

Received: 26 November 2019

Revised: 21 February 2020

Accepted: 7 April 2020

DOI: 10.1111/gcbb.12690

ORIGINAL RESEARCH



WILEY

Commercial experience with miscanthus crops: Establishment, yields and environmental observations

Anita Shepherd¹  | John Clifton-Brown²  | Jason Kam³ | Sam Buckby³ | Astley Hastings¹

¹Institute of Biological and Environmental Sciences, School of Biological Sciences, University of Aberdeen, Aberdeen, UK

²Institute of Biological, Environmental & Rural Sciences (IBERS), Aberystwyth University, Aberystwyth, UK

³Terravesta, Stable Court, South Carlton, UK

Correspondence

Anita Shepherd, Institute of Biological and Environmental Sciences, School of Biological Sciences, University of Aberdeen, 23 St. Machar Drive, Aberdeen AB24 3UU, UK.

Email: anita.shepherd@abdn.ac.uk

Funding information

Natural Environment Research Council, Grant/Award Number: NE/P019951/1 and NE/M019691/1; University of Aberdeen; UK Research and Innovation, Grant/Award Number: EP/S029575/1

Abstract

This study investigates the condition of commercial miscanthus fields, growers' concerns and reasons for growing the crop and also the modelling of a realistic commercial yield. Juvenile and mature *Miscanthus × giganteus* crops of varying age are surveyed in growers' fields across mid-England. We record in-field plant density counts and the morphology of crops of different ages. Mature crops thrive on both clay and sandy soils. Plants surveyed appear robust to drought, weeds and disease, the only vulnerability is rhizome condition when planting. Mature miscanthus planted pre-2014 continues to develop, spreading into planting gaps and growing more tillers. In stands planted post-2014, improved planting techniques reduce planting gaps and create a reasonably consistent planting density of 12,500 plants/ha. The main reason for growers' investment in miscanthus is not financial return, but relates to its low requirement for field operations, low maintenance cost and regeneration. This offers practical solutions for difficult field access and social acceptability near public places (related to spray operations and crop vandalism). Wildlife is abundant in these fields, largely undisturbed except for harvest. This contributes to the greening of agriculture; fields are also used for gamebird cover and educational tours. This crop is solving practical problems for growers while improving the environment. Observed yield data indicate gradual yield increase with crop age, a yield plateau but no yield decrease since 2006. In stands with low planting densities, yields plateau after 9 years. Surveyed yield data are used to parameterize the MiscanFor bioenergy model. This produces options to simulate either juvenile yields or a yield for a landscape containing different aged crops. For mature English crop yields of 12 t ha⁻¹ year⁻¹, second- and third-year juvenile harvests average 7 t ha⁻¹ year⁻¹ and a surrounding 10 km by 10 km area of distributed crop age would average 9 t ha⁻¹ year⁻¹.

KEY WORDS

bioenergy, bioenergy industry, bioenergy yield, commercial growers, grower experience, MiscanFor, miscanthus, modelling, survey, wildlife

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1 | INTRODUCTION

Miscanthus × giganteus (referred to as $M \times g$; Figure 1) is a sterile hybrid of *Miscanthus sacchariflorus* and *Miscanthus sinensis* (Greef & Deuter, 1993; Hodkinson & Renvoize, 2001). It is a crop mainly used for combustion in the United Kingdom for heat and power generation. Harvested yields of $M \times g$ cane from mature crops are typically 12–20 t ha⁻¹ year⁻¹ dry matter biomass in Europe (Harvey, 2007). When harvested, miscanthus has a higher dry matter content than trees or short-rotation coppiced willow (Defra, 2019), and the energy content of the feedstock is 18 KJ/kg, as much energy as wood, only quicker to grow.

For bioenergy power stations it is a field-to-furnace local resource, where it is used as a feedstock in various forms (as bales, pellets or dust) either alone or used in co-firing in conjunction with coal or wood. Around 55 kT of miscanthus was used in UK power stations for electricity in 2016/17, this was around three quarters of all miscanthus produced in England that year (Defra, 2019). Continuous increases in tonnage occurred since 2013/14, increasing 57% from 2015/2016 to 2016/17. This reflects a transition to increased biomass capacity by existing power stations, and new localized biomass power stations.

In the United Kingdom miscanthus is not converted into liquid biofuels as it has been proposed in North America (Heaton, Dohleman, & Long, 2008), and miscanthus has other niche markets, such as being converted into livestock bedding or domestic fuel (fire logs, barbecue briquettes and fire starters; Terravesta, 2019). It can also be used as in-fill in timber frames for building construction (Centre for Alternative Technology, 2017).

Once planted and fertilized in the first two seasons, miscanthus is a permanent crop requiring no field management except harvest. This makes it a rare field crop and may influence both the economic decisions of the grower, and its environmental effects. Therefore we need to understand the environmental effects of $M \times g$, vulnerabilities of $M \times g$ and why growers choose to invest in the crop as an aid to determining its long-term development and its effects on the countryside.

Miscanthus is a perennial long-lasting crop, requiring little management beyond harvesting, therefore in a commercial

field it may have to withstand drought and flood events. Although resistant to most pests and diseases, overtime it may become vulnerable to fungal pathogens (Beccari, Covarelli, Balmas, & Tosi, 2010; Scauflaire et al., 2013). If rhizomes are mechanically damaged at planting it can reduce the yield of the following year (Meehan, McDonnell, & Finnan, 2012; Nixon & Bullard, 2003). In the previous years, some young plants have not survived planting or the first winter, and rhizome damage has depended on the quality of the planting method and machinery. Of interest is the morphology of the plants and how they have changed with age and planting technique. Rhizome planting machinery has developed and improved over the years, and especially since 2014. Originally, rhizomes were broadcast planted using a manure spreader followed by cultivation and rolling, this resulted in unpredictable plant spacing and low establishment rates (Defra, 2007). Then potato planters were used, and then 2009–2012 the miscanthus development company Bical developed miscanthus planters which had a randomized distribution of rhizomes along the row, and planted at a greater spacing than modern planters. Since 2014 precision planting machinery has been developed (Fulghum, Fazio, Spell, Sawyer, & Hedrick, 2016, for example).

$M \times g$ may not obtain the same yields in commercial fields as in plot trials. Plots are representations of the farm, and they contain youthful plants with vigour. A crop's vigour is not sustained at a high level for the full potential commercial life of up to 15–20 years (Lesur et al., 2013).

The growth, yield and carbon sequestration potential of this useful crop is often modelled for quantifying the supply chain of bioenergy generation, or the potential of carbon capture schemes. MiscanFor (Hastings, Clifton-Brown, Wattenbach, Mitchell, & Smith, 2009) is a miscanthus growth, environmental system and power generation model. MiscanFor is a useful tool for policy support or the grower industry to calculate net present value and economic payback or break-even years, known to be highly sensitive to yields (Yesufu, 2019). It is a daily mechanistic simulation requiring soil and climate databases, and outputs average annual yield values on a gridded basis globally. It has six phenological stages of crop development and senescence: rhizome dormancy, shoot development, leaf development, leaf senescence, plant senescence and peak harvest. The model assumes a full-grown crop producing mature yields. Best practise guidelines (Defra, 2007) state that miscanthus reaches mature yields in 3–5 years depending on site conditions and agronomic practices, and this study investigates if this is true across England for a range of locations and crop ages.

