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ORIGINAL RESEARCH

Influence of cutting height on biomass yield and quality of miscanthus genotypes

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Abstract
Commercially achieved biomass yields are often lower than those obtained in scientific plot trials and estimated by crop models. This phenomenon is commonly referred to as the 'commercial yield gap'. It needs to be understood and managed to achieve the yield expectations that underpin business models. Cutting height at harvest is one of the key factors determining biomass yield and quality. This study quantifies the impacts of cutting heights of diverse genotypes with different morphologies and in years with contrasting weather conditions before and during harvest. Harvests were made in March 2015 and March 2018 of six diverse miscanthus genotypes planted as part of the 'OPTIMISC project' in 2013 near Stuttgart, Germany. Biomass yield, dry matter content and nutrient concentrations were analysed in four 10 cm fractions working upwards from the ground level and a fifth fraction with the shoot biomass higher than 40 cm. As stems are slightly tapered (i.e. diameter decreases slightly with increasing cutting height), it was hypothesized that low cutting may lead to yield gains, but that these may be associated with lower quality biomass with higher moisture and higher nutrient offtakes. We calculated average yield losses of 270 kg ha^{-1} (0.83%) with each 1 cm increase in cutting height up to 40 cm. Although whole shoot mineral concentrations were significantly influenced by both genotype and year interactions, total nitrogen (1.89 mg g^{-1}), phosphorus (0.51 mg g^{-1}), potassium (3.72 mg g^{-1}) and calcium (0.89 mg g^{-1}) concentrations did not differ significantly from the concentrations in the lower basal sections. Overall, cutting height had a limited influence on nutrient and moisture content. Therefore, we recommend that cutting is performed as low as is practically possible with the available machinery and local ground surface conditions to maximize biomass yield.

KEYWORDS
cutting height, harvest loss, Miscanthus, perennial biomass crop, stubble height, yield difference

Elena Magenau and Andreas Kiesel should be considered joint first author.

1 | INTRODUCTION

The development of a sustainable bioeconomy as an alternative to the conventional, fossil-based economy is supported by both the European Union and national policies of several member states. Such a bioeconomy will generate a growing demand for sustainably produced biomass for the manufacture of an increasing number of biobased products and bioenergy. The perennial grass miscanthus is a promising crop for this feedstock provision. Once successfully established, it is highly stress-tolerant, can produce high biomass yields with low inputs and is well suited to a wide range of marginal land types less suitable for food production (Lewandowski et al., 2016).

The genus *Miscanthus* comprises approximately 14 species of perennial C4 grasses mainly originating from Eastern Asia (Clifton-Brown et al., 2011). In the last 20 years, miscanthus research activity has rapidly expanded in Europe and worldwide (Jones, 2020), and several breeding programmes are in place to develop novel, improved varieties (Clifton-Brown et al., 2019). The most common commercially used variety is *Miscanthus* x *giganteus* (Mxg), a natural, sterile hybrid of *Miscanthus sinensis* and *Miscanthus sacchariflorus*. Mxg is harvested annually in spring and has a yield potential of up to 25 t ha^{-1} $year^{-1}$ dry matter under favourable soil and humid, southern European climatic conditions (Hastings et al., 2008; Lewandowski & Schmidt, 2006). It has a productive lifespan of more than 20 years (Lewandowski et al., 2003) and achieves its full yield potential after an establishment period of 2–4 years, depending on environmental conditions. It has high photosynthetic efficiency (Beale & Long, 1997; Davey et al., 2017), and fertilizer, herbicide and pesticide demands are low due to its high nutrient recycling capacity, competitiveness against weeds after the establishment phase and absence of pests and diseases (Jones, 2020). To minimize competition with other land uses, miscanthus cultivation methods are being developed for marginal and/or contaminated lands (Pogrzeba et al., 2017) because miscanthus tolerates drought, heavy metals and salinity (Chen et al., 2017; Hastings, Clifton-Brown, Wattenbach, Mitchel, Stampfel, et al., 2009, Hastings et al., 2014; Lewandowski et al., 2016; Rusinowski et al., 2019). It offers different habitats compared to annual arable crops and improves landscape biodiversity by enriching structural heterogeneity within intensively used agricultural areas. Miscanthus promotes species richness and abundance by providing shelter for small mammals and birds and offering habitats for plants and arthropods (Lask et al., 2020). The crop's perennial nature means soil cover is provided throughout the year, mitigating soil erosion and run-off (Ferrarini et al., 2017). The efficient and deep rooting system and the low fertilization requirements minimize nitrate leaching risks and make miscanthus highly suitable even for cultivation on buffer strips (Ferrarini, Fornasier, et al., 2017). In addition, miscanthus cultivation increases the water-holding capacity of the soil and improves its structure compared to annual crops. It increases the soil organic matter of former arable land and provides a sequestration potential of 2.5–7.9 t CO_2 ha^{-1} a^{-1} (McCalmont et al., 2017).

The high biomass production potential and environmental benefits have led to an increase in research activities aimed at developing miscanthus as a feedstock for various applications. These range from bioenergy, for example, biogas and bioethanol, to biobased materials, including platform chemicals, lightweight concrete and fibre panels (Kiesel & Lewandowski, 2017; Rivas et al., 2019; van der Weijde et al., 2017). Replacing annual crops such as maize by perennial miscanthus or replacing fossil fuels by miscanthus-derived biofuels often leads to greenhouse gas savings and thereby improves the sustainability of the production system (Felten et al., 2013; Kiesel et al., 2017; Robertson et al., 2017; Wagner et al., 2017, 2019). Although it is in the process of being developed as a promising multipurpose crop, miscanthus is currently still underutilized in Europe (Jones, 2020).

