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Assessing the impact of within crop heterogeneity ('patchiness') in young *Miscanthus* × *giganteus* fields on economic feasibility and soil carbon sequestration

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Abstract

In Ireland, *Miscanthus* × *giganteus* has the potential to become a major feedstock for bioenergy production. However, under current climatic conditions, Ireland is situated on the margin of the geographical range where *Miscanthus* production is economically feasible. It is therefore important to optimize the yield and other ecosystem services such as carbon sequestration delivered by the crop. A survey of commercial *Miscanthus* fields showed a large number of areas with no *Miscanthus* crop cover. These patches can potentially lead to reduced crop yields and soil carbon sequestration and have a significant negative impact on the economic viability of the crop. The aim of this research is to assess patchiness on a field scale and to analyse the impacts on crop yield and soil carbon sequestration. Analysis of aerial photography images was carried out on six commercial *Miscanthus* plantations in south east Ireland. The analysis showed an average of 372.5 patches per hectare, covering an average of 13.7% of the field area. Using net present value models and a financial balance approach it was shown that patchiness has a significant impact on payback time for initial investments and might reduce gross margins by more than 50%. Total and *Miscanthus*-derived soil organic carbon was measured in open patches and adjacent plots of high crop density showing significantly lower *Miscanthus*-derived carbon stocks in open patches compared to high crop-density patches (0.47Mg C ha^{-1} ± 0.42 SD and 0.91Mg C ha^{-1} ± 0.55 SD). Using geographic information system (GIS) it was shown that on a field scale *Miscanthus*-derived carbon stocks were reduced by 7.38% ± 7.25 SD. However, total soil organic carbon stocks were not significantly different between open patches and high crop density plots indicating no impact on the overall carbon sequestration on a field scale over 3–4 years since establishment for these *Miscanthus* sites.

Keywords: bioenergy, crop patchiness, ecosystem services, gross margins, *Miscanthus*, net present value, soil carbon sequestration, soil organic carbon

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Introduction

In recent years the use of biomass for energy production, particularly in Europe and North America, has increased significantly (Sims *et al.*, 2006; European Commission, 2011). The main drivers of this development are the possible reduction in greenhouse gas (GHG) emissions and independence from fossil fuels. While national and international legislation is promoting the use of bioenergy by setting mandatory renewable energy targets or subsidizing biofuel production (e.g. European Parliament, Council, 2009; Department of Agriculture, Fisheries & Food, 2010) the costs and benefits of producing bioenergy have generated controversy within the scientific community. Major concerns are the impact on biodiversity and the efficiency of carbon saving (e.g. Dauber *et al.*, 2010; Anderson-Teixeira *et al.*, 2011; European Commission, 2011; Jorgensen, 2011).

The use of *Miscanthus* × *giganteus* (Greef et Deu ex Hodkinson et Renvoize) (Greef & Deuter, 1993; Hodkinson & Renvoize, 2001) as a bioenergy crop has been a focus of research in the last decade (e.g. Lewandowski *et al.*, 2000; Clifton-Brown *et al.*, 2007; Styles *et al.*, 2008). This perennial, rhizomatous C_4 grass, originating from south-east Asia is highly adaptable to most of European climates with estimated yields between 13

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and 25.8 Mg ha^{-1} (Clifton-Brown *et al.*, 2004). In Ireland, the introduction of *Miscanthus* has been subsidized by the government for the last few years with the most recent bioenergy scheme having come into operation in August 2012 (Department of Agriculture, Fisheries & Food, 2010). In the Irish context, *Miscanthus* has been estimated to have both economic and environmental benefits with gross margins of 326 to 383 € ha^{-1} when used for direct combustion (Styles *et al.*, 2008) making it a viable alternative to conventional crops. However, the estimates of the gross margin are particularly dependent on market dynamics and the total biomass yield.

Miscanthus has a carbon mitigation potential of 4.0–5.3 Mg C ha^{-1} yr^{-1} (Clifton-Brown *et al.*, 2007) and has been shown to sequester significant amounts of carbon into the soil (e.g. Clifton-Brown *et al.*, 2007; Dondini *et al.*, 2009). Furthermore, Zatta *et al.* (2013) and Zimmermann *et al.* (2012) found that the introduction of *Miscanthus* to arable or grassland does not lead to a significant reduction in soil organic carbon. To optimize carbon benefits from *Miscanthus* it is important to understand all factors influencing soil carbon sequestration.

Recent studies conducted in the United Kingdom and Ireland have reported patchiness in *Miscanthus* fields (Semere & Slater, 2007; Bellamy *et al.*, 2009; Sage *et al.*, 2010; Zimmermann *et al.*, 2012). Possible reasons for this patchiness are problems with the planting technique, bad rhizome quality, poor overwintering, or small-scale variations in the soil quality (Lewandowski *et al.*, 2000; Price *et al.*, 2004; Atkinson, 2009). Most of these earlier studies focussed on the impact of patchiness on biodiversity, but it can be expected that the patchiness also has a significant impact on the biomass yield, which especially in the Irish context could compromise the economic performance of *Miscanthus*. Economic studies show relatively low sensitivity of the economic viability of *Miscanthus* production to a reduction in the expected yields (Styles & Jones, 2008; Styles *et al.*, 2008), assuming lower yields are associated with lower inputs. Currently gaps in the crop cover are not covered by economic models. As Ireland is situated on the margin of economically viable *Miscanthus* production (Clifton-Brown *et al.*, 2004; Stampfl *et al.*, 2007) site specific yield losses due to gaps in the crop cover might render the *Miscanthus* production uneconomic for farmers. Furthermore, due to its high establishment costs, *Miscanthus* introduction represents a considerable financial risk to producers, and financial returns in the initial years of production are especially important to pay back initial debt and therefore improve the perceived risk balance of *Miscanthus* to farmers (Styles *et al.*, 2008).

