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Claire Lesur-Dumoulin, Mathieu Lorin, Mathieu Bazot, Marie-Helene Jeuffroy, Chantal Loyce. Analysis of young *Miscanthus x giganteus* yield variability: a survey of farmers' fields in east central France. *Global Change Biology - Bioenergy*, 2016, 8 (1), pp.122-135. 10.1111/gcbb.12247 . hal-01532528

**HAL Id: hal-01532528**

**<https://hal.science/hal-01532528>**

Submitted on 28 May 2020

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# Analysis of young *Miscanthus* × *giganteus* yield variability: a survey of farmers' fields in east central France

CLAIRE LESUR-DUMOULIN<sup>1,2,3</sup>, MATHIEU LORIN<sup>1,2</sup>, MATHIEU BAZOT<sup>1,2</sup>,  
MARIE-HÉLÈNE JEUFFROY<sup>1,2</sup> and CHANTAL LOYCE<sup>1,2</sup>

<sup>1</sup>UMR 211 Agronomie, INRA, F-78850 Thiverval Grignon, France, <sup>2</sup>UMR 211 Agronomie, AgroParisTech, F-78850 Thiverval Grignon, France

## Abstract

*Miscanthus* × *giganteus* is often regarded as one of the most promising crops to produce bioenergy because it is renowned for its high biomass yields, combined with low input requirements. However, its productivity has been mainly studied in experimental conditions. Our study aimed at characterizing and explaining young *M. giganteus* yield variability on a farmers' field network located in the supply area of a cooperative society in east central France. It included the first three growth years of the crop. We defined and calculated a set of indicators of limiting factors that could be involved in yield variations and used the mixed-model method to identify those explaining most of the yield variation. Commercial yields averaged 8.1 and 12.8 t DM ha<sup>-1</sup> for the second and third growth year, respectively. However, these mean results concealed a high variability, ranging from 3 to 19 t DM ha<sup>-1</sup>. Commercial yields, measured on whole fields, were on average 20% lower than plot yields, measured on a small area (two plots of 25 m<sup>2</sup>). Yields were found to be much more related to shoot density than to shoot mass, and particularly to the shoot density established at the end of the planting year. We highlighted that planting success was decisive and was built during the whole plantation year. Fields with the lowest yields also had the highest weed cover, which was influenced by the distance between the field and the farmhouse, the preceding crop and the soil type. Our findings show that growing young *M. giganteus* on farmers' fields involves limiting factors different from those commonly reported in the literature for experimental conditions and they could be useful to assess the economic and environmental impacts of growing *M. giganteus* on farmers' fields. They could also stimulate the discussion about growing bioenergy crops on marginal lands.

**Keywords:** bioenergy, commercial yield, *Miscanthus* × *giganteus*, on-farm research, perennial crop establishment, regional agronomic diagnosis

Received 17 June 2014; revised version received 24 December 2014 and accepted 5 January 2015

## Introduction

*Miscanthus* × *giganteus* (hereafter called *M. giganteus*) is a C4 perennial rhizomatous grass originating from east Asia, which has been studied as an energy crop since the mid-1980s, mostly in the European Union (Lewandowski *et al.*, 2003) and more recently in the United States (Heaton *et al.*, 2008). *M. giganteus* rhizomes are planted in spring. As crop production during the first growth year is not sufficient to make harvest profitable, the crop is crushed to establish a mulch on the soil surface. From the second year on, the crop is harvested annually. Despite biomass losses during winter, *M. giganteus* is usually harvested at the

end of winter to improve combustion quality, to reduce the energy demand for drying (Lewandowski & Heinz, 2003) and to enable nutrient recycling between the above-ground and the below-ground biomass (Strullu *et al.*, 2011; Cadoux *et al.*, 2012). Yields increase during 3–5 years before reaching a ceiling phase during which a peak productivity is achieved. After establishment, the crop can be harvested annually for 20–25 years (Lewandowski *et al.*, 2003). Crop nutrient requirements are said to be low thanks to (i) high nutrient absorption and use efficiency and to (ii) nutrient cycling between the above-ground and the below-ground biomass, as well as through leaf fall before harvest. Cadoux *et al.* (2012) recommend a maximum nutrient fertilization of 73.5, 7.0 and 105.0 kg ha<sup>-1</sup> of N, P and K respectively, for a dry matter yield of 15 t ha<sup>-1</sup> at winter harvest. *M. giganteus* requires few pesticides except for herbicides during the first 2 years (Lewandowski *et al.*, 2000).

<sup>3</sup> Present address: UE 411 Alénya Roussillon, INRA, Le Mas Blanc, F-66200 Alénya, France

Correspondence: Claire Lesur-Dumoulin, tel. + 33 4 68 37 74 15, fax +33 4 68 37 74 10, e-mail: claire.lesur-dumoulin@supagro.inra.fr

*Miscanthus giganteus* is often regarded as one of the most promising crops to produce bioenergy and in particular second-generation biofuels because it is renowned for its high yields (Lewandowski *et al.*, 2003; Heaton *et al.*, 2004, 2010; Dohleman & Long, 2009) combined with low input requirements. High productivity is indeed very desirable for energy crops as the assessment of several environmental and economic indicators such as energy yield, land area requirement, production costs and gross margin is mostly based on yields. Assessments of *M. giganteus* were based mostly on yields recorded from small areas in field experiments (Zegada-Lizarazu *et al.*, 2013) (e.g. 12–30 t DM ha<sup>-1</sup> when harvested in December; Lewandowski & Heinz, 2003) or made from models predicting yields (e.g. 20 t DM ha<sup>-1</sup> of peak productivity for late winter harvesting; Styles & Jones, 2007; 15–25 t DM ha<sup>-1</sup> for spring harvesting; Smeets *et al.*, 2009). However, Miguez *et al.* (2008) reported a high between-site yield variability in a meta-analysis on *M. giganteus* yields [with a standard deviation (SD) of 4.53 t DM ha<sup>-1</sup> for ceiling winter yields averaging 18.4 t DM ha<sup>-1</sup>]. In the meanwhile, Sensitivity analyses revealed the strong influence of yield estimates on land requirement (Styles & Jones, 2007), crop production costs (Smeets *et al.*, 2009), profitability (Styles *et al.*, 2008), energy yields (Eranki & Dale, 2011) and on the greenhouse gas balance (Hillier *et al.*, 2009; Eranki & Dale, 2011).

Yields recorded in farmers' fields can be quite different from yields recorded in experimental plots due to two factors. First, commercial fields cover a higher range of environments (soil types) and cropping systems (preceding crop, crop management of *M. giganteus*) than experimental fields in which several factors are fixed. For example, Cadoux *et al.* (2012) suggested that the absence of response to increasing nitrogen fertilization observed in several studies could be related to high soil nitrogen (N) supply due to the preceding crop or to significant net N mineralization. In on-farm conditions, soil nutrient supply might be much more variable, as well as soil water supply. As observed in several yield gap analyses on arable crops (Becker & Johnson, 1999; Wopereis *et al.*, 1999; Becker *et al.*, 2003; De Bie, 2004), yields recorded in farmers' fields are lower than potential yields (limited by solar radiation and temperature only) due to suboptimal growing conditions (regarding nutrient or water availability, pest pressures, etc.). Secondly, the assessment of yields in farmers' fields may be lower due to higher losses during the harvest process. The difference between experimental yields measured on small plots and field-scale yields was examined by Monti *et al.* (2009) for switchgrass. To our knowledge, no similar study has been carried out for *M. giganteus*, and its productivity has not been

assessed in on-farm conditions. However, studies dedicated to the impact of cropping *M. giganteus* on biodiversity and soil carbon storage were carried out in on-farm conditions (Semere & Slater, 2007; Bellamy *et al.*, 2009; Sage *et al.*, 2010; Zimmermann *et al.*, 2013). They reported heterogeneity in *M. giganteus* fields, which may significantly affect the economic viability of the crop (Zimmermann *et al.*, 2013). The difference between yields measured in experimental and in on-farm conditions might be especially significant for *M. giganteus* as growing the crop on marginal lands is seen as a way to reduce competition for land with food production.