Increasing the use of miscanthus biomass as a feedstock to expand the bioeconomy will require reliable yield data. The yield potential of miscanthus has been assessed extensively across Europe and been found to range from 10 to 25 t ha^{-1} (Christian et al., 2008; Gordana et al., 2017; Himken et al., 1997; Jørgensen, 1997; Kalinina et al., 2017; Lewandowski, Clifton-Brown, et al., 2003; Schorling et al., 2015; Schwarz et al., 1994). Higher yields were generally determined in regions of south Central Europe with sufficient water availability, while lower yields were found in more marginal, drier and cooler climates. Model projections of yield potentials based on climate and soil data are used to estimate regional opportunities (Hastings, Clifton-Brown, Wattenbach, Mitchel, & Smith, 2009). However, both modelled and scientifically measured yields are often well above those actually achieved in commercial-scale harvests. The difference is known as the 'commercial yield gap'. This gap can be attributed to multiple factors including higher harvest losses, gaps in stands where establishment was patchy and weed cover (Lesur-Dumoulin et al., 2016). In this study, we consider the yield lost due to changes in cutting height. In scientific plot trials, a cutting height between 5 and 10 cm is widely used, while in commercial fields, the cutting height depends largely on the harvest technology available and the evenness of the soil surface, which can vary widely within the same field. It has been found that harvest residues (mainly stubble) on the field account, on average, for 16.5% of the standing biomass (Kahle et al., 2001) and that commercially harvested yields are 20% lower than those in scientific trials (Lesur-Dumoulin et al., 2016). However, in both these studies, the cutting height was not defined in detail. In our study, we aimed to assess the impact of cutting height on: (i) biomass yield; (ii) biomass quality; and (iii) nutrient offtake, in a range of genotypes with different morphologies. The following hypotheses were developed: (a) increasing cutting height leads to over proportional yield losses; (b) an increased cutting height improves biomass quality by decreasing moisture, ash and nutrient contents; and (c) lowering cutting height leads to higher nutrient removal by the harvested biomass.

2 | MATERIALS AND METHODS

2.1 | Field trial

The field trial is located at the research station 'Ihinger Hof' in southwest Germany (latitude 48°7′N, longitude 8°9′E, approx. 480 m a.s.l.). It was planted by hand as a randomized complete block design with vegetatively in vitro propagated seedlings of 15 miscanthus genotypes in May 2012. Each plot is 5 m × 5 m in size and contains 49 plants, resulting in a planting density of 1.96 plants per m^2. In the present study, the following genotypes are analysed: OPM 2—*M. sacchariflorus* (Msac); OPM 6, 7, 10—*M. sacchariflorus x M. sinensis* genotypes (Msac x Msin); OPM 9—*Miscanthus x giganteus* (Mxg); and OPM 11—*M. sinensis* (Msin) variety Goliath. OPM 2, 6, 7 and 10 originate from the miscanthus breeding programme at Aberystwyth University and Julius Kuehne Institute (JKI), Braunschweig. The trial was fertilized with 60 kg nitrogen (N), 44 kg phosphorous (P) and 140 kg potassium (K) ha^{-1} a^{-1} in 2013, the second growth period, to replace nutrient losses. The fertilizers used were calcium ammonium nitrate (27% N, 10% calcium (Ca)), monocalcium phosphate (18% P) and potassium sulphate (50% K). Due to the high nutrient status of the soil (data not shown), it was decided to apply only 40 kg N ha^{-1} a^{-1} in 2017. The field trial was harvested annually in March. Further trial details are described in Kalinina et al. (2017).

Weather data at the trial station were measured at hourly intervals using a standardized weather station from the Agricultural Technology Center Augustenberg (LTZ, 2020). These data were used to calculate average temperature and total precipitation per month from April 2014 until March 2015 and from April 2017 until March 2018.

In late October 2014, the senescence of the genotypes was assessed, and photos were taken of each (Figure 1a). To analyse the effect of cutting height on the biomass quantity and quality, field samples of six genotypes were taken. The samples were cut by hand at a height of 5 cm above the ground on 18 March 2015 and on 19 March 2018, when the stand was 3 and 6 years old, respectively. In 2015, shoots of five plants, and in 2018, shoots of eight plants were taken from the row next to the sampled harvest area of each plot. Two shoots were harvested per plant. More shoots were taken in 2018 than in 2015 to ensure sufficient material for all analyses planned.