MiscanFor has already been developed and updated (Shepherd, Littleton, Clifton-Brown, Martin, & Hastings, 2020) to predict mature $M \times g$ crop yields globally. There are several reasons why we aim to further improve its harvest yield simulation.



FIGURE 1 *Miscanthus × giganteus* seen in June 2019, rhizomes planted 2015 (left) and 2006 (right)

- a. The current model has been parameterized and validated using mature yield data from experimental plots. In order to further calibrate the model, we need to know what realistic average yields are obtained by commercial growers and for a range of crop ages in a parcel of landscape.
- b. The current model does not calculate the ramp up of year-on-year yields during establishment years, this study uses commercial data to quantify a gradual increase of yield increase during establishment. This option would effectively treat crops as a stand of a single age increasing to maturity.
- c. The MiscanFor model determines biomass, decarbonization and energy per hectare, then averages that value over the bioenergy crops in a grid square parcel of land (often 10 km × 10 km for the United Kingdom) so that it can map the results. It also totals these parameters for national or global results. This means that as an alternate option to (b) within a grid square of land, we require a realistic simulated yield instead of a mature yield that reflects a mix of miscanthus crops of various ages in the landscape.
- d. We would like to see how a $M \times g$ crop grows as it ages, and how the yield increases. Despite growers being advised that miscanthus will produce yields for at least 15 years (Defra, 2007), there is not much literature on the yields and plant development of older $M \times g$ crops in the UK.

Factors (a) to (d) above make up part of the ‘yield gap’ between experimental plots and commercial practice, and models and measurements in the real world, and have a significant impact on the economics of the crop for farmers and the feedstock users.

Bioenergy developments have become a cause for concern due to the potential negative impacts on food security (FAO, 2010). Studies are involved with the issue of reconciling food and bioenergy and their competition for land resources (Kline et al., 2017; Popp, Lakner, Harangi-Rákosa, & Fáric, 2014). Although this is a small study, part of its aim was to find out what the growers thought and were concerned with. In the United Kingdom, with a miscanthus crop bringing a price per tonne equal with wheat, would growers choose to plant it instead of food crops?

It is generally recognized that the miscanthus bioenergy crop is better for the environment than annual monocultures. It is seen as a zero emissions crop because it stores more carbon in the soil than it releases, and after establishment requires little pesticide and no fertilizer (Fernando, Duarte, Almeida, Boléo, & Mendes, 2010). $M \times g$ has substantial leaf-fall and deep roots, both of which increase organic matter and improve soil structure. This enhances rainwater percolation into the soil, decreasing water run-off. The leaf cover also reduces erosion of soil (Fernando et al., 2010). It also

protects the soil from compaction due to heavy machinery (Finch et al., 2009). Because it requires minimal nutrients and management, it is seen as a beneficial use of degraded or waterlogged land and shallow soils that are of little use for food crops (Jeżowski et al., 2017; Mann, Barney, Kyser, & Tomaso, 2012).

It is also thought to encourage biodiversity, it is recommended to have a buffer around a crop of $M \times g$ to manage hedgerows and allow bird flight into surrounding trees or hedges. Additionally, a buffer of wildflowers encourages pollinators in the landscape, and increases biodiversity of birds, insects, weeds and invertebrates (Lighthouse, 2010).

Our objective is to study commercial fields, crop metrics and yield, and their surrounding environment and talk with growers, and discover why the growers chose to invest in miscanthus. This study uses year-on-year commercial yield measurements to parameterize the MiscanFor model to represent the establishment period, and modify yield to better represent a mix of crop ages contained within a grid square of 10 km by 10 km.

2 | MATERIALS AND METHODS

2.1 | Sites and resources

This study used a grower network affiliated with our industrial partner Terravesta Assured Energy Crops Ltd. Terravesta is the largest supplier of miscanthus in Britain, providing 50 kT/year of miscanthus bales from its growers to dedicated 40 and 44 MW straw burning power stations near Lincoln (Brigg) and in Norfolk (Snetterton) respectively (Brigg biomass, 2019; Snetterton biomass, 2019). In 2016, Terravesta negotiated 15-year contracts to supply these two power stations. To support the expansion of miscanthus biomass, Terravesta supplies its growers with rhizomes of $M \times g$ and specialized rhizome planting machinery, assists in the development of harvesting technology and manages the sale of the biomass to the renewable energy power stations. Although protocols for establishment of $M \times g$ rhizomes are relatively mature, a Terravesta agronomist fine tunes the recommendations according to site-specific temporal and spatial conditions to maximize the establishment success (percentage of rhizomes planted growing into plants). This attention to detail at planting delivers high establishment rates, plants in the second year form a canopy in June, and weeds are suppressed without further herbicide applications. After the second growing season, harvests are made annually in springtime following overwinter senescence. During senescence growth nutrients are returned to the rhizome for the next year's growth, and the biomass quality is improved through lower moisture and ash contents. No other field management is

required. In mild winters, where senescence is incomplete in genotypes such as *M. × giganteus*, mowing and then windrowing before baling will remain an important harvest method even though harvest losses are higher (Lewandowski et al., 2016).

Terravesta asked their growers across England to collaborate on our grower survey and crop surveys. This was a small project and funding was sufficient for two 5-day working weeks of field time for one person, which resulted in surveys of 10 *M × g* fields. Terravesta growers were centred in the region around Terravesta's Lincolnshire headquarters but also spread across mid-England. In May 2019, we visited growers' fields who had sourced *M × g* rhizomes from Terravesta (see Figure 2 of field locations underlain by the Soilsmap map at 1:250,000 scale; Cranfield Soil & AgriFood Institute, 2019). As Terravesta provides an assured bioenergy market for the growers and buys back the crop, it holds records for the harvests, as do most growers.

2.2 | Grower questionnaire

A list of growers was contacted for permission to access the fields and participate in a questionnaire on their miscanthus crop. The year of rhizome planting was noted, and growers were asked for yield data on the field sampled for as many years as they had available.

Each grower was asked a set of questions about the condition of their land and why they chose to plant *M × g* which is currently the only commercially grown variety of miscanthus (see Appendix SI—survey questions and Appendix SII—survey responses).

2.3 | Field survey

Records of yield were obtained for a specific field, calculated from miscanthus average bale weight and number of bales harvested, and the crop area, obtained from both grower and Terravesta records.