Our paper aims to describe the variability in *M. giganteus* yields in a set of farmers' fields at a regional scale and to identify the main limiting factors and cropping practices affecting *M. giganteus* yields. We applied the methodology framework of the regional agronomic diagnosis (Doré *et al.*, 1997, 2008) to a farmers' field network of young *M. giganteus* crops grown in the Bourgogne (Burgundy) region of east central France. We used a two-step approach. First, we analysed the variations in yield and yield components observed in the farmers' field network. Then, we identified the main limiting factors responsible for yield variation within fields.

## Materials and methods

### *The farmers' field network*

Data were collected in 20 commercial fields located on 19 farms in the Bourgogne region (Burgundy) in France (Table 1). Fields were located in a 1500 km<sup>2</sup> area ranging from 46°54' to 47°16'N and from 5°02' to 5°46'E in east central France. The field survey was carried out during three growing seasons between 2009 and 2011. Water deficit (estimated as the difference between evapotranspiration and precipitation accumulated over the whole growing period from April to October) reached over the 3 years 241, 143 and 276 mm, respectively. This can be compared with a long-term annual average (estimated over the past 20 years) of 222 mm. All fields were located in the supply area of a cooperative society created in 2009 in Burgundy to commercialize pellets of *M. giganteus*, switchgrass and wood. Ten fields were planted in spring 2009 and ten in spring 2010 after two kinds of preceding crops: (i) annual crops such as wheat, corn, sunflower or (ii) set-aside (for more than 5 years). These fields covered four soil types: three deep soils (clay soils, clay-loamy soils, hydromorphic loamy soils) and moderately deep soils located on alluvia. Soil depth (estimated from soil core samplings) exceeded 120 cm for deep soils and ranged between 80 and 110 cm for moderately deep soils. *Miscanthus giganteus* was planted on small fields (from 0.67 to 5.50 ha, mean: 2.35 ha). Twelve of the 20 fields were of an irregular shape (defined by the number of angles around the perimeter) and/or a very elongated shape (defined by a ratio of width to length  $\leq 20\%$ ). Thirteen of the 20 fields were described by the farmers as

**Table 1** The farmers' field network

Planting year	Preceding crop	Area (ha)	Soil type	SWC <sub>MAX</sub> (mm)	Number of angles	Ratio width to length	Distance (km)*
2009	Set-aside	1.61	C	228	7	0.20	2
		2.46	A	53	4	0.35	49
		1.59	LC	231	4	0.40	0
	Annual crop	1.31	C	152	3	0.75	0
		0.75	C	222	4	0.13	4
		3.04	C	222	6	0.30	0
		3.68	C	222	5	0.50	4
		2.20	LC	207	4	0.60	0
		1.61	L	225	4	0.20	0
		2.07	L	231	4	0.40	3
2010	Set-aside	2.90	C	226.5	8	0.07	0
		0.70	C	228	4	0.20	6.5
		1.54	A	156	4	0.43	7.5
		5.50	LC	224	10	0.24	20
		1.64	L	221	4	0.15	0
	Annual crop	2.30	L	221	4	0.25	13
		2.99	L	222	5	0.40	3
		3.35	C	222	8	0.10	2.5
		2.26	A	99	4	0.60	0
		1.75	A	90	5	0.56	0

C, clay soil; CC, calcareous clayey soil; A, alluvial soil; LC, loamy clay soil; L, hydromorphic loamy soil; SWC: soil water content. \*0 indicates that the field and the farmhouse are located on the same municipality.

having problematic behaviour regarding water: one field, belonging to the moderately deep soil category, was said to be prone to water stress, while the others, assigned to the deep soil class, were described as wet to hydromorphic and had mostly hydromorphic loamy soils. Finally, three fields were located far from the farmhouse.

Fields were planted mechanically with rhizomes at densities varying from 15 300 to 22 750 rhizomes per hectare in 2009 (mean: 18 900) and from 17 400 to 25 150 in 2010 (mean: 19 650) following advice from the cooperative technician. More than three quarters of the rhizomes were supplied by the British environmental and rural consultant ADAS. Analysis on the mitochondrial genome confirmed that all fields had been planted with *M. giganteus*. All fields but one were chemically weeded during the year of establishment, before the first regrowth and occasionally (for four fields) during the second growth year. One field was also weeded before the second regrowth. Eighteen of the 20 fields were not fertilized. The two remaining fields were fertilized once in 3 years with <30 kg N ha<sup>-1</sup> at the beginning of spring. Due to low biomass production, fields were not harvested at the end of the establishment year but were crushed in the field to establish a mulch on the soil surface at the end of December. In subsequent years, the entire fields were mechanically harvested from mid-March to early April in bulk (4 field-years) or in bales (26 field-years).

### Measurements

Measurements were taken for three crop ages: growth year 1 (GY1), that is the planting year, growth year 2 (GY2), that is the first harvested year, and growth year 3 (GY3).

*Growth years 2 and 3.* *M. giganteus* yields were measured at the end of winter 2010–2011 (at the end of GY2, which is the first harvested year) and 2011–2012 (at the end of GY3) for fields planted in 2009 while they were only measured at the end of winter 2011–2012 for fields planted in 2010 (at the end of GY2). Two types of yields were measured in each field: commercial yields (cYIELD) and plot yields (pYIELDS). Commercial yields (cYIELD) were measured on the whole field area during the mechanical harvest with a method defined according to the harvest type. When *M. giganteus* was harvested in bulk, each truck containing the harvest was weighed and a sample was oven dried to determine the dry matter percentage. When *M. giganteus* was harvested in bales, the number of bales per field was counted. Then, an average bale mass per field was estimated by weighing the trailers containing the harvest and the dry matter percentage was determined with a sampling probe. pYIELD were measured in the fields at the beginning of February on small plots of 25 m<sup>2</sup>. Each plot included six rows of *M. giganteus* and was randomly located. However, precautions were taken to avoid field borders and extreme field areas in terms of shoot density (i.e. areas that were not representative of the field). Shoot density (SH\_DENS) was measured on the whole area of both plots. A total of 250 shoots were then randomly selected in each plot (from all the rows and different plants), cut approximately 10 cm above ground and weighed. Twenty of these shoots were subsampled to assess shoot height and diameter. Shoot mass (SH\_MASS) was estimated from the fresh mass of 250 shoots. Moisture content of aerial biomass was determined in a subsample of around one kg by oven drying for 72 h at 105 °C. Both types of yield provide complementary information: pYIELD is similar to experimental yields and can be related to yield components whereas cYIELD gives

access to productivity data under real farming conditions and has a better ability to take into account field heterogeneity. In addition to yields and yield components, weed cover (WEEDS) was assessed on ten 0.25 m<sup>2</sup> microplots located at random throughout the field at the end of winter (March): on each microplot, the percentage of weed cover was estimated visually.