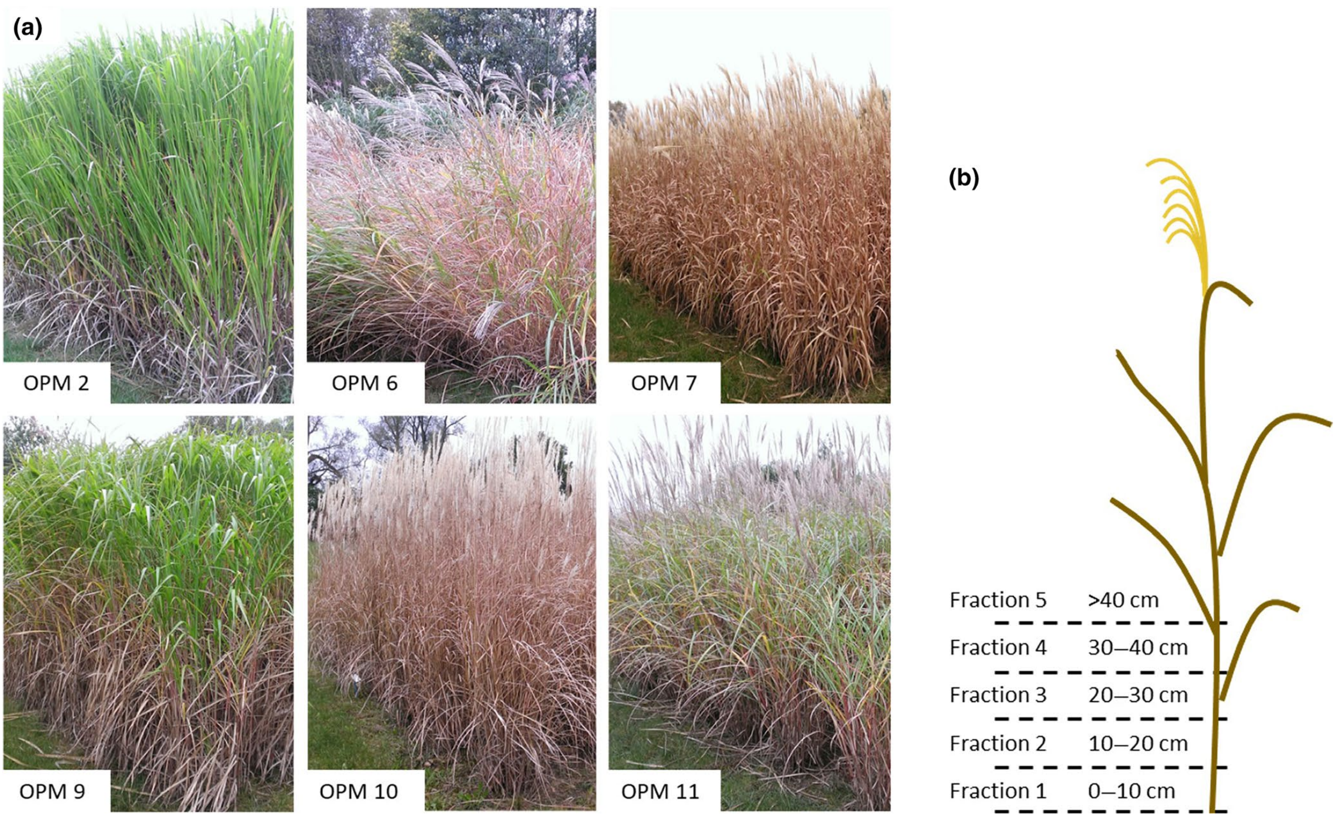

FIGURE 1 (a) Assessed miscanthus genotypes at trial site in southwest Germany (photo taken in late October 2014). (b) Fraction numbers and corresponding plant parts

The random selection of shoots was ensured by placing a marked stick through the centre of the sampling row and selecting the two shoots closest to the marks. Only stems with a height of at least 60% of the canopy height were included in the sampling. Each shoot was cut into five fractions: the first four at 10 cm intervals from the initial cutting point of 5 cm above the ground, and the remaining stem as the fifth fraction (Figure 1b). The biomass yield per hectare was determined by harvesting a central quadrat of 4.6 m^2 (nine plants) using a hedge trimmer at a cutting height of 5 cm. The yield per hectare for each fraction was calculated from its proportion of the shoot.

A subsample of the biomass harvested in the quadrat was taken to determine the dry matter content of the aboveground biomass and used to estimate the dry biomass yield per unit area. This subsample was dried to constant weight at 60°C.

2.2 | Laboratory analysis

The samples of the five shoot fractions were dried to constant weight at 105°C in a drying cabinet to determine the dry matter (DM) content. Each sample was milled using a 1-mm sieve SM 200 (Retsch). Ash content and mineral concentrations were determined following VDLUFA Method Book III. For ash content, the samples were incinerated in a muffle kiln at 550°C for 4 h (Naumann & Bassler, 1976). For P, K and Ca concentrations, 0.5 g of each sample was diluted with 8 ml HNO_3 (concentration 65%) and 6 ml H_2O_2 (concentration 30%) and digested in an ETHOS.lab microwave (MLS GmbH). The N concentration was determined according to the DUMAS principle using a Vario Macro Cube (Elementar Analysensysteme GmbH; Naumann & Bassler, 1976).

2.3 | Statistical analysis

Data were analysed using a mixed model approach. To analyse the effect of the five fractions, they were taken as a characteristic of one plant. For each year, a multivariate model was fitted to account for the co-variance between fractions. The multivariate mixed model can be described as:

$$y_{ijk} = \mu_j + g_{if} + r_{jk} + e_{ijk}, \qquad (1)$$

where y_{ijk} is the observation of genotype i, fraction j and replicate k; μ_j is the intercept for fraction j; g_{ij} is the ith genotype effect in fraction j; r_{jk} is the effect of the kth field replicate in fraction j; and e_{ijk} is the residual error term corresponding to y_{ijk}. Replicate effects for each fraction were taken as fixed, all other effects (except μ_j) were assumed to be random to explore potential correlations between genotype and error effects of different fractions. For the five effects (one for each fraction) of each genotype and plot, a 5 × 5 variance–covariance matrix was fitted. Both an unstructured variance–covariance structure and a first-order autocorrelated variance–covariance structure with homogeneous or heterogeneous variances were fitted for each effect. The final model and, thus, the fitted variance–covariance structure for genotype and plot effects were selected via Akaike information criterion (Wolfinger, 1993) from the list of converging models. Note that most often a first-order variance–covariance structure with heterogeneous variances was used for both effects. As genotype effects were assumed as random, best linear unbiased predictions (BLUP) were calculated to estimate random effects. Additionally, pairwise differences of BLUPs were estimated as contrasts. The significance of BLUPs and contrasts ($\alpha = 0.05$) were then used to create a letter display to allow multiple comparisons (Piepho, 2004). No adjustment for multiple comparisons was made.

For data measured once per plot, another model was fitted across both years. It can be described as:

$$y_{ilk} = \mu + g_i + t_l + r_k + (gt)_{il} + (tr)_{lk} + e_{ijl}, \qquad (2)$$

where μ is the intercept; g_i is the ith genotype effect; t_l is the lth year effect; r_k is the effect of the kth field replicate; $(gt)_{il}$ is the interaction effect of the ith genotype with the lth year effect; $(tr)_{jk}$ is the effect of the kth field replicate in the jth year; and e_{ilk} is the residual error term corresponding to y_{ilk}. All effects except the error were assumed as fixed. For the error effects of the same plot, an unstructured 2 × 2 variance–covariance matrix was fitted, and thus, the model allows for year-specific variances and a correlation across years. Where significant differences measured via global F test were found, a Fishers least significant difference test was performed for multiple comparisons. The least square means were estimated and are presented with their standard error and a corresponding letter display in Section 3. For both models, pre-requirements of homogeneous variance and normal distribution of residuals (despite the heterogeneity already accounted for by the model) were graphically checked using residual plots.

The statistical analysis was performed using the PROC MIXED procedure of Statistical Analysis Software SAS version 9.4 (SAS Institute Inc.). Figures were produced with the package ggplot2 (Wickham, 2016) of the R program (R Core Team, 2019).