Four quadrats of 5 m width by 25 m length were set out in fields of various sizes, distributed evenly in four quarters of the field but at least 10 m from field buffers. Crops too near a field buffer do not show representative crop metrics. This is an area the growers tend to reseed if sparser than the inner field, so growth will not be as advanced, and therefore representative, of the main crop. Since 2014, miscanthus has been planted in rows with 1 m spacing, so this area should ideally contain 125 plants. Crops planted prior to 2014 were not planted in rows and had a wider spacing. The amount of missing plants was estimated in each quadrat. Once familiar with a field, this was not difficult to determine since plants had an approximately even spacing, and a space had either other plants encroaching and no remnant pattern of a rhizome (a space from planting), or it had a wider space and a remnant

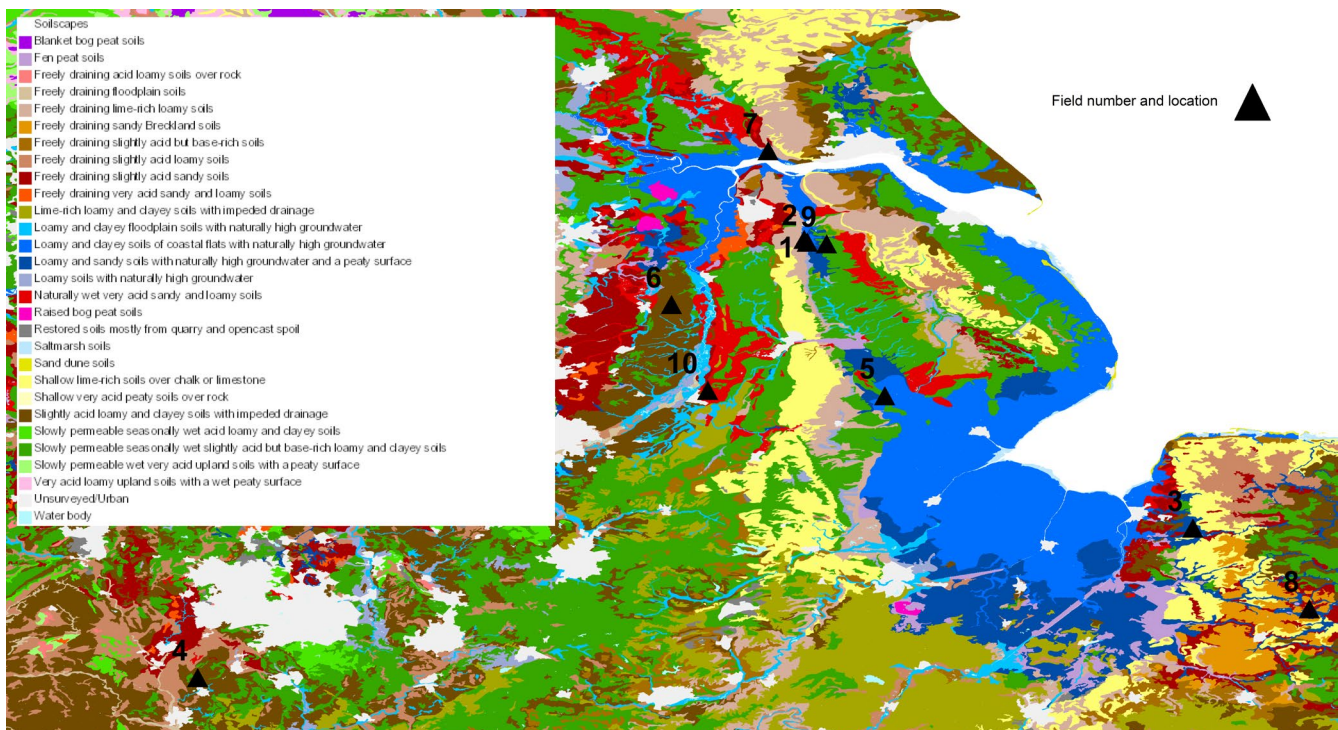


FIGURE 2 Eastern and central mid-England showing location of miscanthus fields surveyed, underlain by the Soilsmap map at 1:250,000 scale (Cranfield Soil & AgriFood Institute, 2019)

pattern of a rhizome under the leaf debris (indicating crop dieback). The height of the plant at sampling date was measured and we counted the number of tillers. Crop density was estimated by taking the no. of tillers per plot, the mean of four plots and multiplying up to the field area to give the crop density. These parameters allowed comparison of the morphology between the crops of different ages countrywide at the same growth stage within a 2 week period of sampling. A mature $M \times g$ shoot is approximately 50 g dry matter, which would allow an approximation of the loss of yield due to plants not surviving (J. Clifton-Brown, pers. comm. gained from extensive in-field experience). Loss was determined from the number of visibly missing rhizomes, multiplied by the average number of tillers per plant in the plot multiplied by 50 g per tiller. The yield measured in bale records was the harvestable yield. There was about 5% wastage of debris remaining on the ground after swathing, which was not counted as yield but was an organic amendment to the soil.

Site crop, soil and environmental data were collated into tables and field notes (Appendices SIII and SIV respectively).

2.4 | Calibrating juvenile crop yield for the MiscanFor model

We defined 'juvenile' as a crop that had not reached its peak potential harvest. We could have defined it as years 1 to 3, but that would be misleading because it may take longer than three years for the yield increase to plateau at maturity, thus it was necessary to determine the number of years to reach a yield plateau using crop yields from a range of ages. The yield data in our sampling included a mixture of crops, younger ones with recent improvements in planting and more sparsely planted older crops. This was representative of a mixture in the landscape for the average yield per 10 km square area. It was the average yield resulting from a mosaic of crop age and planting type that we were interested in to calibrate a model for a realistic picture of energy potential and soil carbon sequestration totals across the landscape.

2.5 | Crop yield correction

2.5.1 | Juvenile yield

The observed data were split into one half for calibration and one half for validation. Yield data from juvenile crops (under 10 years) showed a gradual increase in yield with age of crop. Linear, polynomial, power and logarithmic regression lines were fitted to the calibration data (half the observed data, Appendix SIII; Table 1). The line of best fit (Figure 3a) was a logarithmic relationship between the yield and the age of the crop below 10 years (juvenile yield = $5.5165 \cdot \ln(\text{years of age}) + 1.0279$).

TABLE 1 Existence of groundwater support

Sand/clay soils and groundwater support	Groundwater support	
	Yes	No
Soil texture		
Tends towards clay	5	2
Tends towards sandy	0	3

age) + 1.0279), r^2 is .72, root mean square error (RMSE) of calibration as % of mean measured value = 16.1%.

We applied the calibration to modify the MiscanFor model which simulates mature yields, as a postsimulation modification to determine juvenile yields. The mean simulated mature yield of the calibration data used is $12 \text{ t ha}^{-1} \text{ year}^{-1}$. The calibrated juvenile yield based on age of crop is divided by 12 and multiplied by the mature yield possible at a location (postsimulation of mature yields). In this way, we multiply modelled mature yields by the proportion of yield reduction expected during stand maturation.

In model simulations, we replace the first 10 years which would have previously been mature crop yields with a reduction factor applied to the location's mature yield value, i.e.