**Establishment year.** As mentioned above, crops were crushed at the end of the first growth year. One 50 m<sup>2</sup> plot was marked out and observed twice during the first year. The density of emerged rhizomes was counted at the end of June (E\_DENS), when emergence was considered to be complete. Shoot density at the end of the first growth year (SH\_DENS\_1) was recorded before crushing. Weed cover (WEEDS<sub>1</sub>) was assessed visually at the end of winter using the same method as during GY2 and GY3.

**Soil and weather data.** Weather data, that is daily mean temperature (T), global radiation (R<sub>g</sub>) and potential evapotranspiration (ETP) were collected from two Météo-France stations (Ouges, 5°04'41"E, 47°15'38"N and Chamblanc, 5°04'41"E, 47°15'38"N) and from a third station set-up at Chissey sur Loue (5°44'12"E, 47°01'37"N). Each field was associated with the closest station, which was always within 20 km.

Soils were characterized by local experts and from soil analysis. Fifteen soil cores were collected throughout each field with a hydraulic coring device to the full soil depth, up to a maximum of 120 cm. Each core was cut into four layers (0–30, 30–60, 60–90, 90–120 cm), and four composite soil samples were obtained by mixing the 15 cores from each depth. The sample from the 0–30 cm layer was analysed to determine particle size and chemical composition: available P (Olsen method), exchangeable Mg and K, total carbon and nitrogen, CaCO<sub>3</sub> and pH. Samples from the 30–60, 60–90 and 90–120 cm layers were mixed, and particle size was determined on the resulting mixture. Maximum rooting depth according to soil type and crop age was assessed on nine contrasting fields digging soil trenches and extrapolated to the other fields belonging to the same category: maximum rooting depth was set at 120 cm for *M. giganteus* crops older than 1 year and planted on deep soils, while it was reduced to 80 cm for 1-year-old crops. On shallower soils, maximum rooting depth was estimated as the maximum sampling depth. Particle size and maximum rooting depth were combined to estimate maximal available soil water content (SWC<sub>MAX</sub>) using the Jamagne method (Jamagne, 1968).

#### *Analysing the variability in commercial yields, plot yields and plot yield components*

Variation in commercial yield (cYIELD) was described and related to variation in plot yield (pYIELD). Then, pYIELD was analysed according to yield components in three steps. First, analyses were carried out for each harvest year and pYIELD was related to its components (SH\_DENS and SH\_MASS). Then, each variable estimated for a given year (pYIELD, SH\_DENS and SH\_MASS) was related to the same variable estimated for the preceding year to study how a growth year affected the following one. Finally, we focused

on the establishment year, relating shoot density (SH\_DENS\_1) to the planting density (P\_DENS) and to the density measured after rhizome emergence (E\_DENS). The effect of the shoot density established at the end of the establishment year (SH\_DENS\_1) on the results of the following year was also assessed. This was all carried out by analysis of variance. The relationship between yield and shoot density was also analysed with a nonlinear model to determine the shoot density above which yield no longer increased. All statistical analyses were carried out with the statistical program R (version R-2.14.2).

#### *Defining indicators of limiting factors*

Several indicators of limiting factors were defined both for harvest years (i.e. growth years 2 and 3) and for the planting year (Table 2).

**Growth years 2 and 3. Water balance.** The dynamic water balance was calculated on a daily basis as follows:

$$SWC(j) = R(j) + I(j) + SWC(j-1) - ETR(j) - D(j),$$

where, SWC(*j*) = soil water content on day *j* (mm); *R*(*j*) = amount of rainfall on day *j* (mm); *I*(*j*) = amount of irrigation applied on day *j*, (mm) (zero in our study); ETR(*j*) = actual evapotranspiration on day *j* (mm); *D*(*j*) = amount of drainage on day *j*, (mm) (assumed to be zero in our study).

Water balance was initialized on March 1st of the growth year, assuming that SWC on that date was equal to SWC<sub>MAX</sub> (i.e. the soil was at field capacity). As *M. giganteus* is a perennial crop, from the second growth year on, the root system is already established when the first shoots emerge in spring. We therefore regarded maximal rooting depth (and as a consequence SWC<sub>MAX</sub>) as constant during the growing season.

ETR was defined as follows:

$$ETR(j) = K_s(j) \times K_c(j) \times ETP(j),$$

where, ETP(*j*) = potential evapotranspiration on day *j*; *K<sub>c</sub>*(*j*) = cultural crop coefficient on day *j*, defined as a function of degree-days [Audoire, 2011]; data from the French multisite experimental network REGIX from the sugarcane as defined by the FAO (Allen *et al.*, 1998); *K<sub>s</sub>*(*j*) = stress coefficient on day *j*; *K<sub>s</sub>*(*j*) = 1 if SWC(*j*) ≥ 2/3\*SWC<sub>MAX</sub> and *K<sub>s</sub>*(*j*) = SWC(*j*)/SWC<sub>MAX</sub> otherwise (Itier, 1996).

An indicator assessing the intensity of water deficit was derived from the above equation on a daily basis as follows:

$$WATER(j) = \frac{ETR(j)}{K_c(j) \times ETP(j)} = K_s(j).$$

It was then averaged over the time period defined for each yield component. For the analysis of SH\_DENS, we assumed from observations of Cosentino *et al.* (2007) combined with local expertise that all effective shoots (which excludes regressive shoots) are established at the end of May, so we calculated WATER<sub>EP</sub> from emergence (~March 25) until May 31. For the analysis of pYIELD and cYIELD, WATER<sub>GP</sub> was calculated over the whole growing period, that is from emergence until first frosts (~October 15th).



*Nitrogen from mineralization.* As most of the *M. giganteus* fields of the network were not fertilized, an indicator of the nitrogen available to the crop was assessed by estimating the quantity of nitrogen mineralized from humus (Mh) using the following equations adapted from the Azodyn model (Jeuffroy & Recous, 1999) and the COMIFER method (COMIFER, 2011):

$$\text{Mh} = \text{TN}_{\text{org}} \times K_{\text{m}} \times \text{ND},$$

where,  $\text{TN}_{\text{org}}$  = humified organic nitrogen stock of the mineralizing layer ( $\text{t organic N ha}^{-1}$ );  $K_{\text{m}}$  = humified organic nitrogen mineralization rate ( $\text{kg mineral N}/(\text{t organic N} \times \text{ND})$ );  $\text{ND}$  = number of normalized days during a given period of time.

$$\text{TN}_{\text{org}} = \text{Nt} \times P \times D_{\text{a}} \times (100 - \text{SR})/100,$$

where,  $\text{Nt}$  = organic nitrogen percentage in the mineralizing layer fine earth;  $P$  = depth of mineralizing layer (cm);  $D_{\text{a}}$  = apparent density of fine earth in the mineralizing layer;  $\text{SR}$  = volumetric coarse fragment percentage in the mineralizing layer.

$$K_{\text{m}} = K_{\text{m}_{\text{sd}}} \times F_{\text{sys}},$$

where,  $K_{\text{m}_{\text{sd}}}$  = standard humified organic nitrogen mineralization rate ( $\text{kg mineral N}/(\text{t organic N} \times \text{ND})$ );  $F_{\text{sys}}$  = increase factor of the quickly mineralizable organic nitrogen pool under the influence of the cropping system organic restitution mode (set to an average value of 1 in our study within a range of 0.8–1.2, as we focused on the first growth years of *M. giganteus*, we considered that *M. giganteus*, as a perennial crop, has not modified soil nitrogen mineralization yet).

$$K_{\text{m}_{\text{sd}}} = 22750/((110 + A) \times (600 + \text{CaCO}_3)),$$

where,  $A$  = clay content of the mineralizing layer (g/kg);  $\text{CaCO}_3$  = limestone content of the mineralizing layer (g/kg).

