine partly the crop profitability (Styles et al., 2008). The greenhouse gas balance associated to the crop was also proved to be sensitive to yields (Styles and Jones, 2007; Hillier et al., 2009; Eranki and Dale, 2011). However, assessment studies are mainly based on experimental yields measured during the first growth years or on models built on those yields (Styles and Jones, 2007, 2008; Boehmel et al., 2008; Styles et al., 2008; Smeets et al., 2009; Hillier et al., 2009; Monti et al., 2009). Our study aims therefore at characterizing the long-term yield evolution of *M. giganteus* to answer the following questions: do yields decline and when? What is the variability of the maximum yield values? How long does it take to reach the ceiling phase?

2. Materials and methods

2.1. Data

Our work was based on a quantitative review of various types of data gathered from across Europe. A database containing 37 experimental units (EU) – defined as the combination of a location and of an experimental treatment over several years – was built by consulting peer-reviewed papers, gray literature and unpublished data from research and research-development European institutions identified as working on *M. giganteus* (Table S1). We focused on institutions located in the European Union where long-term trials were available, while research on biomass crop in the United States of America was during a long time focused on switchgrass (Lewandowski et al., 2003; Heaton et al., 2010). Experimental units were included in the database if the trial duration was more than 12 years and if yields had been measured on average at least every two years.

Supplementary material related to this article found, in the online version, at http://dx.doi.org/10.1016/j.fcr.2013.05.004.

The 37 experimental units spanned five countries and 16 sites representing different pedo-climatic conditions (Fig. 1): Denmark (site 1: 4 EU, Jorgensen, 1996; site 2: 6 EU), United Kingdom (site 3: 3 EU, Christian et al., 2008; site 4: 4 EU, Riche et al., 2008), Austria (sites 5–9, one EU per site, Liebhard, 2002), Germany (site 10: 5 EU; site 11: 3 EU; sites 12–14: one EU per site; site 15: 2 EU), Ireland (site 16: 1 EU). For the last site (Ireland), data were collected from Fig. 2 of Clifton-Brown et al. (2007) using the freeware Digitizer. Each EU is characterized by the pedo-climatic conditions (soil type, mean annual rainfall, and temperature), the duration of the experiment, the experimental treatment or the crop management, and the yield measurement method (Table S1). Pedo-climatic conditions
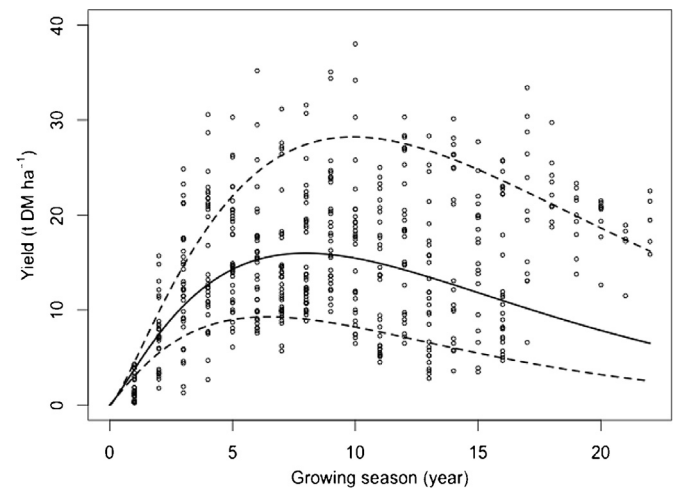
are mainly representative of Northern Europe. Experiment duration ranged from 12 to 22 years. The establishment method (plantlets or rhizomes), the plantation density and the fertilization were precised for all experimental treatments. Chemical and/or mechanical weeding was applied on every EU during the establishment years as well as during the following years, though not every year. None of the site was irrigated. Yield evolution of *M. giganteus* of all sites and EU depending on plant age is presented in Fig. 1.

2.2. Statistical models used to describe yield evolution

Five types of statistical growth models linking the yield (Y) and the growing season (T) were compared (Fig. 3):

(1) 'linear + plateau' models based on a maximum yield (Y_{max}) and a threshold growing season (T_{max}):

$$\text{if } T \geq T_{max}, \quad Y = Y_{max} \tag{1}$$

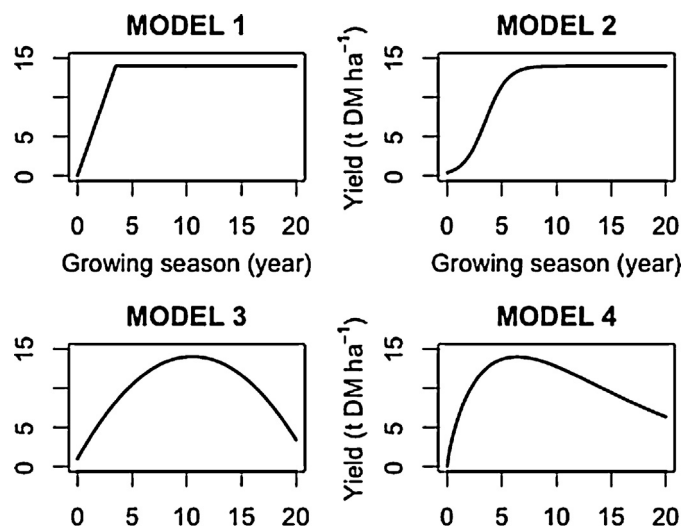$$\text{if } T < T_{max}, \quad Y = Y_{max} + S * (T - T_{max})$$

Fig. 3. Compared models for long-term yield trends.