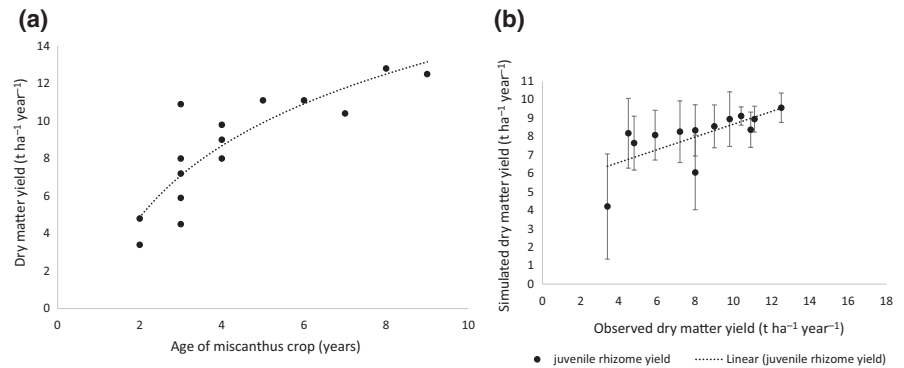
$$\text{juvenile yield} = (5.5165 \cdot \ln(\text{years of age}) + 1.0279) \times \text{max yield}/12.$$

The data are amended for juvenile plants postsimulation in the model, it is shown plotted against measured yield with standard error bars (Figure 3b), r^2 is 0.5, RMSE 24.4%. The r^2 and RSME are limited by the size of the dataset in this small project. MiscanFor overestimates the juvenile yield below 7 t/ha. Another limitation with the simulated-observed plot of Figure 3b represents the model data from a grid with 10 km spatial resolution have been used for model comparison to the observed yield from a specific location and soil, hence we have shown the simulated yield variation using local soil types within that grid square. In a prestudy analysis (not shown), it was discovered that observed yield differences were not discernible pre- and post-2014 planting for the same juvenile crop age, so there was no need to split the dataset any further. The overestimation could be related to the scale of soil parameters used in the model and the soil parameters at the sampling location, but the overestimation is consistent and so infers a slight bias in the model.

2.5.2 | Even crop age distribution of yield

Prior to this study, the MiscanFor model was used to simulate mature yields. We applied the calibration, as a postsimulation

FIGURE 3 (a) Juvenile rhizome yield regression with rhizome age, r^2 .72, RMSE 16.1%; (b) Simulated juvenile yield with standard error reflecting uncertainty for model scale plotted against observed yield, r^2 .5, RMSE 24.4%



modification, to determine yields for areas of mixed crop ages, from juvenile to mature. It was assumed that a 10 km by 10 km grid square contained an even distribution of crop ages from juvenile to mature. We used the calibrated curve of gradual yield increase with crop age to a plateau at 10 years, and took the area under the calibration curve (Figure 3a). The definite integral of $y = 5.5165 * \ln(x) + 1.0279$ between 1 and 10 years = 92.4 t/ha, divided by 10 years produced an average yield of 9.24 t ha⁻¹ year⁻¹ for miscanthus crops from juvenile to maturity, where a mature crop would have had a yield of 12 t ha⁻¹ year⁻¹ for these locations. We applied this age-related correction to variable mature yields, and multiplied the mature yield by the fraction 9.24/12 (mean variable minus age yield divided by its equivalent mature yield) which is 0.77. We summarized the correction factor for a yield of mixed crop ages, extracted from a yield increase over 10 years as

$$\frac{\left(\sum_{\text{age}=1}^{\text{age}=10} \text{yield}(\text{age})\right) / 10}{\text{yield}(\text{age} = \text{maturity})}$$

and applied it postsimulation to mature yields at other locations.

3 | RESULTS

3.1 | Grower questionnaire and field survey

The percentage responses from growers about problems encountered in pre- and post-2014 crops were represented in a bar chart constructed from a contingency table (Figure 4). Four out of six post-2014 fields were randomly picked to create the same sample sizes for pre- and post-2014 planting. Only a visualization of the association between categories could be made, between-variable interpretation was not possible (Beh, 2008). Nearly all field soils were over 60 cm depth, all fields were agricultural land grade 3–4. Few growers reported problems with weeds, waterlogged harvest or summer drought. Furthermore, there was no major difference reported by growers in terms of crop dieback or weeds, water logging or drought between miscanthus crops sown

pre- and post-2014. The graphs indicated low level reporting of reduced weed severity post-2014. A grower reported crop dieback in problematic field no. 4 of the data. Although planting gaps were seen they were visually different from plant dieback (as explained in Section 2), and crop dieback was not observed in any fields except field 4. The grower reported that field 4 had been planted with dry rhizomes in dry soil. It is commonly accepted in industry and among growers that miscanthus rhizomes need to be cool and well-watered prior to planting (Defra, 2007). Tables for grower survey response data for the 10 fields can be seen in Appendix SII—Grower survey responses. Tables summarizing collated data for the 10 fields can be seen in Appendix SIII—Collated crop survey metrics, soil and environmental data.

Farmers were asked to choose a suitable field for us to survey, this could have been skewed by roadside access but was not, several fields chosen were nowhere near a road, being half a mile or more down a field track. A wide variety of field sizes were chosen and surveyed (Figure 5).

Bioenergy crops are not irrigated in England. We considered groundwater support, and defined it as an easily available or high water table from which water could be drawn by capillary action under a strong soil matric potential during a drought. Based on responses from growers on existing groundwater support, most soil with groundwater support was found to contain slight clay rather than sand (Table 1). No fields had heavy clay soil except field 4, which was located in the west of England. Fields in Lincolnshire sit on recurring bands of clays and sands, dry periods can be variable spatially and a local phenomenon. Lincolnshire and Norfolk also have many land drains running across the landscape to prevent waterlogged fields but during a drought, water may seep back to the field. Based on third crop year yield data, there was no difference in median yield (Figure 6) between groundwater-supported crops and nonsupported. There was however a higher groundwater-supported mean yield, with a wider inter-quartile range and higher maximum yield. The nonsupported yield had a greater number of minimum yield outliers. Our May survey occurred during a spring drought of several weeks with hardened soils, this appeared to have no effect on the crops which were robust and healthy during