$\text{ND}$  was computed as a function of mean temperature and soil moisture content using the following equation:

$$\text{ND} = \sum_j \exp(K \times (T(j) - T_{\text{ref}})) \times K_{\text{s}}(j),$$

where,  $K$  = a temperature coefficient equal to 0.115 (Jeuffroy & Recous, 1999);  $T(j)$  = mean temperature on day  $j$  ( $^{\circ}\text{C}$ );  $T_{\text{ref}}$  = reference temperature ( $15^{\circ}\text{C}$ ) (COMIFER, 2011);  $K_{\text{s}}(j)$  = water stress coefficient computed on day  $j$  from the water balance.

$\text{Mh}_{\text{EP}}$  and  $\text{Mh}_{\text{GP}}$  were computed differently for  $\text{SH}_{\text{DENS}}$ ,  $\text{cYIELD}$  and  $\text{pYIELD}$  using the same time periods as those used for both  $\text{WATER}$  indicators.

*Weeds.* The indicator related to weed cover ( $\text{WEEDS}$ ) was defined as the mean of the measurement described above.

*Shoot density of the establishment year and crop age.*  $\text{SH}_{\text{DENS}_1}$  and crop age ( $\text{AGE}$ ) were chosen as proxy variables to take into account the perennial character of the crop, that is the initial growth conditions and the effect of a growing season to the following one, respectively. The crop development in a given year can indeed affect its development in the

following year through nutrient translocation between the aerial biomass and the rhizome, as described by Beale & Long (1997) and Strullu *et al.* (2011).

### Establishment year

The same indicators of limiting factors were calculated to characterize the establishment year through the shoot density established at the end of the year ( $\text{SH}_{\text{DENS}_1}$ ). The water balance computation was however, slightly different. First, as the above-ground growth of the crop is postponed and lower than that in the following growth years, we defined cultural crop coefficients suited to the establishment year based on French unpublished phenology data (INRA UR AgroImpact, personal communication). Unlike in growth years 2 and 3, we cannot assume maximal rooting depth to be constant during the first growing season: we assumed that rooting depth increased from 20 cm to the maximal rooting depth, which occurred during the establishment year (80 cm, as defined in section *Measurements*).  $\text{WATER}_1$  and  $\text{Mh}_1$  were computed over the whole growing period from the planting date (~April 1) to the first frosts (~October 15).

### Selecting indicators of limiting factors explaining yield and yield component variations

Indicators of limiting factors explaining yield and yield component variations were identified with a three-step method, which was applied on both yield measurements ( $\text{cYIELD}$  and  $\text{pYIELD}$ ) to assess the robustness of the results against the yield measurement method. First, yield and yield components were successively related to the candidate explanatory variables using linear regression models defined by  $y = \varphi_0 + \varphi_1 x_1 + \dots + \varphi_p x_p + \varepsilon$ , where  $y$  is the response variable ( $\text{cYIELD}$ ,  $\text{pYIELD}$  or yield components),  $x_1, \dots, x_p$  are the explanatory variables (indicators of the limiting factors), and  $\varepsilon$  is the residual error term. The mixed-model method (Burnham & Anderson, 2002) was used to select the explanatory variables  $x_1, \dots, x_p$  and to estimate the model parameters  $\varphi_0, \dots, \varphi_p$ . The mixed-model method, as proposed by Casagrande *et al.* (2009) to identify the main factors limiting the grain protein content of organic winter wheat, consists of fitting all possible linear combinations of the explanatory variables by least squares and in computing, for each combination, the Akaike Information Criterion (AIC) value (Akaike, 1974) and the Akaike weight (Burnham & Anderson, 2002).

The Akaike weight was computed for each regression model as:

$$w_i = \frac{e^{-0.5(\text{AIC}_i - \text{AIC}_{\text{min}})}}{\sum_{i=1}^n e^{-0.5(\text{AIC}_i - \text{AIC}_{\text{min}})}},$$

where  $w_i$  is the weight obtained for the  $i$ th combination of explanatory variables,  $\text{AIC}_i$  is the AIC value computed for the corresponding model, and  $\text{AIC}_{\text{min}}$  is the minimal AIC value obtained among all the possible combinations. The weight  $w_i$  is the probability that, given a set of models, model  $i$  would be the AIC-best model (Burnham & Anderson, 2002). The relative

importance of the variable  $x$  is then estimated by  $w_+(x)$ , the sum of the Akaike weights across all models in the set where this variable occurs. The larger  $w_+(x)$ , the more important is  $x$  (Burnham & Anderson, 2002). Using these sums, all the variables can be ranked according to their importance. The mixed-model method was computed using the MMIX package of the R statistical software (Morfin & Makowski, 2009).

In a second step, the stability of the mixed-model method results was assessed using the bootstrapping method, as described by Prost *et al.* (2008), to identify and rank the limiting factors of wheat yield. The principle of bootstrapping is to generate a large number of new data sets from the initial data set by randomly sampling data with replacement to study the uncertainty in the results of selection methods. A total of 1000 bootstrap samples were generated from the initial data set, and the mixed-model method was applied on each sample using the MMIX package of the R statistical software (Morfin & Makowski, 2009). For each explanatory variable were computed (i) the frequency of selection of each variable across the bootstrap samples, (ii) the mean of the estimated parameter values across the bootstrap samples, and (iii) the SD of the estimated parameter values across the bootstrap samples. For a variable  $x$ , a high frequency of selection combined with a low SD indicates that the result of the selection method is stable.

#### Selecting indicators of limiting factors explaining shoot density measured at the end of the establishment year

The same procedure was used to identify indicators of limiting factors explaining shoot density established during the first growth year. Finally, the selected limiting factors for the establishment year were related to the field environmental conditions and to the cropping system characteristics. For each selected limiting factor, we defined a set of field cropping system characteristics likely to affect the selected factor and assessed their influence using an analysis of variance.

For instance, regarding weed cover, we selected four variables, which were likely to induce high weed pressure or influ-

ence the efficiency of weed management. DIST represented the distance between the field and the farmhouse and AREA the field area: we assumed based on discussions with some famers and with the advisor of the cooperative society that farmers would be less likely to supervise and manage weeds in remote and/or small fields. SA-PREC gave information on the preceding crop to account for the fact that set-aside land exerts a higher weed pressure than annual crops. L-SOIL indicated hydromorphic loamy soils: we assumed that wet soils favour weed development. Variables describing weed management (based on herbicide applications) were not included because we could not assess whether the timing of herbicide application was appropriate or whether herbicide treatments were efficient, and thus relate weed management to weed cover. For instance, similar herbicide programs based on three applications a year resulted in weed prevalence varying from 10% to 90%. SA-PREC and L-SOIL were defined as binary variables. DIST, AREA, SA-PREC and L-SOIL were included in an analysis of variance to identify the influential variables that was carried out using the following model (R Development Core Team 2008, version 2.14.2):

$$\sqrt{WEEDS_1} = l + a_1DIST + a_2AREA + a_3SA - PREC + a_4L - SOIL + a_5SA - PREC : L - SOIL + e$$

where  $l$  is the intercept;  $a_1, a_2, a_3, a_4, a_5$  are unknown parameters;  $e$  is the error term,  $e = N(0, r)$ . We used a square root transformation for weeds to reduce skewness. The distribution of the model residuals was checked for pattern and normality. Significance of the effects was assessed.