(2) logistic models:

$$Y = \frac{Y_{max}}{(1 + (\exp(\varphi_1 - T)))/\varphi_2} \qquad (2)$$

This model was used by Miguez et al. (2008) to describe *M. giganteus* growth over years.

(3) quadratic models:

$$Y = \varphi_1 + \varphi_2 * T + \varphi_3 * T^2 \qquad (3)$$

(4) exponential models:

$$Y = \varphi_1 * T^{\varphi_2} + \exp(\varphi_3 * T) \qquad (4)$$

(5) linear + plateau + linear models, with two threshold years T_1 and T_2

$$\text{if } T_1 < T < T_2, Y = Y_{max} \qquad (5)$$

$$\text{if } T < T_1, Y = Y_{max} + S_1 * (T - T_1)$$

$$\text{if } T > T_2, Y = Y_{max} + S_2 * (T - T_2)$$

Models were chosen according to available knowledge on *M. giganteus* yield evolution in order to account for *M. giganteus* establishment phase and 'plateau' phase as described qualitatively by Lewandowski et al. (2000) and quantitatively by Miguez et al. (2008). Two family of models were compared regarding long-term yield evolution: (i) models (1) and (2) where yields remained constant in the long run and (ii) models (3)–(5) which included a yield decline phase.

Due to the data structure (repeated measurements of yield over years in each EU), the models were defined as mixed-effect models, *i.e.* as models including one or several random parameters. For each type of model (linear + plateau, logistic, quadratic, exponential), several variants including 1, 2, or 3 random parameters were defined. For example, the model exponential including 3 random parameters was defined as follows:

$$y_{ij} = \varphi_{1i} * t_{ij}^{\varphi_{2i}} * \exp(\varphi_{3i} * t_{ij}) + \varepsilon_{ij}$$

$$\varphi_i = \begin{pmatrix} \varphi_{1i} \\ \varphi_{2i} \\ \varphi_{3i} \end{pmatrix} = \begin{pmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{pmatrix} + \begin{pmatrix} b_{1i} \\ b_{2i} \\ b_{3i} \end{pmatrix} = \beta + b_i$$

$$b \sim N(0, \psi), \varepsilon_{ij} \sim N(0, \sigma^2)$$

where (y_{ij}) stood for *M. giganteus* dry biomass, (t_{ij}) is the *j*th growing season in the *i*th experimental unit. The fixed effects β represented the mean values of the parameter φ_i over all experimental units, and the random effects b_i represented the deviations of φ_i from their mean value. The random effects were assumed to be independent for different EUs and to follow a normal distribution with a variance–covariance matrix ψ. The within-group errors ε_{ij} were assumed to be independent for different *i* and *j*, and to be independent of the random effects.

Models were fitted using the method described in Pinheiro and Bates (2000) implemented with the R software (R Core, 2006) using the nlme (Pinheiro et al., 2007) and lattice (Sarkar, 2007) packages.

Models were assessed by calculating the Akaike Information Criterion (AIC) and Schwartz Criterion (BIC) (Akaike, 1974; Burnham and Anderson, 2002). The best models are those with the lowest AIC and BIC. The distributions of the model residuals were checked for patterns, normality (with estimation of Skewness and Kurtosis) and autocorrelation.

Two sensitivity analyses were carried out to assess the robustness of the AIC and BIC-based model ranking. The first one was made at the EU level: each EU was removed from the data one by one and effects on the model ranking were noted. The second sensitivity analysis was made with a similar method but at the site level.

2.3. Characterization of yield trend and variability

The best model (*i.e.* the model with lowest AIC and BIC values) was used to estimate three characteristics of yield trends over years:

(1) the maximum yield Y_{max} reached across years (t DM ha^{-1});
(2) the growing season when the maximum yield Y_{max} was reached T_{max} (year);
(3) the yield decrease rate ΔY (t DM ha^{-1} y^{-1}), defined as follows:

$$\Delta Y = \frac{Y(22) - Y_{max}}{22 - T_{max}} \qquad (6)$$

where 22 was the last year simulated by the model and $Y(22)$ the yield reached that year.

When Y_{max} and T_{max} were not model parameters, they were computed using the model equation. For instance, for model (4):

$$Y_{max} = \varphi_1 * \left(\frac{-\varphi_2}{\varphi_3}\right)^{\varphi_2} * \exp(-\varphi_2) \qquad (7)$$

$$T_{max} = -\frac{\varphi_2}{\varphi_3} \qquad (8)$$

$$\Delta Y = \frac{(22 * T_{max})^{\varphi_2} * \exp(22)}{\text{exo}(T_{max})^{\varphi_3}} \qquad (9)$$

$$\Delta Y = \frac{\varphi_1 * (22^{\varphi_2} * \exp(22 * \varphi_3) - (-\varphi_2/\varphi_3)^{\varphi_2} * \exp(-\varphi_2))}{22 + (\varphi_2/\varphi_3)}$$

The values of the three variables were estimated for each EU separately and the estimated values were related to several explanatory variables:

– groups of EUs based on Y_{max}, T_{max} and ΔY; they were defined from a cluster analysis using the Euclidean distance measure and the ward agglomeration method;
– latitude and longitude;
– crop management techniques (planting method, planting density, fertilization regime).