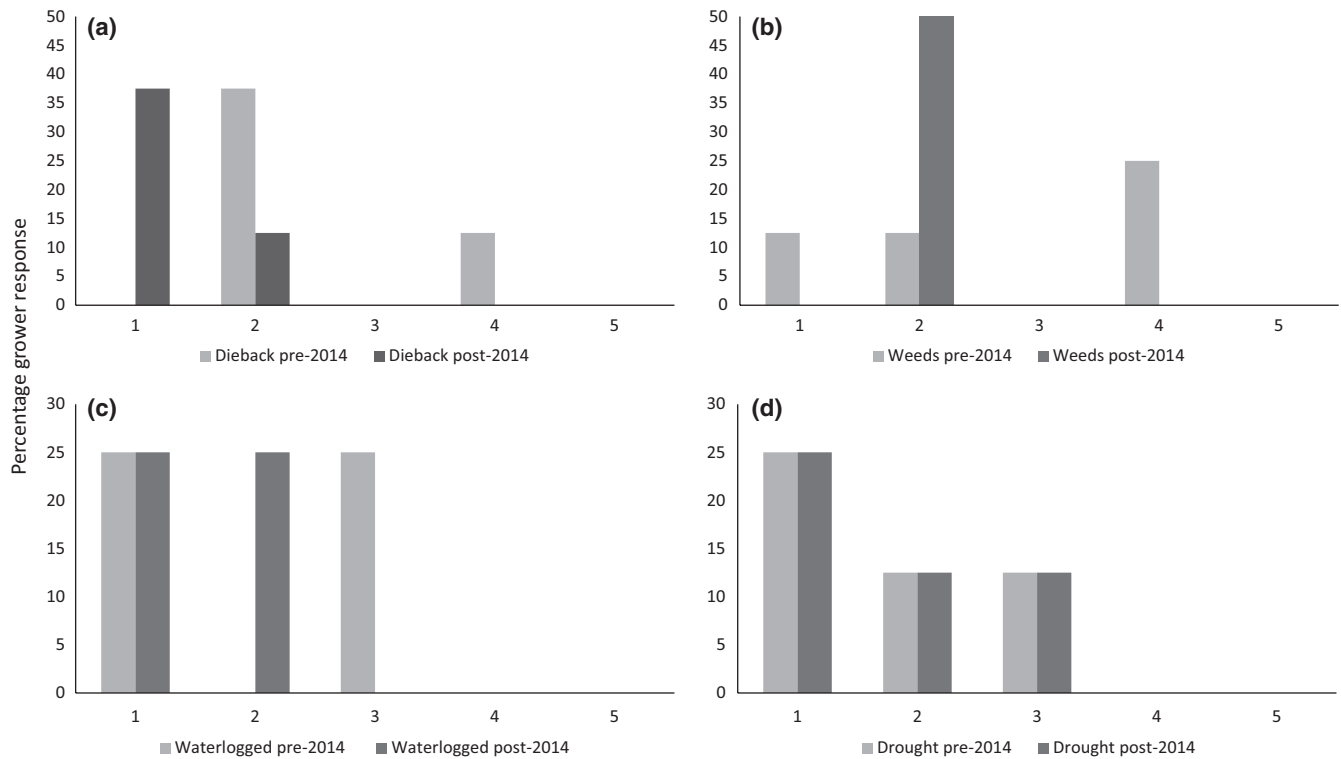


FIGURE 4 Percentage grower response pre- and post-2014 to problems of: (a) crop dieback, (b) weeds, (c) waterlogged harvest and (d) summer drought. Response: 1 = none/very little up to 5 = very much. Number of replies: $n = 10$

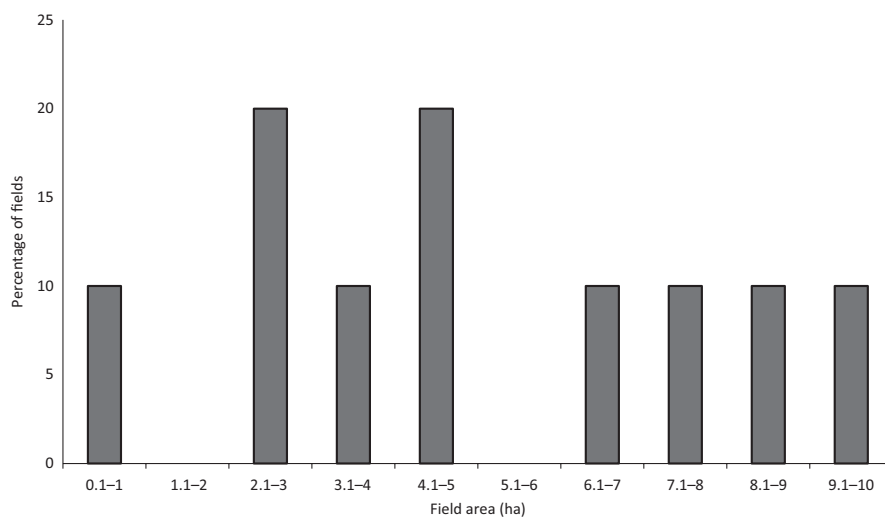


FIGURE 5 Size of surveyed fields (ha)

the survey. Nevertheless these statistics support the fact that yields improve with a source of water support.

Based on our crop yield data collated with reported weed problems from the grower's survey, there was no evidence to show that the level of weed pressure made any difference to the yield in the third crop growth year (Figure 7). The median and mean yield differences were minimal, fields with very little weed cover had a wider inter-quartile range from higher and lower yields, and the outlier values were similar. Thus we found little evidence of weed pressure affecting

yield. It should be noted that by the third year, the crop was establishing itself, but that initial weed spraying with a broad spectrum herbicide would have been carried out at initial establishment in first and second growth years. During our crop survey, no heavy weed pressure was seen, weeds were seen in areas of some fields where there was a lower density of plants, although a good ground cover of debris will help kept weed cover low.

It is also worth noting that, when asked about the possibility of rhizome fungal infections, growers had neither

FIGURE 6 Box and whisker plot of third year yield with groundwater support (YES) and without groundwater support (NO)

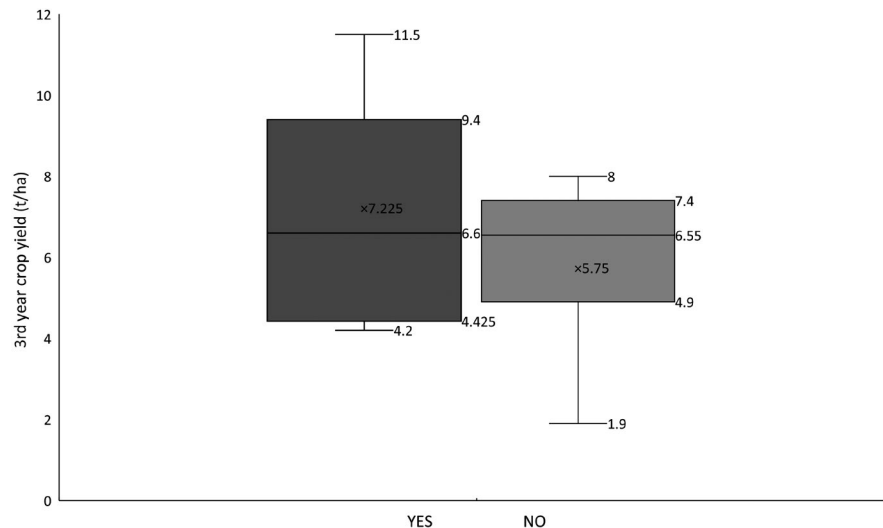
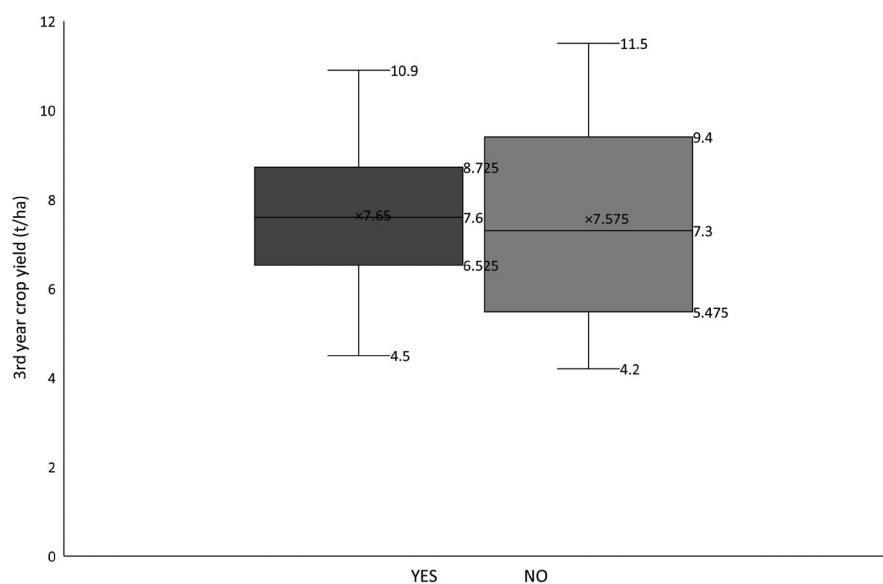


FIGURE 7 Box and whisker plot of third year yield in a field with heavy weed cover (YES) and light weed cover (NO)



experienced this, nor heard of any other grower in their network having experienced it.