## Results

### *Analysing the variability in commercial yields, plot yields and plot yield components*

*Relationship between commercial and plot yields.* Commercial yields (cYIELD) averaged 8.1 t DM ha<sup>-1</sup> for growth

**Table 2** List of abbreviations

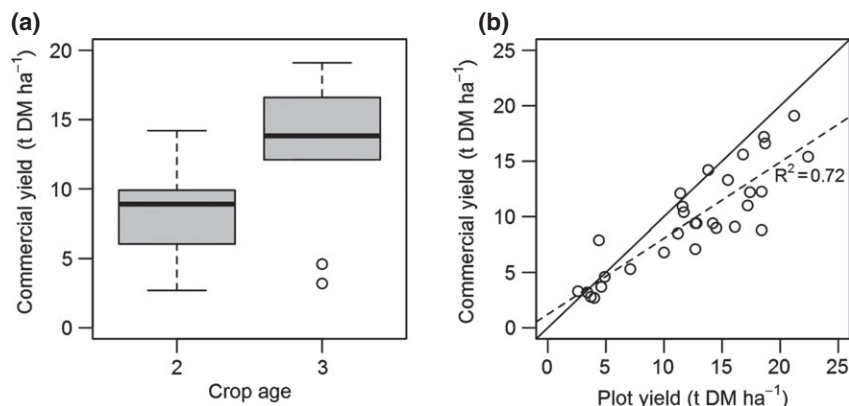
AGE	Crop age
AREA	Field area
E_DENS	Rhizome emerged density
P_DENS	Rhizome planted density
DIST	Distance from field to farm
L-SOIL	Fields with hydromorphic loamy soil
Mh	Mh: indicator of available nitrogen (Mh <sub>CP</sub> : calculated during the whole growing period; Mh <sub>EP</sub> : calculated during the shoot emergence period; Mh <sub>1</sub> : calculated during the establishment year)
SA-PREC	Fields which were set-aside before the plantation of <i>M. giganteus</i>
SH_DENS	Shoot density
SH_DENS_1	Shoot density established during the first growth year
SH_MASS	Shoot mass
WATER	Indicator of water deficit (WATER <sub>CP</sub> : calculated during the whole growing period; WATER <sub>EP</sub> : calculated during the shoot emergence period; WATER <sub>1</sub> : calculated during the establishment year)
WEEDS	Weed cover (WEEDS <sub>1</sub> : measured during the establishment year)
cYIELD	Commercial yield
pYIELD	Plot yield

year 2 (GY2) and 12.8 t DM ha<sup>-1</sup> for GY3 (Fig. 1a) but were mostly highly variable: cYIELD ranged for instance from 3.2 to 19.1 t DM ha<sup>-1</sup> for GY3. cYIELD was closely related to plot yield (pYIELD) ( $P < 0.01$ ,  $r^2 = 0.72$ ) (Fig. 1b), the difference between them being greater for high plot yields. cYIELD was on average 20% lower than pYIELD, but this difference was highly variable with extreme values close to 50%.

*Relationship between yield and yield components within 1 year.* Plot yield (pYIELD) was highly variable in the network of farmers' fields: it ranged from 2.6 t DM ha<sup>-1</sup> to 22.4 t DM ha<sup>-1</sup> (mean = 12.6 t DM ha<sup>-1</sup>). pYIELD depended more strongly on shoot density (SH\_DENS) ( $P < 0.001$  and partial  $r^2 = 0.61$ ) than on shoot mass (SH\_MASS) ( $P < 0.001$  and partial  $r^2 = 0.31$ ) (Table 3). It also depended on an interaction between shoot density and shoot mass. Yield was also related to shoot height ( $P < 0.001$  and partial  $r^2 = 0.24$ ), but was not related to shoot diameter (data not shown). pYIELD increased with shoot density up to about 390 000 shoots m<sup>-2</sup> (Fig. 2).

*Relationship between yields from two successive years.* pYIELD reached at the end of GY3 was closely related to that of GY2 ( $P < 0.001$ ,  $r^2 = 0.74$ ; Fig. 3a). Yield components were also closely correlated from one growth year to the next:  $r^2$  reached 0.62 for shoot density ( $P < 0.001$ ) and 0.78 for shoot mass ( $P < 0.001$ ) (Fig. 3b and c, respectively). Shoot density increased more between GY1 and GY2 than between GY2 and GY3 as shown in Fig. 3b while shoot mass remained stable between GY2 and GY3 (Fig. 3c).

*Yield components of the first growth year.* Shoot density established at the end of the first growth year (SH\_DENS\_1) was not statistically related to the planting density P\_DENS ( $P > 0.5$ ) (Fig. 4a). SH\_DENS\_1 was statistically related to the emerged rhizome density

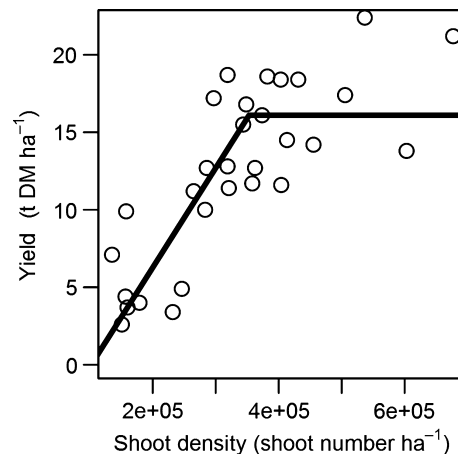


**Fig. 1** (a) Variation in commercial yields as a function of crop age; (b) commercial yields as a function of plot yields.

**Table 3** Analysis of variance of plot yield for growth years 2 and 3 (\*\*\*\*Significance with  $P < 0.001$ )

	P-Value	Partial $r^2$
SH_DENS	$8.4 \times 10^{-18}$ ****	0.63
SH_MASS	$2.7 \times 10^{-14}$ ****	0.33
SH_DENS $\times$ SH_MASS	$1.4 \times 10^{-5}$ ****	0.04

SH\_DENS, shoot density; SH\_MASS, shoot mass.



**Fig. 2** Variation in yield as a function of shoot density for growth years 2 and 3 (the straight line stands for the nonlinear equation between yield and shoot density).

measured at the end of June (E\_DENS), but not particularly strongly ( $P < 0.01$ ,  $r^2 = 30\%$ ) (Fig. 4b). E\_DENS of about 14 000 shoots ha<sup>-1</sup> (average value of our network) resulted in SH\_DENS\_1 ranging from 37 000 to 151 000 shoots ha<sup>-1</sup>. We therefore concluded that the number of shoots per rhizome established after rhizome emergence (i.e. the tillering process) affected the most the elaboration of SH\_DENS\_1.