3. Results

3.1. Model selection

Models are compared in Table 1 with different combinations of random *vs.* fixed parameters. Some of the models were excluded when the convergence criteria of nlme were not satisfied. As all models (5) did not converge, they were not further included in the analysis.

Model (4g) with φ_1 and φ_3 defined as random parameters minimized both AIC and BIC. Model (3) led to intermediate AIC and BIC values. Models (1h), (2d), (2e) and (2g), which are characterized by a fixed Y_{max}, showed the highest AIC and BIC. The AIC and BIC were decreased when Y_{max} was defined as a random parameter – as for instance in models (1b), (1c), (1f), (1g), (2b), (2c), (2f) and (2g). This result was consistent with the high variability of maximum yields reported for the different EU. The AIC values of models (2b), (2c), (2f), and (4g) were similar, but model (4g) showed a lower BIC. Models (4b) and (4g) had very close AIC and BIC.

Table 1
Comparison of different yield evolution models for *M. giganteus*.

Model	Parameter(s) defined with random effect	AIC	BIC
(1a)	None	3433.1	3504.0
(1b)	All	2914.8	2944.6
(1c)	Y_{max}	2922.3	2943.5
(1d)	S	3435.1	3456.4
(1e)	T	NC[a]	NC
(1f)	Y_{max} and S	2918.3	2943.8
(1g)	Y_{max} and T	2912.8	2938.3
(1h)	S and T	3437.1	3462.6
(1a)	None	3433.2	3450.2
(2b)	All	2884.2	2913.9
(2c)	Y_{max}	2881.1	2902.3
(2d)	φ_1	3435.2	3456.4
(2e)	φ_2	3435.2	3456.4
(2f)	Y_{max} and φ_1	2882.6	2907.6
(2g)	Y_{max} and φ_2	2883.1	2908.6
(2h)	φ_1 and φ_2	3437.2	3462.7
(3a)	None	3487.0	3504.0
(3b)	φ_2	3128.5	3149.7
(4a)	None	3462.2	3479.2
(4b)	All	2854.4	2884.2
(4c)	φ_1	2954.5	2975.8
(4d)	φ_2	2947.1	2968.3
(4e)	φ_3	2987.6	3008.9
(4f)	φ_1 and φ_2	2896.8	2922.3
(4g)	φ_1 and φ_3	2852.4	2877.9
(4h)	φ_2 and φ_3	2885.8	2911.3

[a] Not computed.

Fig. 4. Sensitivity analysis to the data: (a) at the experimental unit level (EU) and (b) at the site level. For each suppressed EU or site (numbered on abscissa) is displayed the model classification result. Symbols stand for the AIC of the different models. Dashed lines stand for the AIC of model (4g).

Fig. 4 shows the robustness of the AIC-based ranking of the tested models. Results obtained for BIC were similar (data not shown). Sensitivity analysis at the EU level showed that model ranking was stable with one exception: when EU 31 (belonging to site 11) was removed from the data, the logistic model (2f) became slightly better than model (4g) (Fig. 4a). At the site level, model classification was quite consistent as well, with two exceptions (Fig. 4b). When site 1 (*i.e.* EU 1–4) was removed, the logistic model (2c) minimized with AIC with 2584.5, the model (4g) was ranked 5th with AIC = 2587.4. The original model ranking was more affected when site 11 (*i.e.* EU 29–31) was removed: models (2c) got the lowest AIC (2495.9) and model (4g) was ranked 8th (2522.6). Logistic models – (2c), (2f) and (2g) – and linear + plateau models – (1b), (1f), (1g) – got a lower AIC than model (4g).

Model (4g) residuals presented no pattern and were consistent with the normality hypothesis (Skewness = 0.1; Kurtosis = 3.7). Model (4g) residuals were compared to those of the best model without decline phase (model 2c) (Fig. 5). Many of the model (2c) residuals were negative for high growing season values showing that model (2c) tended to overestimate yields for $T > 15$ years. Fig. 5 shows that model (4g) was more in agreement with the observed yield data.

Based on these results, the exponential-based model (4g) was selected for further analysis. The mean yield response curve predicted by the model (4g) is displayed in Fig. 2. The 2.5 and 97.5% yield percentiles computed from the random parameter distributions (Fig. 2) showed high yield variations between experimental units. This result was confirmed in Fig. 6 that revealed a strong variability of the fitted individual response curves between the different experimental units.