Although soil carbon sequestration currently has no direct impact on the economic feasibility of *Miscanthus*, it is an important ecosystem service. Land-use change related carbon dynamics is an important part of the national greenhouse gas inventory report (NIR) as defined in the Kyoto protocol (United Nations, 1998) and the loss of soil organic carbon due to land-use change has been identified as a major factor in increasing atmospheric CO_2 levels (Smith *et al.*, 2008). During the 1990s, soils have emitted about 1.6 ± 0.8 Pg C yr^{-1} of carbon to the atmosphere due to land-use change (Schimel *et al.*, 2001; IPCC, 2007). Historical carbon losses due to cultivation and disturbance have been estimated to be between 40 and 90 Pg carbon globally (Schimel, 1995; Houghton, 1999; Houghton *et al.*, 1999; Lal, 1999). The support of soil carbon sequestration through clean development mechanisms under the Kyoto Protocol is currently focussed on afforestation and reforestation, however, the importance of soil carbon sequestration in agriculture in relation to land-use, land-use change, and forestry (LULUCF) is well recognized (IPCC, 2000, 2006). It is likely that in the future soil carbon sequestration in agriculture will become a part of the NIR, and that carbon credits will be allocated to this ecosystem service.

It can be expected that in open patches sequestration of *Miscanthus*-derived soil organic carbon is significantly lower than in areas of normal or high crop density. As the main sources of soil organic matter are plant litter and root material (e.g. Schneckenberger & Kuzyakov, 2007) large gaps in the crop cover can significantly reduce the soil organic carbon input and therefore directly influence soil carbon sequestration. Whether non-crop plants that have been observed to reach high cover densities in such gaps (Semere & Slater, 2007; Bellamy *et al.*, 2009) can compensate for the lower levels of *Miscanthus*-derived soil organic carbon is currently not known.

The aim of this study is to assess the patchiness in commercial *Miscanthus* fields and analyse the impacts on the crop yield and soil carbon sequestration using an integrated field-measurement, and remote sensing approach. The study comprised three major steps. (i) Field measurements of the difference in soil carbon sequestration in open patches and high crop density plots in *Miscanthus* fields; (ii) assessment of the patch properties in selected fields using remote sensing; (iii) assessment of the impact of patchiness on soil carbon sequestration and crop yield on a field scale. It is hypothesized that the patchiness will significantly reduce the crop yield and soil carbon sequestration on a field scale, and that the yield reduction will significantly increase the payback time, as well as lower the gross margin for *Miscanthus* producers.

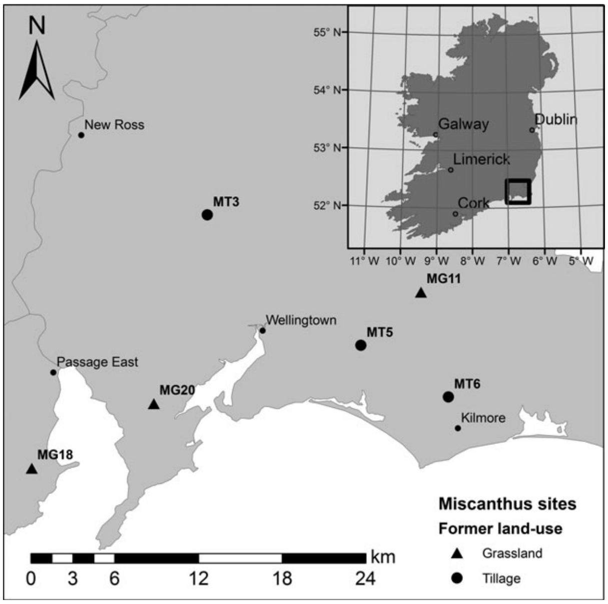

Fig. 1 Location and site ID of field sites and former land-use of *Miscanthus* fields.

Materials and methods

Field sites

The soil sample collection was conducted in May/June 2010. Figure 1 shows the locations and the field codes of the sites. Further information is shown in Table 1. All *Miscanthus* fields were planted in 2006 or 2007, so that the *Miscanthus* plantations were at the end of the establishment phase (Karp & Shield, 2008) at the time the experiment was conducted. The selection criteria were an elevation of maximum 120 m a.s.l., a minimum field size of 2 ha, and the availability of an adjacent on farm control site. The control site was a field representing the former land-use, grassland or tilled land, of the *Miscanthus* field. For the analyses it was important that both the *Miscanthus* and the control sites had not recently been used to cultivate a C_4 crop (i.e. maize). The planting of the *Miscanthus* crop has been carried out by an external contractor; therefore the farmers were not able to provide information on planting techniques used. However, as all farms were supplied by the same contractor it can be assumed that no differences in planting technique were apparent.

Soil sampling and sample preparation

Soil from four treatments, i.e. high crop-density *Miscanthus*, open patch, for the two former land-use categories, grassland and tillage, respectively, as well as from the respective on farm control sites was collected. The open patch and high crop-density plots were sampled as matched pairs. A matched pair was defined as two adjacent subplots nested within each farm. Within each category four randomly distributed subplots were sampled using a soil auger (Ø 5.6 cm). Five soil samples up to 30 cm soil depth were taken in each subplot situated at least 1m from the edge of the subplot. The soil samples were divided into three depths 0–10 cm, 10–20 cm, and 20–30 cm. Four of the samples were then pooled according to depth to account for small-scale variation. The fifth sample was used for bulk density measurement. Soil bulk density was measured by weighing a known volume of oven dried soil (105 °C), afterwards stones (>2 mm) were removed and their volume and weight determined. The core weight and volume was corrected for stone content and the bulk density was then calculated by dividing the corrected soil weight by the corrected volume.