The pre-2014 plants continue to change as individual plant's rhizomes widen their circumference, in-filling planting gaps, starting to growing tillers in the centre again, increasing the number of tillers. This was observed during fieldwork (Figure 1 shows a rhizome from 2006) and was also reported by growers. Four random fields in pre- and four in post-2014 plantings were chosen, each field parameter was averaged from its four plot measurements. Measurements show that the morphology of the older crops under a less dense planting technique was quite different to that of more recent plantings (Table 2). The morphological difference between the older crops and the more recent plantings was visually discernible in the field.

Older crops had more tillers than younger crops, but smaller tiller height at the June sampling and plants per unit area were less dense, planted wider apart pre-2014. More space per plant allows more tillers per plant, but the older crops have been improving yields in those fields since 2006,

and the morphology is evolving with the plant tillers having expanded outwards, and now in-filling the centre. Best practise guidelines (Teagasc-AFBI, 2011) advised planting 125 rhizomes in 100 m of field row length, and our post-2014 measurements (Table 2) suggested that figure is roughly being adhered to. Plots were 25 m × 5 m. Since plant spacing post-2014 is roughly 0.8 m, there was room for five rows of plants within a plot, and roughly 150 plants per plot.

The mean 2018 dry matter yield for pre-2014 crops was higher than more recent plantings. It is well known that mature crop yields (typically 12–15 t ha⁻¹ year⁻¹ dry matter biomass for the United Kingdom; Defra, 2019) are larger than that for young crops.

Using the third-year yield maximized the available data points and using the same age would have given even weight to young and old crops to discern pre- and post-2014 planting technique effects on yield. Unfortunately, there were only two pre-2014 third year yield values available. A same-age yield comparison was not valid on such a small sample.

	Mean no. tillers		Mean height (cm)		Density of rhizomes (no. per plot)		Yield 2018 (t/ha)	
	Pre-2014	Post-2014	Pre-2014	Post-2014	Pre-2014	Post-2014	Pre-2014	Post-2014
	115.5	68.75	50	67	40	184	12.9	8.7
	111	62	55	63	30	153	12.5	7.2
	85	66.25	61	83	79	65	9.8	10.6
	57.25	72.25	65	83	70	131	12.2	9
Mean	92.19	67.31	57.75	74	54.75	133.25	11.85	8.88
SD	26.89	4.31	6.60	10.52	23.46	50.43	1.40	1.39

^aThis is a study of the difference in morphology of crop age, and will also be affected by planting method pre- and post-2014.

TABLE 2 Plant morphology and pre- and post-2014 plantings^a across mid-England, all crop measurements taken 20–31 May 2019. Random sampling to give $n = 4$ fields planted pre-2014, $n = 4$ fields planted post-2014

	1	2	3	4	5
Least strongly					Most strongly
Good return	50%	20%	10%	—	20%
Ease of operations	30%	—	20%	—	50%
Low cost e.g. fertilizer	40%	—	—	50%	10%
Guaranteed market	50%	—	—	20%	30%
Good for the environment	60%	10%	—	30%	—
Degraded/problem land	40%	—	—	40%	20%
<i>Other reasons: individual responses</i>					
Next to playing fields, kids destroy cereal crops					
Small fields, difficult for machinery					
Near play area limits spraying, awkward small field					
Cannot spray near play area, awkward small field near village					
Poor fertility, game cover, crop regenerative					
Field far away from farm, narrow access, have to cross fast busy road					

TABLE 3 Reasons growers gave for investing in miscanthus

At the current time, miscanthus is giving very good financial returns, however that is far from the only reason growers invest in the crop (Table 3). Only 20% gave high returns as the main reason, and 50% gave it as the lowest reason, as post-2014 crop growers said it was initially a gamble in the years when they invested in the crop. Fifty per cent said the main reason was the ease of operations, 50% gave the second main reason as the low cost, thereby saving money on resources and labour costs, and 50% said they did not invest for a guaranteed market, 60% also said that they did not invest in a crop based on improving the environment. However, when given the option, to cite other reasons, they came out with a more unexpected consensus, of miscanthus being the solution to practical considerations limiting regular field operations. Considerations ranged from nearby playing fields either limiting spraying or vulnerable crops being vandalized, accessibility of machinery or the desire for a regenerative cover crop suitable for gamebirds.

3.2 | Juvenile and mixed-age yield correction

Figure 8a–c shows simulated mean yield for 2016 and 2017 over the United Kingdom. Figure 8a simulates yield from a mature $M \times g$ crop. Figure 8b simulates yield from a juvenile rhizome in its second and third years of growth during 2016 and 2017. Figure 8c simulates the yield of crops with an even crop age distribution between juvenile and mature, i.e. second year yield to the mature plateau of yield. The patterns of yield were influenced by climatic patterns, with the rainfall under the CRU TS4.01 climate data used, showing a heavier east to west trend. A limitation with the mapping display of yield was that the colour of the map plots created directly from within the model were fixed, determined by a Python routine and out of our control. The difference between the maps should be particularly noted between the yield scales. We accept that this is a weakness of the model with regard

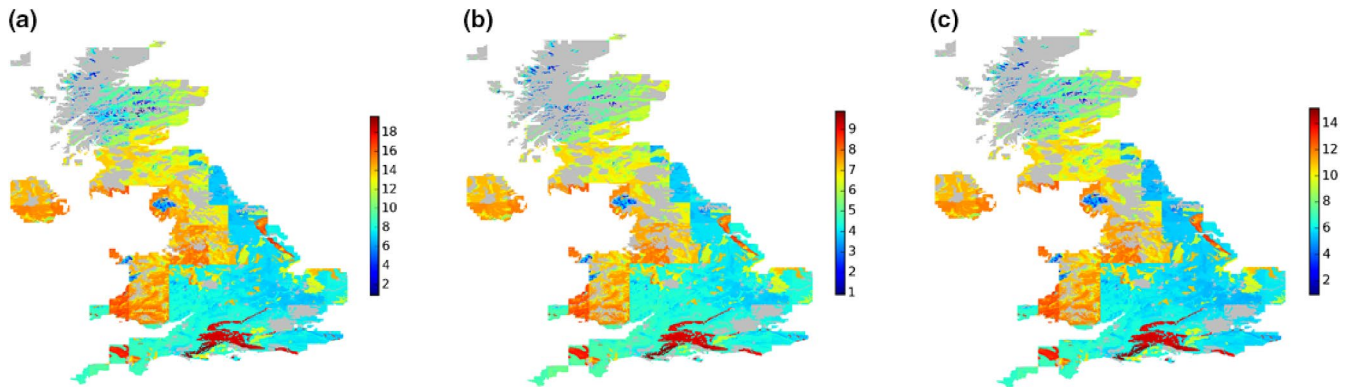


FIGURE 8 Simulations of mean miscanthus yield ($\text{t ha}^{-1} \text{ year}^{-1}$) for 2016–2017 (a) for a mature rhizome, (b) for a juvenile rhizome in second and third year growth (c) for an even age distribution, juvenile to mature

to comparisons, but with an auto-produced plot, it would not be feasible to edit a Python routine for each simulation. There is also a lumpy appearance of squares and sharp lines in Figure 8 due to the influence of low resolution climate, and discontinuity of precipitation. We are developing a higher resolution climate dataset to correct this.