3.2. Yield trends and variability: analysis from model (4g)

Parameter estimates of model (4g) are shown in Table 2. Long-term yield trends can be quite different across the experimental units (Fig. 6): some EUs such as EU 24 or 28 showed a
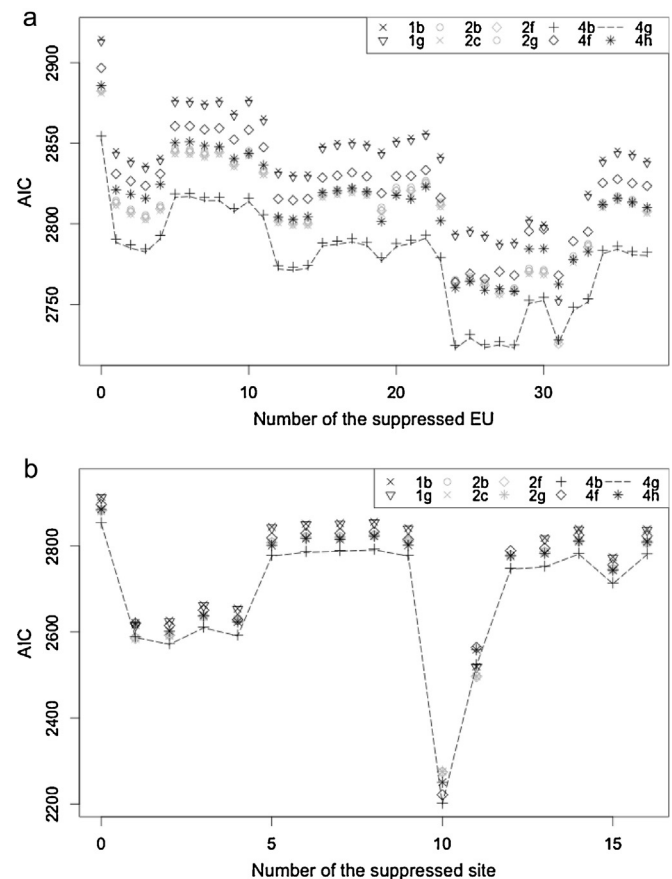
significant yield decline whereas yields of other EUs such as EU 29 or 31 remained almost stable, even after 20 years of growth.

On average over EU, Y_{max} was equal to 16.8 t DM ha^{-1} y^{-1} (sd = 6.86), T_{max} was equal to 8.33 years (sd = 1.95), and ΔY was equal to -0.647 t DM ha^{-1} y^{-1} (sd = 0.243).

Cluster analysis (Fig. 7) splitted EUs into three groups of yield trends (Fig. 8):

(1) Group 1 includes experimental units 1–18 (*i.e.* locations 1–4), 34–37 (*i.e.* locations 14–16). It was characterized by maximum yields (Y_{max}) ranging between 8.4 and 16.3 t DM ha^{-1} y^{-1} with a median equal to 11.6 t DM ha^{-1} y^{-1}. These maximum yields were reached after 5.9–9.2 years with 7.2 years as a median. ΔY varied from -0.65 to -0.36 t DM ha^{-1} y^{-1}, with a median equal to -0.65 t DM ha^{-1} y^{-1}.

(2) Group 2 includes experimental units 19–23 (locations 5–9), 30, 31 (from location 11) and 33 (location 13). Y_{max} were higher,

Table 2
Parameter estimates of the selected model (model 4g) – E stands for the parameter φ_i expectation and $V(\varphi_i)$ for parameter φ_i variance.

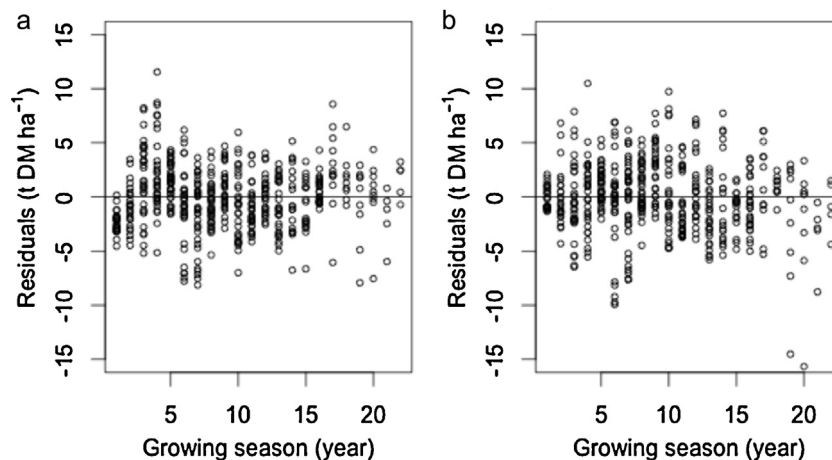| Parameter	Estimated value
$E(\varphi_1)$	4.37
$E(\varphi_2)$	1.21
$E(\varphi_3)$	1.69
$V(\varphi_1)$	2.85
$V(\varphi_2)$	0
$V(\varphi_3)$	1.46
σ^2	9.61