The collected soil was air dried and passed through a 2 mm mesh-size sieve and residual biomass larger than 2 mm was removed manually. The soil was then ground using a ball mill and approximately 30 mg were transferred into silver capsules. Any carbonate carbon was removed using the acid fumigation method (Harris *et al.*, 2001). In addition, soil pH was measured from 3 g soil suspended in 12 ml distilled water using a Jenway 4330 pH meter.

Carbon measurements

Miscanthus-derived carbon (SOC_{Mis}) was determined using the ^{13}C natural abundance method. While photosynthesis generally leads to lower ^{13}C values in plant organic matter compared with atmospheric CO_2, the degree of depletion is dependent on the photosynthetic pathway. Organic matter in C_4-plants shows distinctly higher ^{13}C abundance than in C_3-plants. In an environment with only one source of C_4-derived soil organic carbon (e.g. *Miscanthus*) the isotopic signal can be used to quantify the amount of carbon derived by that given source (Balesdent & Balabane, 1992).

Table 1 Parameters of the sampled *Miscanthus* sites, elevation was measured using one GPS measurement. Particle size distribution, bulk density, and pH values are averaged over 30 cm sample depth and the subplots

Site ID	Former land-use	*Miscanthus* planted in	Elevation (m a.s.l.)	Clay (%)	Silt (%)	Sand (%)	pH	Bulk density (g cm^{-3})
MT3	Tilled land	2006	73	4.6	21.9	73.5	5.98	1.03
MT5	Tilled land	2006	38	12.2	34.8	53.0	6.39	1.04
MT6	Tilled land	2006	13	11.5	31.0	57.5	6.29	1.17
MG11	Grassland	2007	90	7.1	29.7	63.2	6.37	1.01
MG18	Grassland	2006	56	4.8	19.8	75.5	5.68	1.02
MG20	Grassland	2006	32	9.9	27.1	63.1	6.78	0.83

The ^{13}C abundance is expressed relative to the international PDB carbon standard (PeeDee formation belemite) according to the equation

$$\delta^{13}C = ((R_{Sample} - R_{Reference})/R_{Reference}) * 1000 \quad (1)$$

where R_{Sample} is the $^{13}C/^{12}C$ ratio of the sample and $R_{Reference}$ the $^{13}C/^{12}C$ ratio of the PDB carbon standard.

Using the stable isotope mass balance the fraction of *Miscanthus*-derived carbon can be calculated, given knowledge about (i) $\delta^{13}C$ of SOC before *Miscanthus* plantation ($\delta^{13}C_{old}$); (ii) $\delta^{13}C$ of SOC after *Miscanthus* plantation ($\delta^{13}C_{new}$); and (iii) $\delta^{13}C$ of *Miscanthus* plant material ($\delta^{13}C_{Mis}$). With x being the fraction of $\delta^{13}C_{Mis}$ the isotope mass balance can be written as

$$x = (\delta^{13}C_{new} - \delta^{13}C_{old})/(\delta^{13}C_{Mis} - \delta^{13}C_{old}) \quad (2)$$

The $\delta^{13}C_{old}$ values were taken from the $\delta^{13}C$ values of the respective adjacent control sites at the corresponding depths. It is important that neither the *Miscanthus* sites nor the control sites had any C_4 cropping history as this could have biased the results. The $\delta^{13}C$ of the *Miscanthus* plant represents an average of shoot, root, and rhizome material (value taken from M. Dondini, personal communication). All $\delta^{13}C$ values, as well as total SOC values, were measured by the UC Davis Stable Isotope Facility using a PDZ Europa ANCA-GSL elemental analyser interfaced to a PDZ Europa 20–20 isotope ratio mass spectrometer (Sercon Ltd, Cheshire, UK). All carbon contents are measured from the depths 0–10 cm, 10–20 cm, and 20–30 cm. Using the measured bulk density the measured carbon contents given in g C kg^{-1} soil were converted into area based carbon stocks (Mg C ha^{-1}).

Data analysis

All data sets showed a normal distribution and no transformations were applied. Due to the nature of the isotope mass balance, negative SOC_{Mis} values result from higher $\delta^{13}C$ values in the control site compared with the corresponding *Miscanthus* site. Negative SOC_{Mis} values can therefore indicate a C_4-history or a local source (e.g. cow dung) of high $\delta^{13}C$. As the analysis is based on the assumption that the control site represents the $\delta^{13}C$ value prior to *Miscanthus* planting, with *Miscanthus* being the only source of higher ^{13}C carbon, a higher $\delta^{13}C$ value in the control site renders a matched pair unfeasible for the analysis. As SOC_{Mis} values can be close to zero, inaccuracy in measurement can also lead to negative values, therefore, to avoid positive bias, only negative outliers were removed. Data points outside the 1.5 interquartile-range were considered outliers.

The statistical analysis was carried out using analyses of variance (ANOVAS) to account for the nested structure of the experimental design (crop density nested in farm) by introducing farm (F) as an error term. *Miscanthus*-derived carbon stocks (SOC_{Mis}) as well as total SOC stocks (SOC_t) were used as response variable. As this study focuses on the field scale, the soil organic carbon stocks were summed over the 30 cm sampling depth for the statistical analysis. Former land-use (LU_f; grassland vs. tillage) and crop density (Dens; open patch vs. high crop density plot) were used as response variables. To account for possible interactions between the response variables an initial model was run, taking all possible interactions into account. In a stepwise selection process all non significant terms were removed ($P > 0.05$). The analysis was carried using the NLME package in the R-project software (Pinheiro *et al.*, 2010; R Core Team, 2012). Differences between numbers of large and small patches were analysed using a paired t-test with numbers: small (≤ 5 m^2) and large (>5 m^2) patches being defined as pairs per farm.