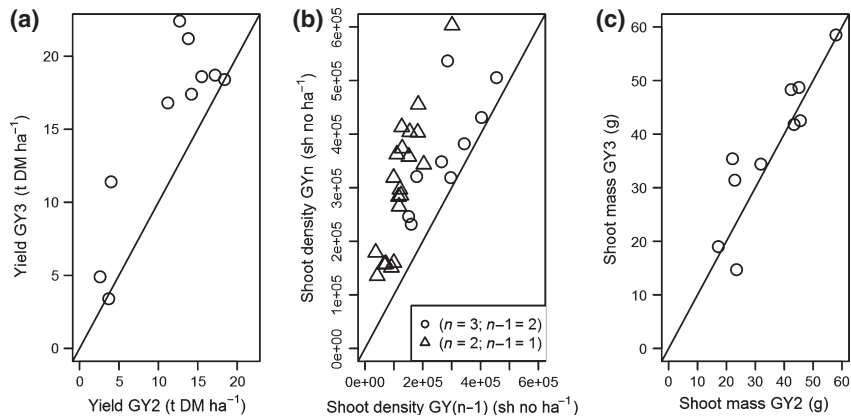


Fig. 3 Interannual relationships between (a) yields, (b) shoot densities and (c) shoot masses (sh: shoot).

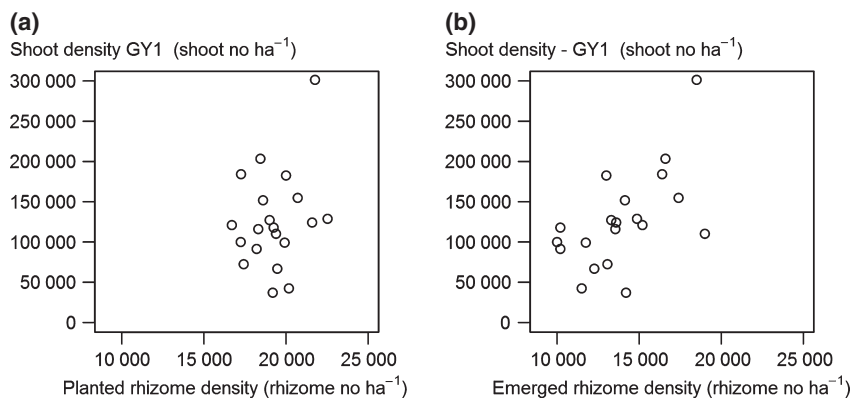


Fig. 4 Shoot density measured at the end of growth year 1 (GY1) as a function of (a) planted rhizome density, (b) emerged rhizome density.

#### Selecting indicators of limiting factors explaining yield and yield component variations

Identification of limiting factors was carried out successively on yield (cYIELD and pYIELD) and shoot density (SH\_DENS), as it is the component which mostly affected yield, as described above. As estimated parameter values and SD were similar before and after the bootstrap procedure, we only give the parameter values computed after bootstrap. Lastly, we show the relative importance values  $w_+$  computed before and after bootstrap (Table 4).

For cYIELD, the factors associated with the highest relative importance values were WEEDS and SH\_DENS\_1:  $w_+$ (WEEDS) had a value of 0.97 while  $w_+$ (SH\_DENS\_1) was equal to 0.92 (after bootstrap). With  $w_+$ (AGE) equal to 0.77, AGE had also some influence. On the other hand, WATER<sub>GP</sub> and Mh<sub>GP</sub> had the lowest relative importance values (0.47 and 0.44, respectively). The probability that these factors would appear in the best model was thus low, and they have lower effect on pYIELD than SH\_DENS\_1, WEEDS and AGE.

The range of values for WATER<sub>GP</sub> was wide (from 0.4 to 1), but WATER<sub>GP</sub> values below 0.65 were recorded in only six field-years. Besides, field-years with similar values for WATER<sub>GP</sub> (or Mh<sub>GP</sub>) were associated with totally different values for YIELD, indicating that other limiting factors had much more influence.

For pYIELD, WEEDS and SH\_DENS\_1 had also the highest relative importance values (0.92 and 0.91, respectively), followed by AGE (0.74). WATER<sub>GP</sub> and Mh<sub>GP</sub> had again the lowest relative importance values (0.47 and 0.44, respectively). Besides relative importance values, the estimations of parameters were also similar to the one estimated using cYIELD. The results were therefore robust against the yield measurement methods. In addition, for cYIELD and pYIELD, the ranking of limiting factors was similar before and after the bootstrap procedure, showing that the results are stable.

For SH\_DENS, SH\_DENS\_1 was the limiting factor associated with the highest relative importance value: with  $w_+$ (SH\_DENS\_1) equal to 1 before and after the bootstrap procedure, that limiting factor was always selected and did not depend on the sample data.

**Table 4** Relationships for growth years 2 and 3 between (a) potential limiting factors and commercial yield, (b) potential limiting factors and commercial yield, (c) potential limiting factors and shoot density

Limiting factors	(a) Commercial yield			(b) Plot yield			(c) Shoot density		
	Parameter value	SD	Relative importance value $w_+(x)^*$	Parameter value	SD	Relative importance $w_+(x)^*$	Parameter value	SD	Relative importance $w_+(x)^*$
			Before bootstrap			After bootstrap			Before bootstrap
AGE	3.2	2.2	0.75	0.77	2.2	0.88	$3.03 \times 10^4$	$3.38 \times 10^4$	0.61
WATER**	-2.4	7.7	0.46	0.47	-0.77	0.30	$-7.34 \times 10^4$	$1.46 \times 10^5$	0.44
Mh†	-0.0051	0.037	0.43	0.44	-0.0076	0.29	$1.60 \times 10^2$	$2.10 \times 10^3$	0.60
SHOOT_DENSITY_1	$3.8 \times 10^{-5}$	$1.6 \times 10^{-5}$	0.91	0.92	$3.8 \times 10^{-5}$	0.98	1.59	0.228	1
WEEDS	-0.40	0.23	0.91	0.97	-0.32	0.97	$-4.70 \times 10^3$	$3.42 \times 10^3$	0.76

AGE, crop age; WATER, indicator of water deficit; Mh, indicator of available nitrogen; Shoot density 1, shoot density established during the first growth year; WEEDS, weed cover.

\*The larger  $w_+(x)$ , the more important variable is  $x$  regarding the explained variable.

†According to the explained variable, WATER and Mh were computed on different period of time.

$w_+$ (WEEDS) amounted 0.81 highlighting the strong relationship between WEEDS and SH\_DENS. With  $w_+$ (AGE),  $w_+$ (WATER<sub>EP</sub>) and  $w_+$ (Mh<sub>EP</sub>) equal to 0.58, 0.52 and 0.60, respectively, AGE, WATER<sub>EP</sub> and Mh<sub>EP</sub> were slightly related to SH\_DENS. As for cYIELD and pYIELD, the ranking of limiting factors was similar before and after the bootstrap procedure, showing that the results are stable.

#### Selecting indicators of limiting factors during the establishment year

The influence of potential limiting factors was analysed on the shoot density established at the end of the first growth year (SH\_DENS\_1):  $w_+$ (WEEDS<sub>1</sub>) amounted to 0.77 and was the only factor that had a high relative importance value (Table 5).  $w_+$ (WATER<sub>1</sub>) was equal to 0.46 and  $w_+$ (Mh<sub>1</sub>) equal to 0.57.

On all fields, weed cover (indicator WEEDS<sub>1</sub>) averaged 18.8% but ranged from 0% to 92% (SD = 27.2%). Analysis of variance showed that DIST was the most influential variable, followed by the interaction between SA-PREC and L-SOIL (Table 6): fields with hydromorphic loamy soil which in addition used to be set-aside before *M. giganteus* had a high weed cover.