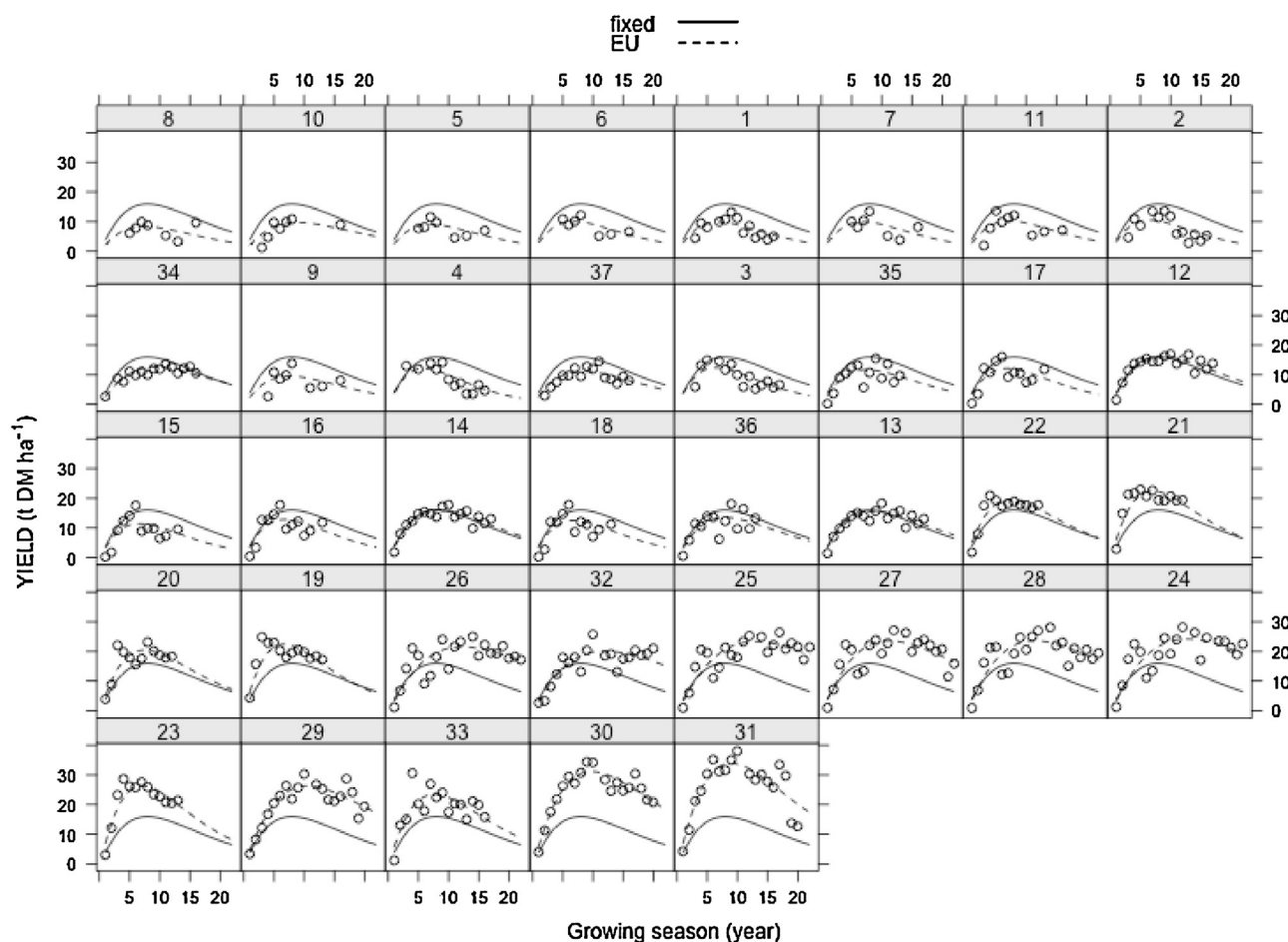**Fig. 5.** Residual distributions for (a) model (4g) and (b) model (2c).

Fig. 6. Mean predictions (solid line) and experimental unit (EU) – adjusted predictions (dashed line) of *M. giganteus* yield trends from the selected growth model (4g).

ranging between 19.5 and 33.9 t DM ha^{-1} y^{-1} with a median of 23.0 t DM ha^{-1} y^{-1}. Maxima were reached after 6.7–9.8 years (median = 6.7 years). Yields declined from −0.880 to −1.27 t DM ha^{-1} y^{-1} (median = −1.05 t DM ha^{-1} y^{-1}).

(3) Group 3 includes experimental units 24–28 (*i.e.* location 10), 29 (from location 11) and 32 (location 12). Maximum yields were high as well, ranging between 21.6 and 24.2 t DM ha^{-1} y^{-1} (median = 23.6 t DM ha^{-1} y^{-1}). Maxima were however reached after 10.5–13.0 years (median = 11.9 years) and ΔY were similar

to those of group 1, ranging from −0.47 to −0.79 t DM ha^{-1} y^{-1} (median = −0.52 t DM ha^{-1} y^{-1}).