Assessment of patchiness

High resolution aerial imagery from Bing maps (Microsoft, Redmond, Washington, USA) was used for the remote sensing analysis for all field sites. To be suitable for the analysis the imagery required a sufficient resolution to enable patch identification. Furthermore, the images must have been recorded when the crop canopy was fully developed (ideally between August and October) as patches cannot be recognized directly after harvest, and are difficult to identify in earlier growth stages or after winter senescence. To assess the number and size of patches in *Miscanthus* fields a geographic information system (GIS)-based analysis of remote sensing imagery was used. Patches were identified using a combination of spatial analysis and manual digitizing. Smaller patches are generally shaded by surrounding *Miscanthus* and can therefore be identified as dark areas. The dark areas were identified and converted into polygons. In a second step, the polygons were compared with the aerial images and errors were corrected manually (typically large patches that were not shaded.) The finished polygons were then used to analyse the patch number, average patch size, and the overall loss of cropped area due to patchiness. All spatial operations were conducted using ArcGIS 10 ($ArcGIS_{TM}$, ESRI, Inc., Redlands, CA, USA). Ground-truthing was carried out by measuring 172 patches randomly distributed among the farms using a hand-held Thales Magellan MobileMapper CE GPS receiver (Arc Pad 7.0). As the data were non normal, the Spearman-rho correlation coefficient was used to compare the field measurements with the remote sensing measurements.

Effect of patchiness on yield

The effect of patchiness on yield was estimated by calculating the loss of total yield in each field due to the reduction in effectively cropped area as a result of patchiness. It was assumed that the yield in the open patches is zero. To assess the economic impact for farmers, two model approaches were used, (i) a net present value model (NPV); and (ii) a financial balance approach. Discounted annualized net present values represented the difference between discounted costs and discounted income over the 21 year plantation lifetime, divided by 21 years. The approach was based on an updated version of the NPV model used in Styles *et al.* (2008). The financial balance approach enabled the determination of the number of years after establishment that plantations break even under different yield and patchiness scenarios. The model parameters

Table 2 List of the financial parameters for the net present value (NPV) and financial balance model. Fertilizer costs were calculated for a nutrient take-off by a 13.5 Mg ha^{-1} (dry matter) harvest and scaled down to fit the alternative yield scenarios (not taking patchiness into account). Harvest and storage were also based on 13.5 Mg ha^{-1} (dry matter) harvest, for alternative scenarios costs were scaled down, also patchiness was taken into account. Removal costs were incurred at the end of year 21.

Parameter	Value	Source
Establishment		
Establishment costs	€ 2595 ha^{-1}	Caslin (2009)
Establishment grant	€ 1295 ha^{-1}	
Total	€ 1300 ha^{-1}	
Fertilizer application		DEFRA (2001) (amount)
Costs		CSO (2012) (Costs)
220 kg 8 : 5 : 18 N : P : K	€ 444 t^{-1}	
255 kg CAN	€ 333 t^{-1}	
140 kg Muriate of potash	€ 462 t^{-1}	
Total for 88 : 11 : 95 N : P : K	€ 248 ha^{-1}	
Spreading	€ 15 ha^{-1}	O'Donovan & O'Mahony (2012)
Harvest and storage	€ 270 ha^{-1} yr^{-1}	Caslin (2009)
Removal cost	€ 200	
Biomass price	€ 75 Mg^{-1} DM	

are shown in Table 2 and apply for both approaches. The biomass price of 75 € Mg^{-1} for dry matter is a conservative estimate based on current market prices of about 60 € Mg^{-1} (20% moisture content) (Caslin, 2009). The NPV approach was employed with an annual discount rate of 5%, while the financial balance approach assumed a 5% annual interest rate applied to all remaining debt. The models were calculated for three yield levels representing dry matter harvested off takes during spring harvest of: 10.5 Mg ha^{-1} yr^{-1}, 12 Mg ha^{-1} yr^{-1}, and 13.5 Mg ha^{-1} yr^{-1}. These yields represent the possible range in Ireland (Clifton-Brown *et al.*, 2000; Stampfl *et al.*, 2007). Fertilizer application rates, and associated costs, were scaled according to the three (expected) yield levels without patchiness. The impact of patchiness was therefore determined in relation to the expected baseline yield of a theoretical non-patchy field. Furthermore, it was assumed that the peak yields were achieved from years 3 to 17 after establishment of the crop. During years one, two, and three crop yields were set at zero, 30% and 60% of the peak yield (Clifton-Brown *et al.*, 2007) while for years 18–21 an annual 10% decline in peak yield was assumed. *Miscanthus* has been postulated to produce stable yields for 15–20 years (Lewandowski *et al.*, 2000) although no yield data are currently available from older *Miscanthus* trials in Ireland to conclusively support this assumption. A fall in yield after 18 years of the crop life-cycle is seen as an incentive for producers to remove the crop (J. Finnan, personal communication). The models were run for five levels of patchiness for each of the three yield types: 0%, 10%, 20%, 30%, and 40%.