3 | RESULTS

3.1 | Environmental conditions

Between 1967 and 2017, the average annual air temperature at the research location was 8.5°C and the total annual precipitation was 686 mm. Figure 2 shows the mean monthly temperature and total monthly precipitation for each year

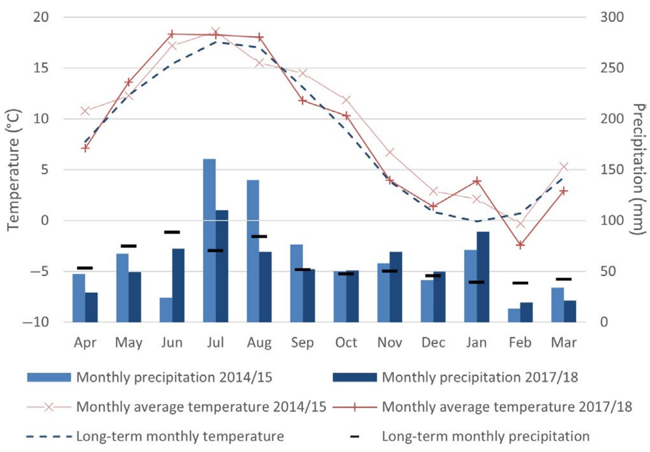

FIGURE 2 Average monthly air temperature (2 m above soil surface) and cumulative monthly precipitation at trial site for the 12 months before harvest in March 2015 and March 2018, and long-term data (1967–2017)

before the harvests in March 2015 and March 2018, as well as the long-term data for April 1967–March 2018. The year 2014 was warmer and more humid than the long-term average (annual average temperature 10.4°C, total precipitation 750 mm). In contrast, 2017 was a fairly average year with a mean annual temperature of 9.1°C and total annual precipitation of 682 mm. Although 2014 was warmer and wetter than 2017, the monthly average temperatures in May, June and July of both years were more or less similar. While August was warmer in 2017 than in 2014, the autumn of 2014 was exceptionally warm (Figure 2). In both seasons, January was relatively mild compared to the long-term data, but cold periods in February promoted ripening (by killing off the aboveground biomass) and thereby drying off the crop. In 2017, the first frost had already occurred at the end of October, while in 2014, it was not until the beginning of December. The early growing season (April–June) was drier than average in both years, particularly in June 2014, but sufficient rainfall in July and August that year allowed the crop to catch up and achieve yield levels typical for the site.

The weather data (temperature, precipitation, wind, hours of sunshine, and humidity) for the week before each year's harvest are shown in Appendix S1. Although the overall weather was relatively dry in February and March of both years, there was some light precipitation in the days before the harvest in March 2018. The temperature was also lower, fewer hours of sunshine were recorded and the humidity was higher in 2018 than 2015.

3.2 | Biomass yield

The harvested biomass ranged from 10 to 16.4 t DM ha^{-1} with a mean of 13.6 DM ha^{-1} in 2015 and 13.3 t DM ha^{-1} in 2018 (Figure 2). Differences between years and genotypes were not significant. In both years, the highest biomass yield was achieved by OPM 6 and the lowest by OPM 11. The highest yield differences between years were found for OPM 7 and OPM 11, both with a lower yield in 2018. A higher total biomass yield was also often associated with a higher absolute and relative share of the fractions 1–4 (Figure 2). However, OPM 6 and OPM 9 had a higher absolute biomass yield in these four fractions in 2018, even though the total biomass yield was very similar in both years. The temperatures over the vegetation periods before the harvests were similar, but the winter before the harvest in 2018 was colder (Figure 2) with more snow, which probably increased the preharvest biomass loss.

In general, the highest proportion of the total aboveground yield was produced by fraction 5, ranging from 59.5% to 73.6% (Figure 3). This is not surprising since this fraction represents approximately 76.9–83.5% of the total height of the genotypes assessed (from Kalinina et al., 2017). For the other fractions, the biomass decreases significantly from fractions 1 to 4 (Appendix S2). Together, these four fractions represent 26.4%–40.5% of the biomass but only 16.5%–23.1% of the height. The individual fractions 1–4 account for only 4.0%–5.8% of the crop height, but in each case, a higher percentage of the biomass (fraction 1: 7.3%–12.7%; fraction 2: 6.7%–10.8%; fraction 3: 6.5%–10.4%; fraction 4: 6.0%–9.5%). All genotypes (expect OPM 7) showed decreasing biomass yield per 10 cm fraction with increasing height, with a correlation coefficient above 0.9 (OPM 7: R^2 = 0.84, 2015). The difference in biomass between adjacent fractions ranges from 0.4% to 1.9%. In general, the proportion of total aboveground biomass of fractions 1–4 was higher in 2018 than in 2015.

3.3 | Dry matter content

Figure 4 shows the dry matter content of each of the five fractions per genotype and year. For both harvests, all six genotypes show an increasing dry matter content from the bottom to the top of the shoot with the significantly highest dry matter content above 40 cm. The total dry matter content was significantly influenced by year, genotype and year × genotype interaction. In both years, OPM 7, 10 and 11 had significantly higher dry matter contents than OPM 2. In 2015, the weather in the week before the harvest was dry, warm and sunny (Appendix S1). These conditions resulted in a high total dry matter content with only minor differences between genotypes (min. 88%, max. 92% total dry matter content). Only OPM 9 and OPM 6 had a relatively low dry matter content in fraction 1 at 72% and 74% respectively. Although the winter before the second harvest