4 | DISCUSSION

4.1 | Grower questionnaire and field survey

Grower's survey responses and the robust state of the fields during a drought-stricken June survey indicate that these crops surveyed are hardy for the United Kingdom. England experienced several weeks of drought during May to June 2019 during spring growth and miscanthus crops were not visibly susceptible to drought nor disease. Joo, Zeri, Hussain, Delucia, and Bernacchi (2017) showed that $M \times g$ was not impacted by drought during the same year, but showed sharp yield reductions the following year. This agreed with our findings for the lack of groundwater support which reduced mean and maximum yield, and the inter-quartile range.

Growers reported that the crops were not susceptible to waterlogged conditions at harvest and that waterlogging at harvest rarely occurred. These findings support Mann et al. (2012) who concluded miscanthus has flood tolerance. In a greenhouse experiment they compared flooded $M. x g$ against control conditions for 16 weeks and found no difference in biomass, with crops showing 100% viability. A modelling study (Environment Agency, 2015) found that the dense nature of the mature miscanthus planting can act like a 'green leaky dam' to hold flood water back, it acts immediately upstream of the crop to slow the speed of the water flow. As a side note, only two weeks after our crop survey was completed nearby areas of Lincolnshire lower than sea level suffered heavy rains that burst waterway embankments and caused extreme floods, ending the period of drought.

We noted more wildlife than expected in a monoculture (Appendix SV). This is because the crop is largely undisturbed except for early spring harvest, provides summer cover and the litter layer, rich in spiders and beetles, provides food. These findings support reports of miscanthus being a benefit to birds, small mammal and invertebrates (Anderson & Fergusson, 2006; Semere & Slater, 2007).

In the fields studied, the crops were all given a field buffer. At the time of surveying in May, half of the grower's buffers were plentiful with wildflowers and pollinators. All fields were surrounded with plenty of trees and high hedgerows, and birds were abundant. Leaf debris in all growers' fields contained insects and some, notably the first field surveyed, was teeming with beetles and small spiders. These measures tie in with EU Agricultural CAP requirements (likely to continue as UK requirements) for the greening of agriculture to combat climate change and conserve biodiversity. This is done by setting up land which contributes to permanent pastures, crop diversification and ecological focus areas, and although miscanthus has not been included so far, it could be in the future (Emmerling & Pude, 2017).

The survey gave a good insight into why growers invest in miscanthus crops. There were a wide variety of answers, and always several reasons from each grower that had led to them making the decision to grow the crop. Surprisingly financial return was not the main reason. Growers showed themselves to be adaptable, looking for practical solutions to remedy farm issues wider than simply low fertile soil, which included social acceptability with the surrounding villages.

From 2015, Terravesta had a burst of activity with a rapid grower investment in planted areas as markets were secured. Agronomic issues associated with patchy establishment were overcome, following new planting techniques resulting in denser rhizome distribution. We looked for problems with pre-2014 crops, or differences pre- and post-2014. There was no discernible difference, except for morphology, as the pre-2014 crops continue to in-fill their original planting gaps. Since investing in miscanthus, Terravesta has established a

reliable market through buying miscanthus biomass on long-term contracts. They have provided agronomic guidance to growers, and reliable planting technology has been developed which halved the cost of establishment to the grower (Clifton-Brown et al., 2017). Preplanting, planting and agronomy support via contractors are available, and Terravesta involves its growers in hosting farm visits to disseminate information and best practice to potential growers. This emphasis on investment and support may explain an increase in take-up by growers since 2015.

4.2 | Crop yield corrections for modelling

We have used site data to calibrate juvenile yields for a 10 km scale model. It is always an issue for modellers to relate measured data at field-scale to models working at larger scales. The impetus and focus of the yield calculations came from requiring an improved yield calibration for a model simulating a realistic picture of bioenergy potential and associated decarbonization totals across the landscape, which are useful policy indicators. The model provides national, and in other studies global, results. National and global simulations would be time-consuming and inefficient to consider a 1 km grid square scale, this is one of the limitations that are common in a landscape scale simulation. Its use at this scale is not intended as a model producing results for individual growers, however its use with higher resolution soil and climate data would allow that.

The simulated juvenile yields in Figure 3b had a wide range, reflecting growth on neighbouring soils to show the spatial variation and uncertainty of a model output based on databases at 10 km scale. In a future study we intend to look at the yield uncertainty introduced by using gridded data input and output for modelling. The model nevertheless has a slight bias, overestimating juvenile data under 7 t/ha, this is not enough to prevent it from simulating yields in range with other literature.

When modelled spatially across the United Kingdom (Figure 8), the difference between the maximum yield of a mature crop and one in its second to third year harvest was 9 t ha⁻¹ year⁻¹ with the younger crop having a smaller range of yield spatially over the United Kingdom. In modelled areas of the United Kingdom at a scale of 10 km there was a mix of crop ages. Assuming an even distribution of crop ages, the maximum modelled yield of 14 t ha⁻¹ year⁻¹ lay between the juvenile to the mature plateau of yield. If the crop age were skewed in either direction, one can see how this varied the maximum towards either extreme of this value, 6–15 t ha⁻¹ year⁻¹.

Based on the measured crop yield data from across mid-England for average yields, where the mature yield was 12–15 t ha⁻¹ year⁻¹, the juvenile crop produced 6–8 t ha⁻¹ year⁻¹, averaging the second- and third-year-old

crop harvests. The model indicated that with a theoretical 10 km² area around the same survey locations and with an even spread of crop age-related yields, the mean yield was 9–12 t ha⁻¹ year⁻¹.

Lesur-Dumoulin, Lorin, Bazot, Jeuffroy, and Loyce (2015) obtained mean yields of 8.1 and 12.8 t DM ha⁻¹ year⁻¹ for the second and third growth year of *M × g*. Our juvenile third-year yield figures (Figure 6 with groundwater support and Figure 7 with weed cover) agreed with Lesur-Dumoulin's second growth year yield. However, their data were from commercial growers' fields in France, and these mean results concealed a high variability, ranging from 3 to 19 t DM ha⁻¹ year⁻¹ which had a larger range and smaller minimum than our juvenile yields. They reported that commercial yields were on average 20% lower than experimental plot yields and were found to be particularly related to the shoot density established at the end of the planting year. Our extraction of an age-related correction factor multiplies mature yield by 0.77 (reduction of 23%) to obtain yield for an even distribution of crop ages across the landscape.