As direct yield measurements were not possible on the surveyed commercial sites, the total yield was estimated using the MISCANFOR model (Hastings *et al.*, 2009). The model was run for the year 2009 using soil data from the Harmonized World Soil Database (FAO, 2009), and CRU 2.1 0.25 degree climate data for the period 1970–2002 (Climatic Research Unit, University of East Anglia). The model was used to calculate peak yield (before senescence) as dry matter. To estimate the harvest yield for spring the results had to be corrected for repartition of nutrients, leaf fall, and stubble left in the field after harvest, using the factor 0.66 based on Clifton-Brown *et al.* (2004). The modelled data were used as a baseline representing a non-patchy field. The reduction in crop yield due to patchiness was then calculated by reducing the effectively cropped area by the sum of the area of all patches in the respective fields.

Effect of patchiness on soil carbon sequestration

To measure the effect of patchiness on soil carbon sequestration the SOC_{Mis} values measured in high crop density *Miscanthus* and open patches were interpolated onto two respective 0.5 m rasters using kriging. The open patch SOC_{Mis} value raster was then clipped using polygons that represented the patchiness for the corresponding fields as derived from the aerial images, creating raster files representing SOC_{Mis} values for the modelled patches of each field. This raster was then merged with the high crop density SOC_{Mis} value raster using the mosaic function, creating a full coverage of modelled patchiness for a field. The average SOC_{Mis} values were then calculated for each raster in each field as well as the high crop density SOC_{Mis} raster file representing a field with no patches. All spatial operations were conducted using ArcGIS 10 and all raster operations were carried out using the spatial analyst toolbox.

Results

Crop patchiness

Analysis of the aerial imagery showed that open patches can be classified into three groups: (i) small randomly distributed patches (see Fig. 2a–f); (ii) linear features with either a number of small patches aligned along a line, or large stretches of open patches (especially visible on Fig. 2a–c); and (iii) as large open areas with few *Miscanthus* shoots growing (Fig. 2a, f, both in the south-eastern corner of the field.) The comparison of patch areas measured in the field and with remote sensing showed a significant ($P < 0.01$) correlation (correlation coefficient 0.55). The results of the GIS-based remote sensing analysis are summarized in Table 3. Standardized to patches per hectare, all sites show similar patch numbers (on average 372.54 ± 31.96 SD). The average patch was 3.67 m^2 ± 1.24 SD. Considering the patch size distribution, it can be shown that about half of the total

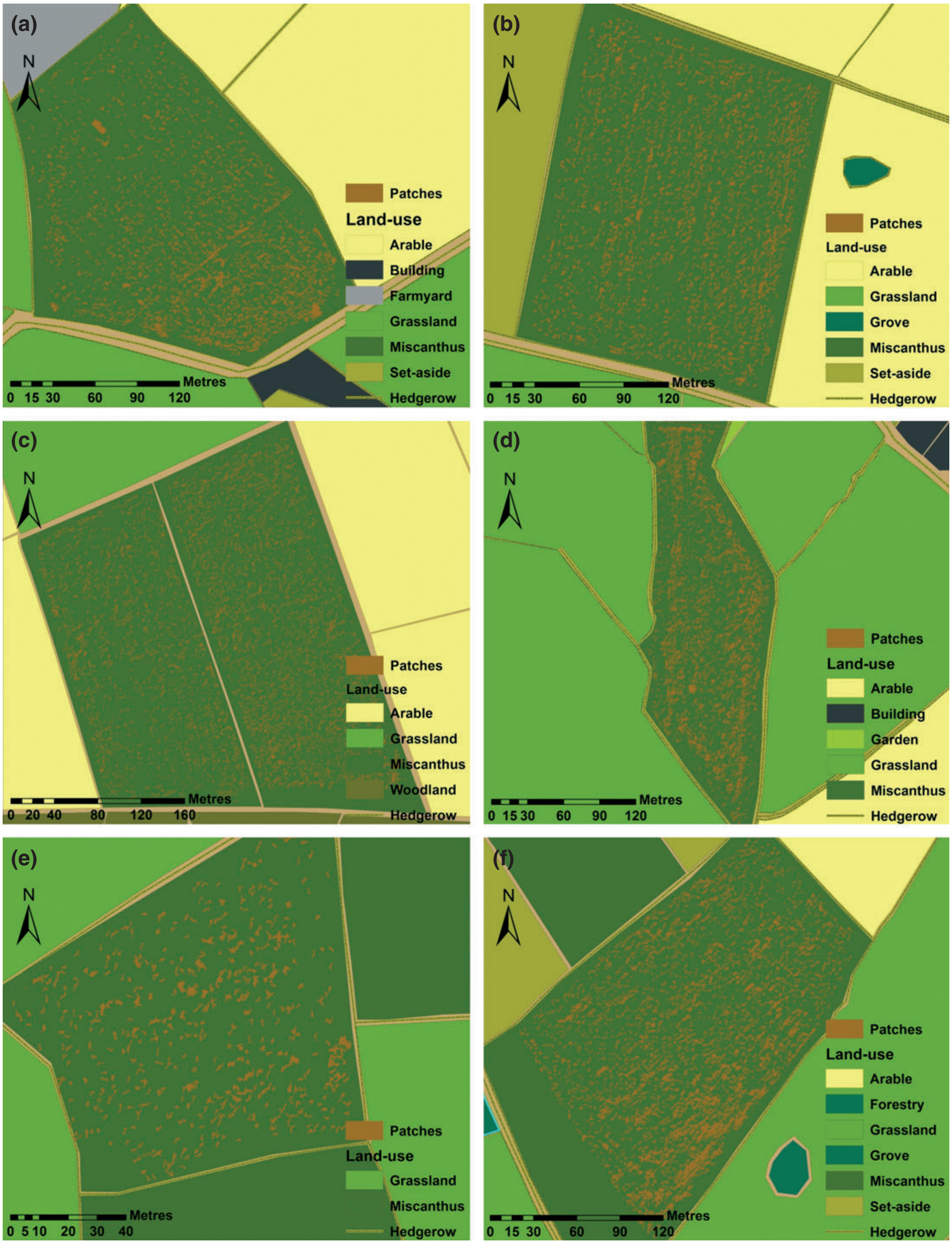

Fig. 2 Map of the patches in the *Miscanthus* field on sites (a) MT3, (b) MT5, (c) MT6, (d) MG11, (e) MG18, and (f) MG20.