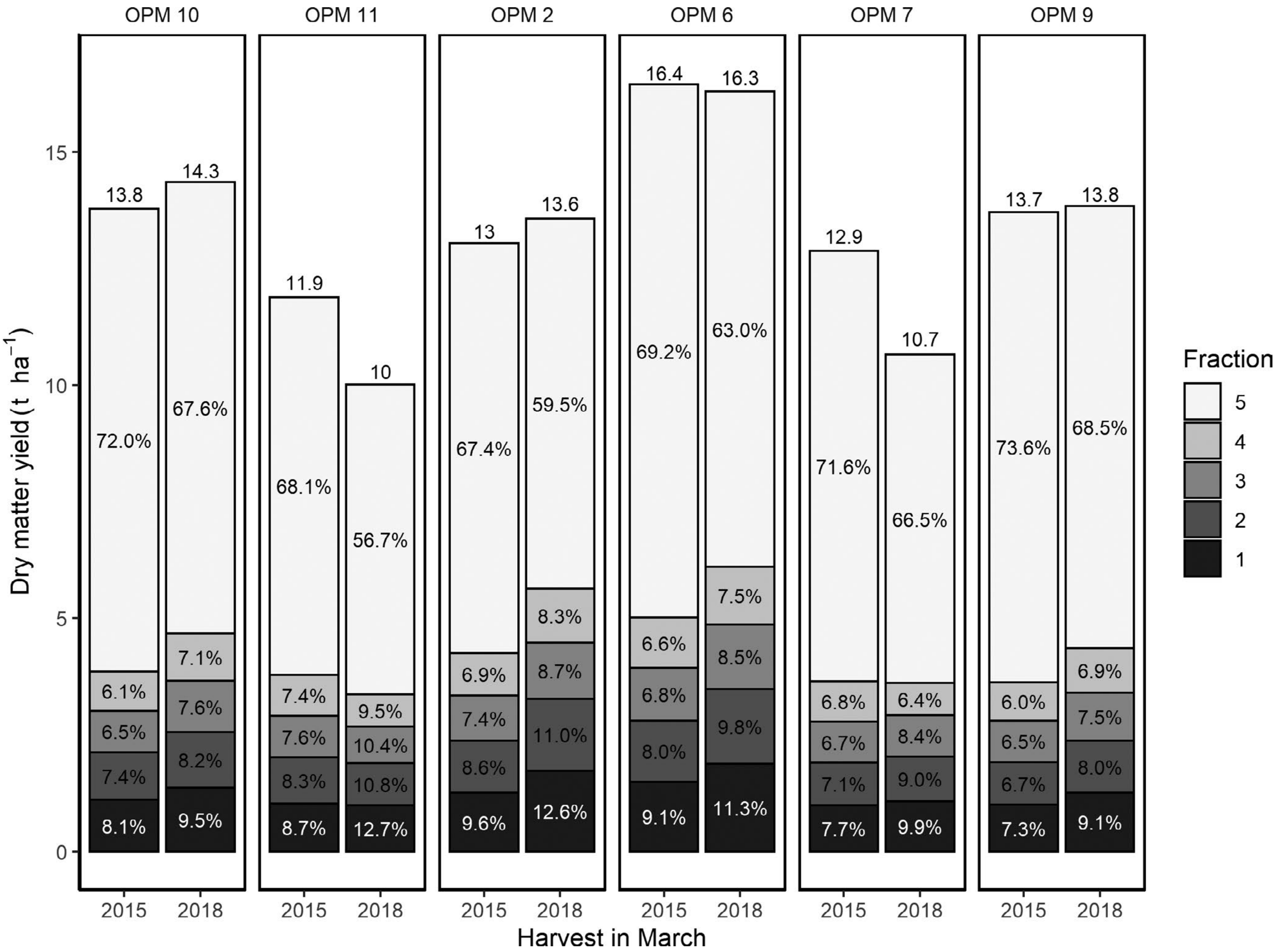

FIGURE 3 Dry matter yield (t ha^{-1}, with cumulative values above bars) and proportion (% within bars) per fraction for all genotypes and both years

in 2018 was colder (Figure 2), which generally accelerates the maturation process by increasing the dry matter content, this was not reflected in the results due to the wet conditions before the harvest (Appendix S1). These weather conditions also led to more significant differences within and between the genotypes. In both years, the largest difference between fractions 1 and 5 was found for OPM 9 and the smallest for OPM 7.

Table 1 shows the effect of harvesting only part of the standing biomass on the theoretical dry matter content of the biomass harvested. Leaving a higher share of the biomass on the field generally increases the dry matter content, especially in years with a low dry matter content of the total biomass, as was the case for the harvest in 2018. While in 2015, a higher cut decreased the moisture content by a maximum of three percentage points, in 2018, a maximum decrease of eight percentage points was achieved. However, the effect of a 10 cm higher cut on the dry matter content decreased with each fraction, since fraction 1 showed the lowest dry matter content for all genotypes in both years.

3.4 | Ash and nutrient content

Figure 5 shows the mean ash, N, P, K and Ca concentrations per genotype, fraction and year. The total ash content and mineral concentration per genotype are significantly influenced by the year and genotype effect. For ash, N and Ca concentrations, a more significant influence of the year ($p < 0.0001$, $p < 0.0001$, $p < 0.0001$) was observed, while P and K were influenced equally by the year ($p = 0.0003$, $p = 0.0001$) and genotype ($p = 0.0004$, $p < 0.0001$). The Ca concentration distribution within the plant shows similar patterns for all genotypes in both years, with a striking exception in fraction 5: in 2015, the Ca concentration of fraction 5 was twice as high as in fractions 1–4 in the same year, and also twice as high as the average of all fractions in 2018. In 2015, the ash content of fraction 5 was also elevated compared to fractions 1–4 (except for OPM 6). On average, higher ash contents were observed in 2015 than in 2018 (except for OPM 2).