Juvenile crop yield increases plateau around 9 years of age, using growers yield data, continuing yield increases far longer than best practise guidelines. We would advise UK growers to keep clear records of their crop, and to note how many years it takes for yield to plateau for their UK location and environment, because our data suggest longer than the guidelines.

Crops planted post-2014 will reduce the time of establishment to achieve maximum yield, in some locations they continue to develop to plateau at a higher yield. The 9 year yield increase to plateau that we found across a range of crop ages comprised a mixture of crops planted before and after 2014 when planting density increased. Crops that were planted in 2015 have had only two, and some three, harvests since planting. There is not enough post-2014 data alone for splitting into calibration and validation data for testing a model and you cannot see the trajectory of yield increase using 2 or 3 yield points on a plot. Unlike a plot trial, most growers were understandably not able to provide every year's yield. The MiscanFor model is not specifically targeted at growers, it is also a policy and environmental tool which indirectly can also benefit the industry. It quantifies the state of play that exists in the landscape, and can act as a baseline compared against future climates. It is made more realistic by using commercial data to calibrate it, as we saw in our crop survey which includes the older existing crops. There are two distinct perspectives on the use of models, related to the prediction of the older and younger crop yields. One approach is to see the potential in how yields improve over time for growers and for breeders concerned with innovations in the younger crops and faster establishment. The other approach is to determine the current state of play for policy

or environment, including crops of all ages and quality presently existing in the landscape. This is necessary as a baseline to compare against future climate or management scenarios. In either case, using commercial data to calibrate a model is a powerful tool.

We have used the latter approach; the model is often used to determine a current baseline and with climate projections for policy support. Also the small number of post-2014 harvest years for calibration at the time of this study exclude a calculation of yield increase to maturity for post-2014 only. Lesur et al. (2013) found $M \times g$ crop yields over Europe peaking and declining at 5–10 years crop age. However, Lesur et al. did caution that time to peak yield and its decline varies with climate vulnerability, that yields incorporate a lot of variability and that they found some crop yields remained nearly steady up to more than 20 years. Gauder, Graeff-Hönniger, Lewandowski, and Claupein (2012) studied yields of the same crops for 14 years with $M \times g$, *M. sacchariflorus*, and *M. sinensis*. They found a shorter establishment period to reach a yield plateau of $M \times g$ and *M. sacchariflorus* than *M. sinensis*, but yields were also variable with climate. Not enough studies have been written about the ageing of miscanthus and in time, the time to yield plateau should become clearer.

In summary, we surveyed commercial fields and talked with growers in a commercial rather than a research environment. The environmental and wildlife notes are related to why the growers chose to invest in miscanthus. The survey results show that growers wanted a crop to increase biodiversity (related to EU financial support and possibly after Brexit), and also that some growers augment their income by using it as a cover crop which encourages game for a local shoot. The observations we made at various locations over England further support published findings of miscanthus being good for wildlife biodiversity (Semere & Slater, 2006, 2007; Thomas & Marshal, 1999). We wanted to look at the surrounding environment integral with a growing miscanthus crop and to determine multiple facets about miscanthus crops. Although we recognize the concern for bioenergy's competition for land with food crops, there was no sign of the growers surveyed replacing viable food crops with bioenergy. Miscanthus was being grown to correct a problem, and was contributing to the greening of agriculture.

The most common reasons for growers' investment of miscanthus were related to its low requirement for field operations, low maintenance cost, its regeneration, all making it a practical solution to difficult field access and social acceptability near public places. Few growers had problems with weeds or crop dieback, no discernible dieback was observed except for one known problematic crop during fieldwork. The only reported influence on rhizomes was condition at planting.

All fields contained plentiful wildlife with an abundance of spiders and beetles in the deep litter layer. This was helped by the fact that all the grower's miscanthus fields were surrounded by a buffer often with wildflowers and pollinators, and surrounded by high woody shrubs and trees. Also we were sampling in a warm sunny May. Nevertheless, the miscanthus was a source of food with abundant insects. Song-birds, ground-nesting birds and birds of prey, butterflies, ladybirds, hares and grouse were seen in the crops. Farmers said they regularly saw voles, deer, foxes and badgers. In-use hawk and owl nesting-boxes were visible, placed on poles along the drainage ditches at the field edges.

The most interesting feature of our observations was that mature miscanthus planted pre-2014 continued to develop its morphology, it spread into planting gaps and grew more tillers. All mature crops thrived on both clay and sandy soils, and although the yield appeared to plateau with age of crop, there was no sign of it falling. Meanwhile, post-2014 crops were still developing, and were planted more densely. This ensured more tillers from young plants per unit area. An early yield calculation, and a distributed crop age-related yield correction were extrapolated from grower's yield data. These were added to the MiscanFor model as a modification of mature yield, which has provided the capability to predict juvenile rhizome yields. A mid-England mature crop harvest averaged $12\text{--}15 \text{ t ha}^{-1} \text{ year}^{-1}$, a second- or third-year-old crop harvest averaged around $6\text{--}8 \text{ t ha}^{-1} \text{ year}^{-1}$, and an even distribution of crop age over a 10 km^2 area averaged $9\text{--}12 \text{ t ha}^{-1} \text{ year}^{-1}$ yield.

This is an analysis of miscanthus based on commercial grower's data and responses. From our observations, and growers' comments, the future yields of miscanthus, from crops young or old, look positive. Plants sown pre-2014 are still increasing in tillers, expanding and in-filling space. Post-2014 the crops are planted more densely, giving confidence in their ability to surpass the pre-2014 yields. Although a small grower group was sampled, from their experiences, it would seem the crop is not being used to replace food crops. This is a crop that is solving practical problems for growers while improving the environment.

ACKNOWLEDGEMENTS

We would like to thank our industry partner Terravesta, developers of miscanthus throughout the UK, and the help of excellent and innovative growers, alphabetically listed, Abbey, Addis, Beedon, Brocklesby, Chappell, Hockham, Hounsfield, Maple and Whinney Moor Farms.

The survey work was made possible by the University of Aberdeen's Industry Fellowship Scheme, as part of the University's Innovation Fund. We were able to develop an improved version of the MiscanFor model, as part of the UKERC (UK Energy Research Centre) Phase 4 research programme,

funded by UK Research and Innovation (EP/S029575/1). Its development was also made possible by ADVENT (Addressing Valuation of Energy and Nature Together) funded by the UK Natural Environment Research Council (NE/M019691/1), and also made possible through FAB GGR (Feasibility of Afforestation and Biomass energy with carbon capture and storage for Greenhouse Gas Removal) funded by the UK Natural Environment Research Council (NE/P019951/1).

ORCID

Anita Shepherd <https://orcid.org/0000-0003-1902-5147>

John Clifton-Brown <https://orcid.org/0000-0001-6477-5452>

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Shepherd A, Clifton-Brown J, Kam J, Buckby S, Hastings A. Commercial experience with miscanthus crops: Establishment, yields and environmental observations. *GCB Bioenergy*. 2020;12:510–523. <https://doi.org/10.1111/gcbb.12690>