Y_{max} was strongly related to latitude (R^2 = 0.67) (Fig. 9): southern sites were those with the highest Y_{max}. It was correlated to none of the management techniques reported in the database. T_{max} was strongly related to the planting mode (Fig. 10): EUs planted with rhizome needed on average 9.6 years to reach their maximum yields compared to 7.4 years for EUs planted with
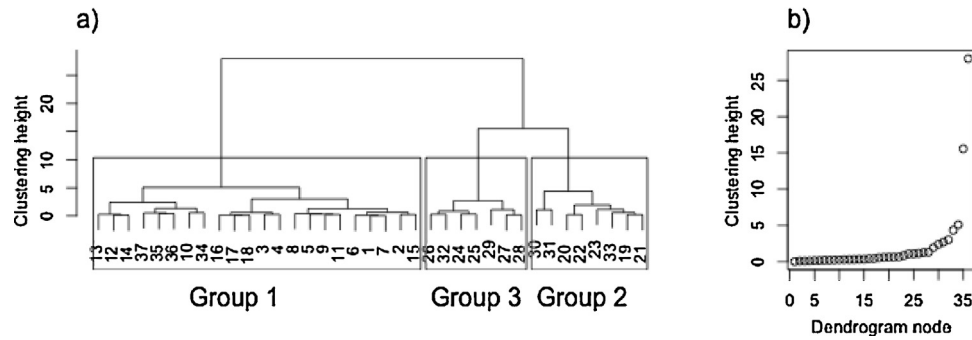
Fig. 7. (a) Dendrogram of the experimental units and (b) node distance graph as basis for grouping them into three groups.
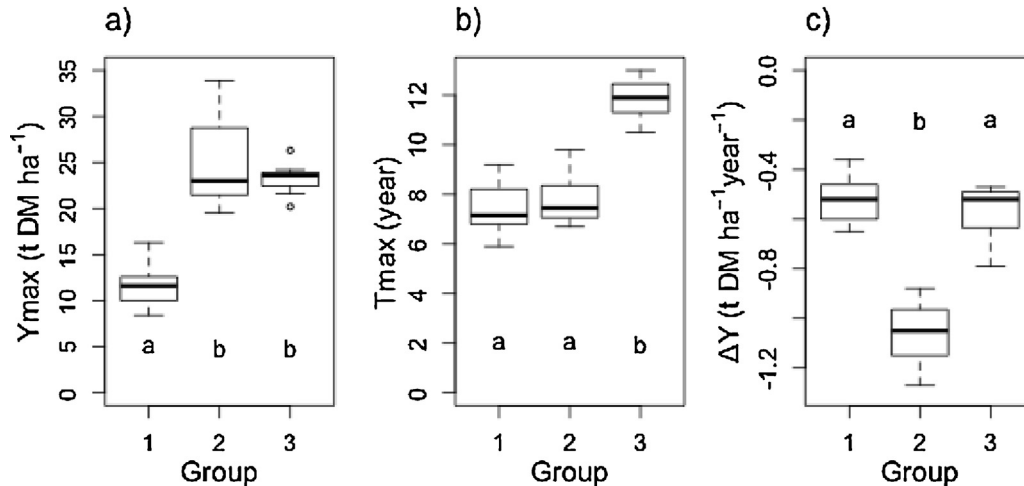

Fig. 8. Variation of (a) Y_{max}, (b) T_{max} and (c) ΔY according to the group of EUs (different letters indicate that the group means are significantly different).

micro-propagated plants. It was not related to other management techniques. It also seemed to be determined by the site potential: the higher Y_{max}, the higher T_{max}. ΔY was found to be related to none of the variables studied here.

Experimental units classified in group 1 were located in the North. Two third of them were planted with micro-propagated plants. Except EU 33, group 2 includes EU located in the South and, for most of them, had crops established by micro-propagation. Group 3 includes EU located in the South planted with rhizomes.
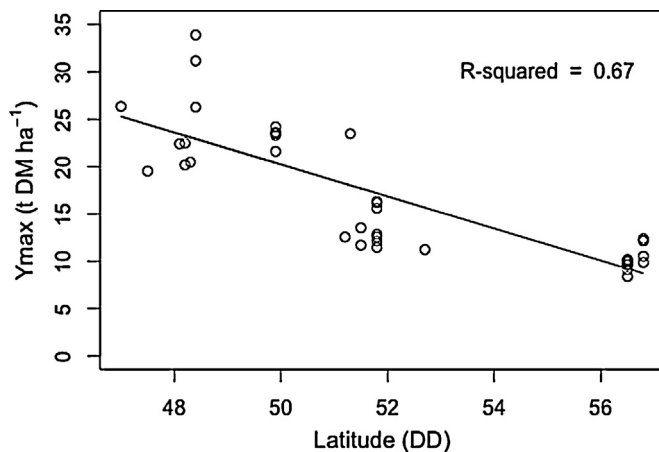
4. Discussion

4.1. Ceiling yields

Y_{max} averaged 16.8 t DM ha^{-1} y^{-1} but was characterized by a large variability (standard deviation: 6.86 t DM ha^{-1} y^{-1}). This is

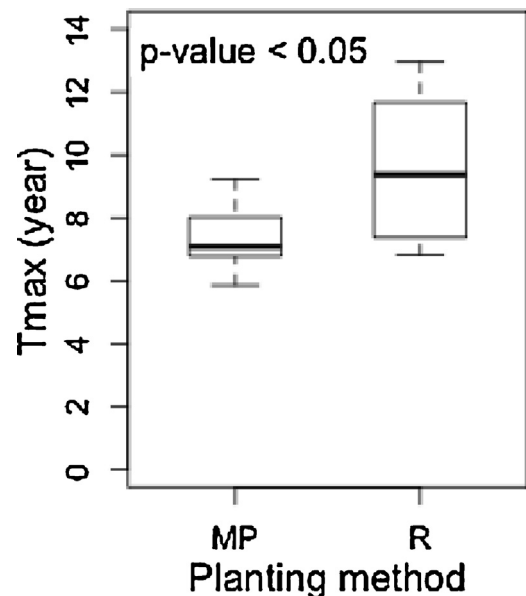**Fig. 9.** Variation of Y_{max} as a function of latitude.

Fig. 10. Variation of T_{max} as a function of the planting mode (MP: micro-propagation, R: rhizomes).

consistent with findings of Miguez et al. (2008) with average Y_{max} of 18.4 t DM ha^{-1} y^{-1} associated with a great variability too. Heaton et al. (2004) estimated higher *M. giganteus* mean yields (22.4 t DM ha^{-1} y^{-1}) but this remains in the same order of magnitude.

In this study Y_{max} appears to be determined by latitude with a strong gradient from North to South: countries at lower latitudes (Germany and Austria) achieved higher Y_{max} as a consequence of a longer growing season accompanied by higher temperatures. This outcome seems to confirm results presented by Miguez et al. (2008), whose database included southern countries (Italy and Greece).