The mean N concentration was lower in 2018 than in 2015 for all genotypes (Appendix S3), however the two years show

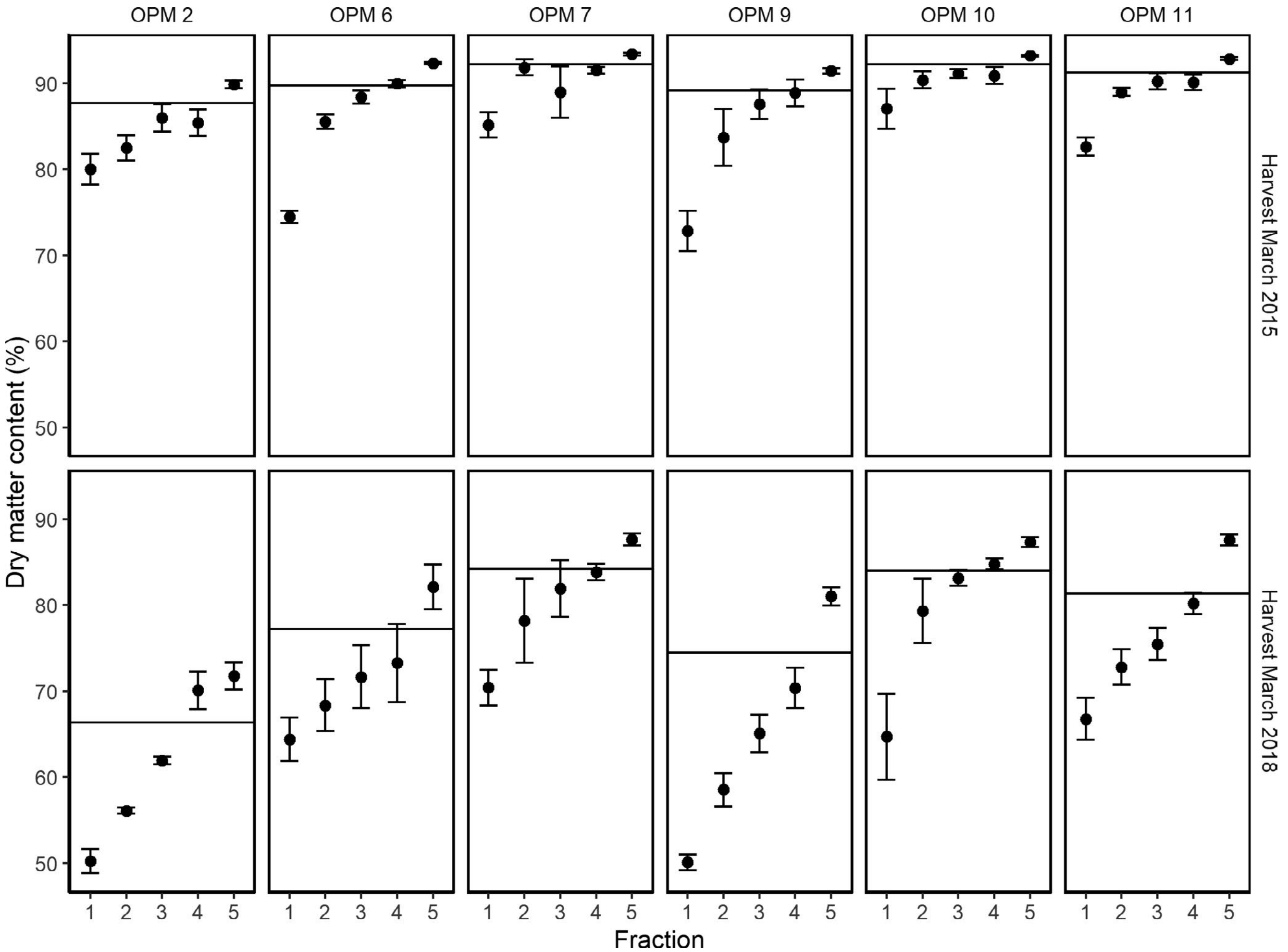

FIGURE 4 Dry matter content per hybrid and fraction for harvests in March 2015 and March 2018, with mean value (horizontal line across all fractions) for all genotypes. The effect of the fraction is significant for each year (2015: $p = 0.0014$, 2018: $p = 0.0004$; $n = 3$)

TABLE 1 Theoretical total dry matter content of biomass harvested in March 2015 and 2018 for all genotypes according to fraction (Fractions 1–5 = total harvested biomass from all fractions, Fractions 2–5 = total biomass without fraction 1, Fractions 3–5 = total biomass without fractions 1 and 2, Fractions 4+5 = total biomass without fraction 1, 2 and 3). Values with the same letter show no significant differences within a year and genotype

	OPM 2		OPM 6		OPM 7		OPM 9		OPM 10		OPM 11	
Harvest March	**2015**	**2018**	**2015**	**2018**	**2015**	**2018**	**2015**	**2018**	**2015**	**2018**	**2015**	**2018**
Fractions 1–5	87% e	65% d	89% e	77% e	92% e	84% e	89% e	73% e	92% e	83% e	91% e	82% e
Fractions 2–5	88% d	68% c	91% d	79% d	93% d	86% d	90% d	76% d	93% d	86% d	92% d	84% d
Fractions 3–5	89% c	70% b	92% c	80% c	93% c	87% c	91% c	78% c	93% c	87% c	92% c	86% c
Fractions 4+5	89% b	72% a	92% b	81% b	93% b	87% b	91% b	80% b	93% b	87% b	93% b	87% b
Fraction 5	90% a	72% a	92% a	82% a	93% a	88% a	91% a	81% a	93% a	87% a	93% a	88% a

Note: The effect of the different biomass fractions is significant for the harvest in March 2015 ($p = 0.0002$) and for the harvest in March 2018 ($p < 0.0001$).

opposing trends. While all genotypes showed a higher concentration in the upper fractions 3–5 in 2015, the N concentration was relatively low in fractions 4 and 5 in 2018, even though the crop was fertilized with 40 kg N ha^{-1} in the vegetation period before harvest in 2018.