## Discussion

### Are *M. giganteus* yields overestimated?

Commercial yields measured in our farmers' field network were on average 30% lower than the mean yields predicted for the same growth years with the statistical model derived from the meta-analysis of Miguez *et al.* (2008). However, the meta-analysis of Miguez *et al.* (2008) was based on experimental yields, which are commonly higher than commercial yields as losses due to the harvesting process are minimums. In our study, plot yields, which are more comparable to experimental yields, were on average 20% higher than commercial yields. However, plot yields remained on average 15% lower than the average yields predicted for the same years from Miguez *et al.* (2008). The average plot yield we measured for the second growth year was for instance closer to the lowest experimental yields measured in different European countries – from 3 to 8 t DM ha<sup>-1</sup> (Clifton-Brown & Lewandowski, 2002; Riche *et al.*, 2008; Schwarz, 1993; Zub *et al.*, 2011) – than to the highest average yields measured for instance in Poland – 15.3 t DM ha<sup>-1</sup> (Jezowski *et al.*, 2011) – or in the United States – 16.5 t DM ha<sup>-1</sup> (Maughan *et al.*, 2012). In addition, we observed a high yield variability between farmers' fields: plot yields varied for instance from 3.4 to 22.4 t DM ha<sup>-1</sup> for the third growth year.

**Table 5** Relationships identified during growth year one between potential limiting factors and shoot density

Limiting factors	Shoot density_1			
	Parameter value	SD	Relative importance value $w_+(x)^*$	
	After bootstrap		Before bootstrap	After bootstrap
Mh <sub>1</sub>	$9.95 \times 10^2$	$1.26 \times 10^3$	0.39	0.57
WATER <sub>1</sub>	$-5.82 \times 10^2$	$9.37 \times 10^2$	0.31	0.46
WEEDS <sub>1</sub>	$-9.33 \times 10^2$	$7.26 \times 10^2$	0.70	0.77

WATER, indicator of water deficit; Mh, indicator of available nitrogen; WEEDS, weed cover.

\*The larger  $w_+(x)$ , the more important variable is  $x$  regarding the explained variable.

**Table 6** Covariance analysis on weed cover (\*\*\*\*Significance with  $P < 0.001$ ; \*\*Significance with  $P < 0.05$ ; \*Significance with  $P < 0.1$ )

	Estimate	P-Value
Intercept	+3.2	$1.7 \times 10^{-2**}$
DIST	+0.15	$7.2 \times 10^{-3****}$
AREA	-0.39	$3.7 \times 10^{-1}$
SA-PREC	-0.37	$7.6 \times 10^{-1}$
L-SOIL	-0.65	$6.8 \times 10^{-1}$
SA-PREC : L-SOIL	+4.41	$5.7 \times 10^{-2*}$

DIST, distance from field to farm; AREA, field area; SA-PREC, set-aside as preceding crop; L-SOIL, hydromorphic loamy soil.

This variability is higher than the one observed on seven experimental sites with varying soil water availability in England: Price *et al.* (2004) measured third year yields ranging from about 5 to 15 t DM ha<sup>-1</sup>.

Following Jezowski *et al.* (2011) and Zub *et al.* (2011), we can regard yields measured in the third growth year in our farmers' field network as a good indicator of *M. giganteus* yield potential. On the basis of the comparisons made earlier, it appears that yield estimates commonly used in assessment studies dedicated to *M. giganteus* – for example 12–30 t DM ha<sup>-1</sup> for Lewandowski & Heinz (2003) and 15–25 t DM ha<sup>-1</sup> for Smeets *et al.* (2009) – tend to be overestimated compared to yields recorded in farmers' fields, especially the highest. We also highlighted the need to account for the reduction between experimental yields and commercial yields. Lastly, given the large yield variability observed between fields, the use of several assumptions on yield values should be generalized in assessment studies dedicated to *M. giganteus*.

*What are the main yield-limiting factors identified in farm conditions?*

We found that young *M. giganteus* yields in our farmers' field network were strongly limited by the shoot density established at the end of the establishment year:

planting success appears therefore to be decisive. Young *M. giganteus* crops with the lowest shoot densities at the end of the establishment year were indeed strongly penalized in terms of yield value and of yield increase the following years. Within a year, we found that yields were strongly related to shoot density, as observed by Clifton-Brown *et al.* (2007), Jezowski *et al.* (2011), Zub *et al.* (2011) and (Gauder *et al.*, 2012). On average, shoot densities reported in the literature – from 570 000 to 740 000 shoots ha<sup>-1</sup> (Clifton-Brown & Lewandowski, 2002; Jezowski *et al.*, 2011; Zub *et al.*, 2011; Maughan *et al.*, 2012) – are higher than the mean shoot density observed in our study. The fields we studied had very uneven stands: several contained areas with very few plants, and sometimes none at all. This is different from experiments in which missing plants are replaced after the planting year, as described by Clifton-Brown & Lewandowski (2002), Clifton-Brown *et al.* (2007) and Maughan *et al.* (2012), but agrees with observations in commercial fields. Zimmermann *et al.* (2013) indeed mentioned that field heterogeneity could be due to problems with the planting technique, bad rhizome quality, poor overwintering or small-scale variations in soil quality. We observed as well that poor tillering occurring after rhizome emergence during the establishment year could be an important source of heterogeneity in commercial fields. Planting success therefore depends on the whole establishment year and not only on the planting operation.

We also found yield variability to be strongly related to weed cover. Similarly, we showed that the shoot density of the first growth year was strongly related to weed cover. As weed competition with early growth of *M. giganteus* was not monitored from the beginning of the growing season, we cannot determine whether weed pressure decreased yields or whether lower biomass encouraged weed development. Our network included fields with high or even extreme weed cover at the end of the establishment year (e.g. 35%, 44%, 92%, Fig. 5). On most fields, weed cover decreased rapidly from the second year: crushing *M. giganteus* at the end of the

planting year allowed the development of a mulch, which was supplemented by the leaves falling during autumn and winter in the following years. However, fields with the highest weed cover at the end of the planting year also had the highest weed cover the later years (Fig. 5). As *M. giganteus* is known for being poorly competitive with weeds during the establishment year (Lewandowski *et al.*, 2000), we assume that on the fields with the highest weed density, weeds limited shoot tilering during the first year. We also suspect that the weed effect that we observed in the later years by the limiting factor selection procedure resulted from an interaction between the poor shoot development and the high weed development which occurred during the planting year.