No correlations were found for Y_{max} and any management factors included in this study. Thus yield performances seemed to be more determined by environmental factors than by management. Heaton et al. (2004) also showed that *M. giganteus* yields were strongly influenced by water, barely influenced by nitrogen and not influenced by growing degree days at all. However, Miguez et al. (2008) found a relatively small effect of nitrogen on the maximum dry matter yield in the long-term, suggesting that the lack of N effect reported in many studies could be due to the short length of experimentation. In a review, Cadoux et al. (2012) indicated the low nutrient requirements of *M. giganteus* compared to other crops. Those low requirements are mainly due to high nutrient uptake and use efficiency, as well as nutrient cycling through translocation between the rhizome and aerial biomass and through leaf fall. Cadoux et al. (2012) also mentioned that studies reporting no response to increasing nitrogen fertilization rate seemed to have benefited from high soil nitrogen levels. This might also have been the case with several experiments in our database. The lack of response to nitrogen could be also due to the presence of another limiting factor as on site 10, where the lack of water might have concealed any fertilization effect (Fritz and Formowitz, pers. comm.). Like Miguez et al. (2008), we did not find any effect of planting densities on Y_{max}. According to Lewandowski et al. (2000) and Jorgensen (1996), higher planting densities increase yields only during the first growing years.

Another part of the inter-location yield variability could be related to the differences in yield measurement method shown in Table S1. Yield measurement method for *M. giganteus* is indeed known to be protocol-sensitive (Brancourt-Hulmel, pers. comm.; Strullu, pers. comm.) but no precise comparisons are available.

4.2. Duration of the establishment phase

High planting densities are expected to reduce the length of the establishment phase. In our model, the duration of the establishment phase can be comprehended thanks to T_{max}, which averaged 8.5 years. The full establishment of a *M. giganteus* stand is more commonly said to be ranging from three to five years (Lewandowski et al., 2000; Miguez et al., 2008, 2012). Since T_{max} is the year where the absolute maximum yield is reached, it does not strictly represent the establishment phase. Assuming that the stand is fully established when 85% of Y_{max} is reached, we could estimate from our model that the establishment phase takes 4.7 years (ranging 3.3–7.3 years).

T_{max} in our study was strongly influenced by the planting method: stands planted with micro-propagated plants establish faster than the ones planted with rhizomes. Lewandowski (1998) found that stands established from micro-propagules were characterized by a larger number of shoots per plant at the end of the first growing season. Shoots were on the other hand thinner and had less numerous and smaller leaves. Differences in shoot numbers and weight were still significant until the fourth growing season. Any influence on yield was on the contrary unclear during the first growing seasons and certainly did not exist in the long run. Clifton-Brown et al. (2007) observed higher shoot densities for

micro-propagated plants from the first to the fifths growing season but plants were shorter. Yields were significantly different for the fifth and the sixth growing season but propagation method had no significant effect on yield over the six years. Effect on T_{max} observed in our study may be explained by the higher shoot density observed for micro-propagated plants: establishment of a closed canopy may be faster and have more influence on yields than shoot weight. Lewandowski (1998) mentioned that micro-propagated stands are more sensitive to lodging, probably because of a smaller shoot diameter. Lodging can lead to yield losses and disturbs the nutrient translocation process. We could not include that factor in our analysis. However, lodging was also observed on stands planted with rhizomes, mostly during very snowy winters with the crop being repeatedly snowed under heavy-slushy snow (Fritz and Formowitz, pers. comm.) Micro-propagated plants are also characterized by a smaller overwintering rate after the first winter. Lewandowski (1998) showed that their rhizomes at the end of the first growing season were smaller than on plants established from rhizome pieces and had a different chemical composition. She assumed that a lack of reserve components in the rhizome resulted in increased susceptibility to frost. Such a phenomenon could not be observed in our study since new plants were planted when necessary after the first winter. Due to micro-propagation costs, commercial fields are nowadays planted with rhizomes, which although cheaper, is still expensive.

Miguez et al. (2008) found that *M. giganteus* reached higher yields faster when planting density was increased from 1 to 4 plants m^{-2}. This is in contrast to our results, where no influence of planting density on T_{max} was observed. The range of planting densities included in our database (from 0.5 to 4 plants m^{-2}) is however large but unequally distributed within the database since lower and higher densities are tested only in Northern latitudes. Therefore, the effect of planting density could have been overcome by the effect of environmental factors.

Clifton-Brown et al. (2001) as well as Zub and Brancourt-Hulmel (2010) reported that ceiling yields were reached faster in warmer countries. Nevertheless, we did not find any relationship between T_{max} and latitude. Two hypotheses can be made. Firstly, potential yields as described by Y_{max}, may overcome the influence of latitude on T_{max}: stands with high potential yields may need more time to reach Y_{max}, even if they are located in southern sites. Secondly, we might have seen this relationship if our database included southern locations such as Italy or Portugal.

Although we did not highlight any effect of management on Y_{max} or T_{max}, it is interesting to notice that during the cluster analysis, all the units of the same site were allocated to the same group except for site 11. The three experimental units of site 11 (EU 29–31) belonged either to group 3 for EU 29 and group 2 for EU 30 and 31. On that site, three nitrogen rates were tested: 0, 75 and 150 kg ha^{-1}. EU 29, where no nitrogen was applied, differed for Y_{max}, T_{max} and ΔY at once: Y_{max} and T_{max} were particularly smaller, suggesting a nitrogen effect on these two parameters at that particular site.