The P and K concentrations showed a reverse trend to that of ash and Ca: Higher concentrations were found in 2018 than in 2015. Across all genotypes, higher P concentrations were observed in nearly all fractions in 2018 than in 2015, which is surprising considering the generally lower ash contents in 2018 than 2015. Also, no additional P fertilizer was applied to the crop after initial fertilization in the second vegetation period in 2013, while steady annual nutrient offtake with the harvested biomass was observed. OPM

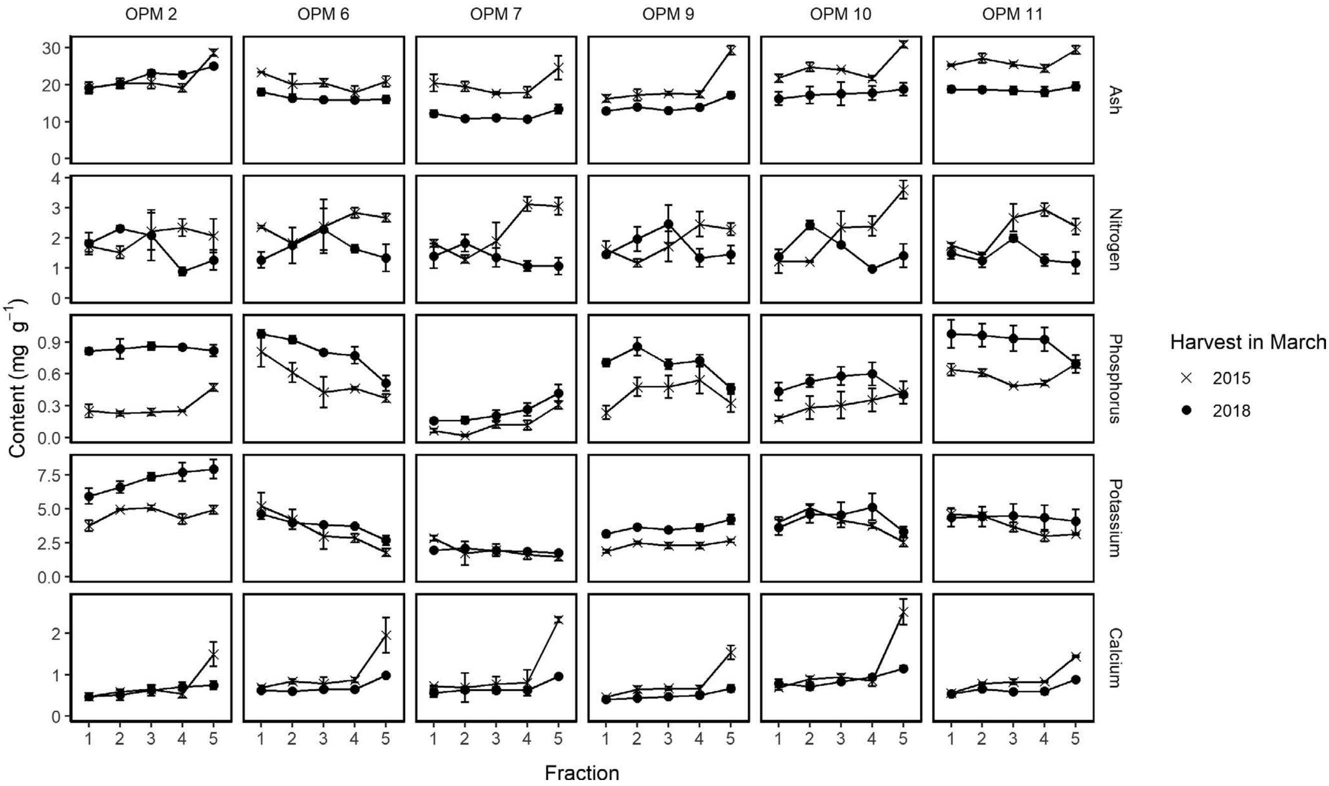

FIGURE 5 Mean ash, nitrogen, phosphorus, potassium and calcium concentration in mg g^{-1} per genotype, fraction and year. Error bars indicate standard error ($n = 3$)

7 and 10 showed comparatively low P concentrations and a decreasing P concentration from the upper to the lower fractions (except fraction 5 of OPM 10 in 2018). Both genotypes can be characterized as relatively early senescing (Figure 1a). The composition pattern of the K concentration was more or less similar in 2015 and 2018, except for OPM 2 and 9. The higher K concentration of OPM 9 in 2018 than in 2015 is somewhat surprising since the overall ash concentration was the reverse. In 2018, the average K concentration of OPM 9 accounted for 25% of the total ash content, while in 2015, it was only 10%.

The senescence behaviour of the six genotypes can be characterized according to greenness as: early for OPM 7 and 10, medium for OPM 6 and 11 and late for OPM 2 and 9 (Figure 1a). The latter two stay green until late autumn. The earlier senescing genotypes OPM 7 and 10 had the highest DM content across all five fractions in both years, while the later senescing OPM 2 and 9 had the lowest (Table 1). Although this relation between DM content and senescence was observed, the impact of senescence on ash content and mineral concentrations was less distinct. In both years, the early-senescing genotypes OPM 7 and 10 showed the lowest average P and highest average Ca concentrations across all five fractions of all genotypes (Appendix S3). The late-senescing OPM 2 had the highest ash content and potassium concentration (average of all five fractions) in both years, and the early-senescing OPM 7 the lowest (Appendix S3). However, no clear trend was observed, which may also be due to the fact that the time of senescence was recorded by visual observation only. Late-senescing genotypes tended to have higher K concentrations, while the reverse was true for Ca (Appendix S3). For an in-depth analysis of the effect of senescence time on ash content and mineral concentration in the harvested biomass, a more precise observation of senescence development is recommended.

Table 2 shows the total N, P, K and Ca amounts accumulated in the total aboveground biomass in kg ha^{-1} per genotype, which is equivalent to the nutrient offtake of the harvested biomass. In addition, the individual fractions' proportion of the overall nutrient offtake is given. For N and Ca, the offtake of all genotypes was higher in 2015 than 2018, while for P and K, it was the reverse (Table 2). In general, fraction 5 accounted for the largest proportion of overall nutrient offtake, which is not surprising since this fraction accounts for most of the DM yield (Figure 3). However, in both years, the percentage Ca offtake of fraction 5 was considerably higher than the percentage DM yield of this fraction. This was also the case for N in 2015, but not in 2018. For P offtake, fraction 5 played a dominant role for OPM 7 and 11 in both years and for OPM 2 and 10 in 2015, while for K offtake, fraction 5's proportion was elevated for OPM 2 and 9 in both years and for OPM 11 in 2018. These over-proportional contributions of fraction 5 to the total nutrient offtake show that, in such cases, the potential of reducing

TABLE 2 Mean nutrient offtakes (kg ha^{-1}) of nitrogen, phosphorus, potassium and calcium and relative nutrients offtakes per fraction (%) for each genotype and year. Fractions 1–5 gives the total nutrient offtake for the biomass of all five fractions analysed