open patch area (47.64% ± 22.31 SD) is contributed by patches larger than 5 m^2. However, the number of large patches is significantly lower than the number of small patches (195.33 ± 91.45 SD vs. 1207.50 ± 813.87 SD, $P < 0.01$). The loss of cropped area due to open patches calculated using the remote sensing approach is shown in Table 6. The average loss of cropped area is 13.69% ± 4.71 SD. Field MG11 showed the highest, and MG18 the lowest reduction in cropped area.

Impact of patchiness on economic feasibility

Figure 3 shows annualized discounted gross margins. For the mid yield estimates (12 Mg ha^{-1} yr^{-1}), dis-

Table 3 Summary of the patchiness estimated using remote sensing

Farm	Field size (ha)	Number of patches		Average patch size (m^2)	Total patch area (ha)
		Total	Per ha		
MG11	2.450	859	350.62	5.51	0.47
MG18	1.061	389	366.78	2.18	0.08
MG20	3.562	1455	408.53	4.72	0.69
MT3	3.691	1217	329.69	3.59	0.44
MT5	3.631	1491	410.63	3.28	0.49
MT6	8.269	3051	368.97	5.78	0.85

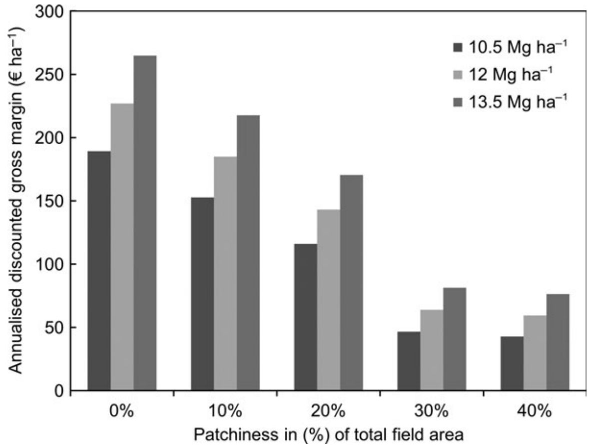

Fig. 3 Annualized discounted gross margins under different yield (Mg ha^{-1}) and patchiness scenarios.

counted gross margins almost halve, from 265 € ha^{-1} yr^{-1} to 170 € ha^{-1} yr^{-1}, as patchiness increases from 0 to 20%. Similar proportionate declines occur for the high and low yield levels. At patchiness levels of 40 to 50 % the gross margin is reduce to one third, compared to a non-patchy field.

The results of the financial balance approach are shown in Figure 4. Changes in patchiness up to 20% lead to a payback period between 4 and 7 years for all modelled baseline yields. When looking at 30% and 40% patchiness, establishment costs are paid back within 9 and 11 years, depending on the baseline yields, independent of the patchiness. Generally the time to pay back initial costs increases with lower assumed yields. The estimated yields of the surveyed *Miscanthus* sites are summarized in Table 3. According to the NPV model, two sites show a reduction in the gross margin of almost 50% due to patchiness (MG11 and MG20).

Total soil organic carbon and Miscanthus-derived carbon

The average total soil organic carbon stocks (SOC_t) and the *Miscanthus*-derived carbon stocks (SOC_{Mis}) under

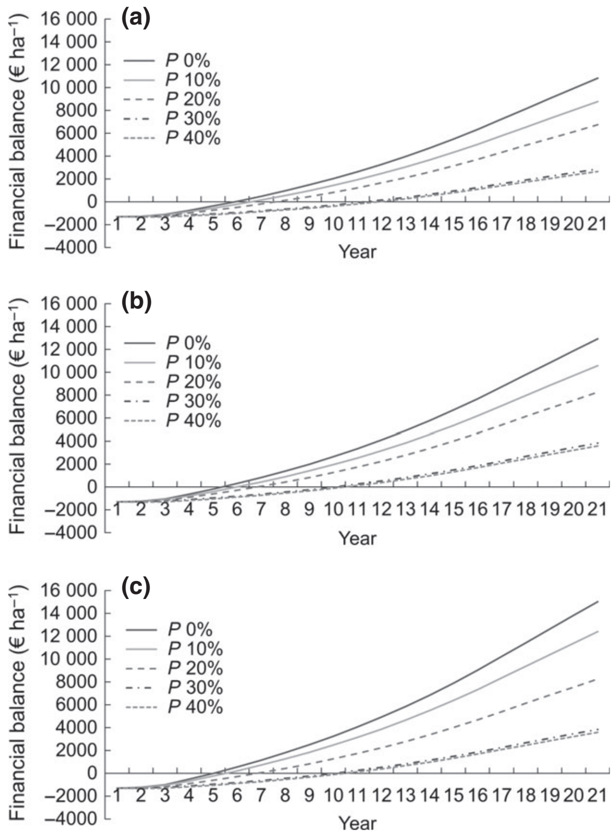

Fig. 4 Evolution of financial balance over plantation lifetime for (a) 10.5 Mg ha^{-1} yr^{-1}, (b) 12 Mg ha^{-1} yr^{-1}, and (c) 13.5 Mg ha^{-1} yr^{-1} harvested yield for the different patchiness scenarios (P in % reduction in crop cover).

either high or low crop density are summarized in Table 4. The final two models describing the influence of the parameters, former land-use (LU_f) and crop density (Dens), on SOC_t, and SOC_{Mis} are shown in Table 5. Crop density did not show any significant influence on SOC_t and was therefore removed in the selection process of the first model. However, *Miscanthus* fields planted on grassland show significantly higher SOC_t values than fields planted on former tilled lands.