4.3. Yield decline

Our results indicated that *M. giganteus* yields followed a general tendency to decline after several years of growth. That tendency had already been observed separately on several experimental locations (Clifton-Brown et al., 2007; Christian et al., 2008; Angelini et al., 2009). However, in a recent report on a fourteen years experiment in Germany, Gauder et al. (2012) highlighted a significant yield fluctuation between years but did not mention any decline. The long-term yield evolution variability observed in experiments was emphasized by the model selection carried out in our study: the mathematical form of the selected model, when used as a mixed

effect model, allows the highest variability between experimental units.

Our analysis did not highlight any influence of management on this decline. Yet, the database used in this study did not allow us to take every management option separately into account. In particular, potassium and phosphorus fertilization was not included, whereas Cadoux et al. (2012) hypothesized that potassium may become a limiting factor for growth, according to *M. giganteus* potassium content in harvested aerial biomass. Even though our results did not show any influence of climatic conditions (summed up by latitude), we could expect a link between climate and yield decline. *M. giganteus* yield elaboration during a growth cycle is indeed divided into two parts (Himken et al., 1997; Strullu et al., 2011). From emergence in early spring to mid-summer, aboveground biomass increases slowly then strongly while nutrients are translocated from rhizomes to shoots. From mid-summer to mid-October, aboveground biomass increases slowly before decreasing until harvest at the end of the winter. Meanwhile, during this second phase, nutrients are translocated from the aerial parts to the rhizome (explaining, along with abscised leaves, above-ground biomass decrease). Early frosts in autumn may lead to insufficient translocation, reducing regrowth potential in the following spring (Clifton-Brown et al., 2001). In the long run, we might hypothesize that early frosts may thus reduce the crop lifetime and further research should be carried out on this aspect. We could also wonder whether an extreme climatic event (*e.g.* drought) would affect not only the yield of the undergoing year but also the following years. Early or late harvesting could also influence the crop decline: early harvests may disturb the nutrient translocation while late harvests may damage newly emerged shoots. Although EUs included in our database displayed some variability in harvest dates, no influence of the date was shown, probably because harvest dates varied both intra- and inter-EUs. Furthermore, soil compaction could also reduce crop yields and its perennity. Such a phenomenon is invoked to partly explain the yield decline observed for sugarcane successive ratoons (Keerthipala and Dharmawardene, 2000; Garside et al., 2005). As for sugarcane, diseases and in particular belowground diseases may also be involved and be impacted by low winter temperatures or by waterlogged soils (Hoy and Schneider, 1988; Keerthipala and Dharmawardene, 2000).

Beside management practices and climate influence, yield decline could be related to the specific plant development. *M. giganteus* rhizomes grow from the inner part to the outer layer, building every year new rhizomes in a circle around the old ones. Thus in spring, new shoots emerge as a crown around the former shoots and the plant circumference increases. Over time the regrowth ability of the inner, older center part is reduced leading to decreased biomass production. A rotary cultivation as done for rhizome harvest might then revitalize the stand, as observed in Denmark (Jorgensen, pers. comm.).

Finally, Y_{max}, T_{max} and ΔY may also be affected by genetics. *M. giganteus* is a natural triploid hybrid between a diploid *M. sinensis* and a tetraploid *M. sacchariflorus* (Greef and Deuter, 1993). Because of its sterility and vegetative propagation, *M. giganteus* has been found to display very little genetic diversity and is therefore often treated as a unique genotype whereas differences can exist between clones in terms of morphological characteristics and yields (Clifton-Brown et al., 2001; Zub et al., 2011; Jezowski et al., 2011). This information is however not available and would require isozyme and DNA studies as performed by Greef et al. (1997) and Hodkinson et al. (2002).

5. Conclusion

Analyzing our *M. giganteus* European long-term yield database allowed us (i) to describe yield evolution across the whole crop lifetime and (ii) to characterize that evolution through key variables such as the maximum yield, the duration to reach that maxima and the decline rate. Maximum yields were found to be highly variable as well and this variability was explained by a climatic influences. *M. giganteus* yield is then determined by growth defining factors, rather than by growth limiting or reducing ones. Yields were also characterized by a strong inter-annual variability. Duration of the establishment phase was again variable and sometimes longer than what was previously suggested by the literature. That duration was strongly determined by the planting method. Model comparisons showed that yield evolution was best described when a decline hypothesis is included. Yet, decline intensity was quite variable: at some stands, yields remained nearly steady up to more than 20 years whereas other stands presented a severe decline. The overall trend is nevertheless a declining one. Various hypotheses related to crop management (fertilization, harvest) and climate were investigated but none could be validated.

Further work is needed to (i) understand the factors inducing yield decline and (ii) study whether that decline can be halted or reversed, for instance by modifying the fertilization or by revitalizing rhizomes through mechanical division. Yield evolution across time is a key element in any assessment work dedicated to a potential energy crop. Energetic viability, carbon mitigation potential and profitability hinge critically on them. Therefore our work could allow to precise such assessments. Our model could for example be coupled to an economical model to assess whether the yield decline intensity influences the crop profitability. In the same way, gathering information on commercial yields compared to experimental yields would be very valuable, as well as getting a better understanding of the yield variability during the ceiling phase.

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