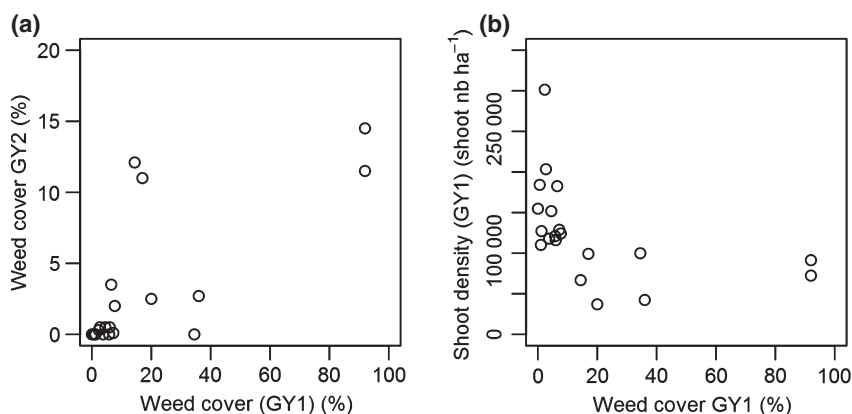
In experimental conditions, several authors (Heaton *et al.*, 2004; Richter *et al.*, 2008; Gauder *et al.*, 2012) reported that *M. giganteus* yields were limited by water availability. On our farmers' field network this was not the case, probably because most fields had a high soil water capacity (mean = 193 mm; range: 42 – 228 mm). Only three fields out of 20 had a soil water capacity of <100 mm. Two of these three fields were located on alluvial gravel soils close to rivers and probably benefited from a high water table. The third is one of the two fields with the lowest shoot densities and the lowest yields. Unlike Heaton *et al.* (2004) and Richter *et al.* (2008), we explored a narrow spatial climatic variability as our fields were located in the same supply area, while compared to Gauder *et al.* (2012), we explored a narrow temporal weather variability. Comparison with long-term climatic averages shows that the years included in our study were characterized by water deficits only slightly higher (241 and 276 mm in 2009 and 2011, respectively) or even lower (143 mm in 2010) than the mean value estimated over 20 years (222 mm). However, as we estimated the water stress indicator by adapting a water balance model commonly used for

annual crops (Sinclair & Ludlow, 1986; Muchow & Sinclair, 1991; Lecoer & Sinclair, 1996; Soltani *et al.*, 2000) and grapevine (Pellegrino *et al.*, 2005a,b), it would be valuable to assess the validity of this indicator for *M. giganteus*. Besides the narrow spatial and temporal variability explored in our field network, we can also hypothesize that the overriding influence of planting success concealed the influence of limiting factors operating at the annual scale. Further research is needed to adapt other stress indicators commonly used for annual crops – for example indicator for the diagnosis of plant N status, as pointed out by Cadoux *et al.* (2012) – and to characterize the crop sensitivity to several stresses according to the growth stage and to crop age. Finally, longitudinal studies would be valuable to see (i) whether yield trends over the years follow a similar pattern in commercial fields compared to the one observed in experimental fields and (ii) whether additional yield-limiting factors appear on the long run: Arundale *et al.* (2014a) showed for instance that nitrogen fertilization affected the intensity of yield decline with stand age observed for *M. giganteus* (Lesur *et al.*, 2013; Arundale *et al.*, 2014b).

*What could explain the large difference between plot yields and commercial yields?*

The large difference between plot yields and commercial yields could be due to three phenomena.

The first one deals with measurement errors. Commercial yields require complex procedures to be measured, especially when different harvesting methods are used and when farmers own several fields. Field heterogeneity makes it difficult to measure representative plot yields. Although our protocol to estimate plot yields was based on random plot selection, we did avoid field borders and areas where densities were so low that we could not have measured yield based on our method. Doing so, we



**Fig. 5** Influence of weed cover: (a) evolution of weed cover between growth year 1 (GY1) and growth year 2 (GY2); (b) shoot density as a function of weed cover at the end of GY1.

did not assess properly whether heterogeneity varied greatly between fields, or how it affected the difference between plot yields and commercial yields. Field heterogeneity combined with the high amount of biomass produced makes it challenging to measure *M. giganteus* yields in on-farm conditions and further research on that aspect would be very valuable. Setting a plot specifically in field borders, which are commonly more heterogeneous, could for instance improve yield estimation. Remote sensing techniques as proposed by Zimmermann *et al.* (2013) could also be improved to assess the effect of patchiness intensity on yield.

The second phenomenon could be related to the interval of time between plot yield measurements, carried out at the beginning of February, and commercial yield measurements, carried out from the end of March to the beginning of April. *Miscanthus giganteus* standing biomass peaks during autumn before declining during winter under the effects of leaf fall and of remobilization between the above-ground and the below-ground biomass (Strullu *et al.*, 2011; Cadoux *et al.*, 2012). Lewandowski & Heinz (2003) reported for instance 13% decline between February and March. In our field network, harvest timing was chosen to maximize the plant dry matter rate to facilitate biomass storage.

Lastly, the difference between commercial yields and plot yields could be due to losses occurring during the harvest process: biomass can be either uncut or not picked up by the harvesting machine. To our knowledge, harvest losses were never studied for *M. giganteus* but Monti *et al.* (2009) observed for switchgrass that biomass losses during the harvest, accounted from 35% to 45% of potential harvestable biomass. We observed in our field network that the cutting height was highly heterogeneous within a single field and between fields. We also observed that the amount of unrecovered biomass appeared visually higher in small fields and/or in fields with irregular shape. Lastly, the amount of unrecovered biomass seemed lower in fields harvested in bulk compared to bales. The harvesting method was, however, determined by the distance between the field and the cooperative society. As a result, harvest in bulk cannot be generalized. We therefore agree with Zegada-Lizarazu *et al.* (2013) who emphasized the need to develop better harvest techniques and to improve harvest machinery to reduce biomass losses in the field.

#### *Cropping M. giganteus on marginal lands?*

Cropping *M. giganteus* on marginal lands may be a way to limit land competition between food crops and non-food crops. Although marginal lands are not clearly defined (Batidzirai *et al.*, 2012), according to CGIAR

(Consultative Group on International Agricultural Research, 1999) they can be land affected by biophysical (drying soil, water saturated soil, steepness of terrain, etc.) or socio-economic constraints (land legal status, remote fields, etc.). In our study, we found that fields with the most weed development (i) were located far from the farm or (ii) combined hydromorphic loamy soil and set-aside as preceding land-use (i.e. large weed-seed banks and physical conditions favouring weed development). The hydromorphic nature of soil might also have affected planting success due to waterlogging (Zimmermann *et al.*, 2013). In parallel, former set-aside fields also have a high click beetle pressure, which can decrease emergence and tillering if it is not controlled (P. Béjot, personal communication). Interviews with the farmers showed that they chose those fields to plant *M. giganteus* because the crop was described as a way to cultivate fields that were left as set-aside lands, located in environmentally sensitive areas or were difficult to manage due to their size, shape, remoteness or environment, to decrease the competition of energy crops with food production. However, our study showed that such marginal lands may require special care during the establishment phase, particularly as regards weed control. In addition, we could also wonder whether marginal lands could have a higher risk of harvest losses. Monti *et al.* (2009) shown indeed for switchgrass that field slope affected the amount of unrecovered biomass during the harvest process. Our field observations suggested that fields of a particular size or shape (small or narrow) could also present a higher risk of harvest losses. Further research would be valuable on that topic: measuring harvest losses for *M. giganteus* would be of particular interest and a special focus should be made on marginal lands, as they can be defined as difficult to manage.

#### Acknowledgements

This study was funded by the Futurol Project. We would like to thank P. Béjot (Bourgogne pellets) for his help in designing the farmers' field network and collecting some of the data related to emergence rate and commercial yields. We also thank the farmers who were involved in the on-farm network, the technical staff of the UMR Agronomie for their valuable support with field work, especially Arnaud Butier, Gilles Grandeau and Dominique Le Floch. We also would like to thank Stéphane Cadoux and Loïc Strullu (INRA) who shared their expertise on *M. giganteus* with us. Finally, we thank Alan Scaife for English revisions and the anonymous reviewers for their constructive comments.

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