Table 4 Summary of the average total soil organic carbon (SOC_t) and *Miscanthus*-derived soil organic carbon (SOC_{Mis}) stocks (±*SE*)

Former land-use	Crop density	Sample depth (cm) 10	20	30
SOC_t (Mg ha^{-1})				
Tillage	H	20.50 (±*0.64*)	20.42 (±*0.98*)	15.73 (±*0.99*)
	L	19.50 (±*0.87*)	20.35 (±*0.80*)	14.73 (±*1.41*)
Grassland	H	28.87 (±*2.47*)	34.25 (±2.84)	21.83 (±*1.74*)
	L	27.88 (±*1.38*)	38.12 (±*4.05*)	19.76 (±*2.80*)
SOC_{Mis} (Mg ha^{-1})				
Tillage	H	1.37 (±*0.17*)	0.94 (±*0.11*)	0.78 (±*0.09*)
	L	0.91 (±*0.19*)	0.60 (±*0.12*)	0.62 (±*0.11*)
Grassland	H	1.71 (±*0.25*)	0.30 (±*0.17*)	0.37 (±*0.17*)
	L	0.78 (±0.19)	−0.21 (±*0.17*)	0.13 (±*0.14*)

Table 5 Summary of the ANOVAS used to explain differences in total soil organic carbon stock (SOC_t) and *Miscanthus*-derived carbon stocks (SOC_{Mis}); * $P < 0.05$ and ** $P < 0.01$

Response variable	Explanatory variables	dF	*F*-value	*P*-value	Sig.
Total soil organic carbon (SOC_t)					
	LU_f	1	13.34	<0.01	**
Miscanthus-derived carbon (SOC_{Mis})					
	Dens	1	15.86	<0.01	**

Table 6 Estimated impacts of patchiness on crop yield, cropped area, and *Miscanthus*-derived carbon (SOC_{Mis}) stocks

Farm	Yield (Mg ha^{-1}) Baseline	With patches	Reduction (%) Cropped area	SOC_{Mis}
MG11	13.2	8.26	−19.31	−11.23
MG18	11.88	10.07	−7.98	−1.75
MG20	13.2	9.18	−19.28	−21.09
MT3	11.88	8.87	−11.85	0.77
MT5	13.2	10.10	−13.54	−8.37
MT6	13.2	10.94	−10.24	−5.00

The second model, best explaining SOC_{Mis} shows an influence of the factor 'Dens', with significantly higher SOC_{Mis} values under high crop density plots compared to open patches. The factor LU_f had no significant influence on SOC_{Mis} and was therefore removed from the second model during the selection process.

Table 6 summarizes the estimated reduction in *Miscanthus*-derived carbon in the top 30 cm of the soil column due to patchiness compared with a non-patchy field. The average estimated reduction on a field scale is 7.38% ± 7.34 SD. The highest estimated reductions are seen on sites MG20 and MG11. Site MG18 shows the lowest reduction. An exception is site MT3 showing an increase in *Miscanthus*-derived carbon with increasing patchiness.

Discussion

The analysis showed a similar abundance of patches on all surveyed farms. The significant correlation between GPS based and remote sensing based area measurements showed sufficient quality of the measured data. The categorization of the patches described earlier allows for possible explanations for the occurrence of patches; (i) linear patches are likely to be explained by congestions in the rhizome planting machinery, which has been reported by landowners (personal communication); (ii) large patches are often situated in depressions (e.g. MG20), suggesting problems with water-logging; and (iii) small randomly distributed patches might occur when single rhizomes are damaged during pre-planting storage, which has been reported by landowners, and therefore are not able to germinate. Furthermore, small-scale variation in the soil properties and poor overwintering might also lead to open patches. The authors are not aware of another study quantifying the patchiness in *Miscanthus* fields therefore a comparison with other data is not possible, however, similar patchiness of around 25% is reported in commercial *Miscanthus* plantations in Lincolnshire (personal communication Blankney Estates Ltd, Blankney, Lincolnshire, UK).

The estimated loss of yield could have a significant impact on the economic viability of *Miscanthus* plantations. The NPV model showed that depending on the expected yield, patchiness can lead to a significantly reduced gross margin over the whole crop life-cycle. In particular, systems with already low baseline yields might not be able to achieve positive gross margins. In our analysis, two sites show a significant reduction in the gross margin with two sites having the gross margin reduced by about 50% (MG11 and MG20). Higher levels of patchiness such as reported in Lincolnshire, UK (25%, personal communication Blankney Estates Ltd) may even lead to a two thirds reduction of the gross margin for farmers, depending on the baseline yield. The financial balance approach shows that *Miscanthus* plantations typically break even after between 4 and 11 years, with patchiness being the main reason for longer amortization times. Increased payback periods are likely to have a significant impact on farmers' acceptance of the crop as a possible alternative to conventional crops, reflecting a typical aversion to commit to long-term financial investments in an uncertain economic climate and fluctuating commodity prices (Styles *et al.*, 2008; Augustenborg *et al.*, 2012). The financial balance model indicates that the economic feasibility of *Miscanthus* is relatively robust to patchiness but does not discount future benefits, and may thus provide an 'optimistic' representation of long-term investments such as *Miscanthus* establishment.

Although soil carbon sequestration has at present no direct financial implications for *Miscanthus* producers, it is an important ecosystem service as it is recognized as a major greenhouse gas sink (e.g. Smith *et al.*, 2008), and it is likely that in future carbon credits will be allocated to it. Therefore, maximization of soil carbon sequestration could become an economically, as well as ecologically, advantageous objective.

Field measurements showed a significant reduction in *Miscanthus*-derived carbon in open patches, compared with directly adjacent high crop density plots. This indicates that processes leading to soil carbon sequestration under *Miscanthus* can be categorized into highly localized and more extensive ones. Localized contributions to the soil organic carbon pool are most likely root excretions and dead root material, whereas plant litter is generally more evenly distributed especially during harvest (Beuch, 1999; Kahle *et al.*, 1999). This might also have implications for the stability of the carbon sequestered, which is subject to further research.

It has been shown that on a field-scale patchiness can lead to a considerable reduction in *Miscanthus*-derived carbon stocks, the only exception being site MT3. However, as MT3 was the first site to be sampled during the field campaign it is possible that open patches were not correctly identified during this early stage of annual growth. Total SOC stocks did not differ significantly between open patches and high crop density. At this early stage of crop establishment, *Miscanthus*-derived carbon does not represent a large portion of the overall soil organic carbon stocks. As shown in Zimmermann *et al.* (2012), there was no significant difference in soil organic carbon stocks between pre-*Miscanthus* land-use and *Miscanthus* plantation. A number of studies have shown a significant shift in the origin of soil organic carbon under *Miscanthus* crops (Schneckenberger & Kuzyakov, 2007; Dondini *et al.*, 2009), indicating that the reduction in *Miscanthus*-derived carbon input under open patches might lead to significant differences in total soil organic carbon stocks during the *Miscanthus* lifecycle. However, Schneckenberger & Kuzyakov (2007) also found no significant differences in total soil organic carbon contents between grasslands and a 9 year old *Miscanthus* site. Long-term changes in soil organic carbon stocks might therefore depend on the former land-use. As most patches had a high cover of grasses and other plants, it is therefore possible that losses in *Miscanthus*-derived carbon will be compensated by inputs of C_3-plant derived carbon. To assess the long-term impact of patchiness on soil organic carbon stocks it is necessary to conduct further research on older plantations.

From an economic point of view it is in the best interest of *Miscanthus* producers to maximize the crop yield. Taking measures to minimize patchiness, such as careful soil preparation and planting should be management priorities. The analysis of remote sensing imagery showed that it is possible to reduce patchiness by about 50% through the avoidance of large patches, therefore significantly reducing the gross margin losses to the farmer. Depending on the source of patchiness, it may be possible to replant open patches. However, if underlying site specific properties such as waterlogging or small-scale variations in soil properties inhibit *Miscanthus* growth it may be assumed that the area is unsuitable for *Miscanthus* establishment. Replanting small random patches is difficult as they can often not be identified due to the height and density of the *Miscanthus* vegetation. In addition, in small patches it is difficult for young infill plants to establish and survive as they are outcompeted for light by the more vigorous established plants (personal communication, Blankney Estates). However, it was shown that the contribution of small patches towards overall patchiness is lower than that of large patches.

This study showed the importance of assessing crop patchiness in *Miscanthus* stands at the field scale especially for economic considerations. Analysis of the impact of patchiness on crop yield and *Miscanthus*-derived carbon stocks showed considerable reductions in both parameters. Using net present value models and a financial balance approach, it was shown that measured levels of patchiness can significantly reduce gross margins and can potentially render *Miscanthus* uneconomical for farmers. Especially in Ireland, where crop yields are already relatively low, patchiness can seriously undermine the economic viability of this energy crop. The study also shows a significant reduction in the *Miscanthus*-derived portion of the soil organic carbon stocks under open patches. However, long-term studies are required to assess if this will lead to an overall reduction in soil organic carbon stocks under *Miscanthus* as grasses and weeds growing in the patches may show similar soil carbon sequestration rates to *Miscanthus* and therefore compensate reductions in soil carbon sequestration.

This study assumed a linear relationship between crop patchiness and yield losses. It is, however, likely that competition levels will change on the edges of patches and directly affect biomass production and soil carbon sequestration in the vicinity of patches. Although effects of water, nutrient, and light availability are well understood (Beale & Long, 1997; Vleeshouwers, 1998), the effects of patchiness on all of these factors are likely to be highly complex. Light availability is strongly influenced by the size of patches as well as the spatial alignment of more linear features (i.e. east-west vs. north-south). Water and food competition are likely to interact with weed cover and composition in open patches. Therefore, any current estimate of competition effects of patches on adjacent *Miscanthus* plants is likely subject to large error and requires more detailed research.

In conclusion, patchiness can be significantly reduced through careful site selection and preparation, and by avoiding congestions in the planting machinery. Areas that are prone to waterlogging are unsuitable for *Miscanthus* cultivation and should be avoided. Large open patches identified after establishment may be replanted. Randomly occurring small patches are difficult to identify on site, however, their proportion of overall patchiness is relatively small and losses in soil carbon sequestration might be compensated by a more abundant non-crop vegetation. Overall, further research on the reasons for and the impacts of crop patchiness in *Miscanthus* stands will be required to fully understand possible challenges and benefits.

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