	OPM 2		OPM 6		OPM 7		OPM 9		OPM 10		OPM 11	
Fraction	**2015**	**2018**	**2015**	**2018**	**2015**	**2018**	**2015**	**2018**	**2015**	**2018**	**2015**	**2018**
Nitrogen												
1–5 (kg ha^{-1})	**27.5**	**21.1**	**41.8**	**24.1**	**35.4**	**22.9**	**29.3**	**17.7**	**42.7**	**21.1**	**27.6**	**17.9**
1	8.0%	14.7%	8.4%	6.8%	5.1%	11.4%	5.6%	8.7%	3.3%	8.2%	6.6%	11.3%
2	5.8%	18.3%	5.7%	10.3%	3.3%	13.3%	3.7%	10.5%	2.9%	12.8%	5.1%	8.3%
3	8.6%	12.5%	6.0%	13.0%	4.6%	21.3%	5.5%	16.6%	5.0%	8.6%	8.8%	12.2%
4	7.0%	4.7%	7.4%	8.2%	7.7%	5.5%	6.6%	5.2%	4.7%	4.5%	9.2%	7.3%
5	70.6%	49.9%	72.5%	61.7%	79.2%	48.4%	78.7%	59.1%	84.2%	66.0%	70.4%	61.0%
Phosphorus												
1–5 (kg ha^{-1})	**5.1**	**11.1**	**7.2**	**10.5**	**3.1**	**5.4**	**4.5**	**6.0**	**5.1**	**6.1**	**7.7**	**11.3**
1	7.2%	12.7%	16.6%	13.0%	2.0%	5.5%	4.9%	12.7%	3.8%	9.0%	8.6%	12.0%
2	5.3%	11.4%	11.0%	12.5%	0.5%	4.8%	9.3%	13.6%	5.3%	9.6%	7.8%	10.3%
3	5.0%	9.3%	6.3%	9.6%	3.3%	5.5%	9.0%	10.3%	5.0%	9.8%	5.7%	9.2%
4	4.4%	8.9%	6.8%	8.7%	3.1%	6.1%	9.4%	8.5%	5.6%	9.5%	5.8%	8.5%
5	78.1%	57.7%	59.2%	56.2%	91.1%	78.1%	67.4%	54.9%	80.3%	62.1%	72.1%	60.0%
Potassium												
1–5 (kg ha^{-1})	**64.3**	**111.3**	**39.5**	**52.6**	**20.8**	**29.6**	**34.4**	**42.6**	**41.5**	**51.0**	**40.6**	**61.5**
1	7.6%	9.3%	19.3%	12.3%	13.6%	12.8%	5.4%	8.0%	10.8%	9.1%	11.8%	9.8%
2	8.4%	10.4%	13.8%	10.9%	7.3%	11.3%	6.6%	8.3%	12.3%	10.1%	11.0%	8.7%
3	7.5%	9.0%	8.2%	9.2%	8.0%	9.0%	5.8%	7.3%	9.0%	9.2%	8.2%	8.2%
4	6.1%	9.0%	7.7%	8.6%	6.7%	7.8%	5.3%	5.9%	7.6%	9.6%	6.5%	7.4%
5	70.5%	62.4%	51.0%	59.0%	64.4%	59.0%	76.9%	70.5%	60.3%	61.9%	62.5%	65.9%
Calcium												
1–5 (kg ha^{-1})	**13.8**	**8.9**	**26.7**	**14.9**	**24.2**	**13.6**	**17.3**	**6.4**	**27.8**	**14.4**	**14.5**	**11.3**
1	4.4%	9.1%	3.9%	5.8%	3.0%	7.7%	2.7%	6.9%	2.7%	7.0%	4.0%	6.6%
2	4.6%	9.0%	4.1%	5.9%	2.5%	7.6%	3.5%	6.6%	3.2%	5.5%	5.4%	6.9%
3	4.9%	8.3%	3.3%	5.6%	2.7%	6.6%	3.5%	6.7%	3.0%	5.9%	5.1%	5.7%
4	3.1%	9.3%	3.6%	5.2%	2.8%	5.7%	3.0%	5.5%	2.5%	6.3%	5.0%	5.4%
5	83.1%	64.3%	85.1%	77.6%	89.0%	72.4%	87.3%	74.3%	88.5%	75.3%	80.5%	75.4%

nutrient offtake through a higher cutting height is relatively limited. However, a higher cutting height could provide a contribution to reducing total nutrient offtake in those cases where the contribution of fraction 5 to the overall nutrient offtake was under-proportional. This was true for the following nutrient offtakes and genotypes: N for all genotypes except OPM 11 in 2018; P for OPM 6 and 9 in both years, and OPM 2 and 10 in 2018; K for OPM 6, 7 and 10 in both years, and OPM 11 in 2015.

4 | DISCUSSION

This study assessed the effect of cutting height on miscanthus biomass yield and quality by analysing the lower 40 cm of the shoots in 10 cm fractions. The results contribute to the understanding of the impact of an increased cutting height on biomass yield, biomass quality and nutrient offtake through harvest. While the impact on biomass yield was negative—as anticipated—the impact on biomass quality and nutrient offtake was less prominent.

The biomass yields recorded are within the typical range for that site (Clifton-Brown et al., 2017; Kalinina et al., 2017; Kiesel, Nunn, et al., 2017; Lewandowski, Clifton-Brown, et al., 2003). However, compared with other locations (Himken et al., 1997; Schorling et al., 2015), they are relatively low. In addition, the height of the miscanthus genotypes assessed is comparatively low (Christian et al., 2008; Fernando, 2017; Gordana et al., 2017). Both these facts presumably have an influence on the results. We observed differences between the genotypes, with the shorter OPM 6 and OPM 11 tending to accumulate more biomass in fraction 1. However, OPM 2—the third highest of the analysed genotypes—accumulated similar amounts in fraction 1. The mean ash concentrations in this study are in the range of Kludze et al. (2013). In 2018, we found a 30% lower ash concentration than in 2018. Similar deviations can also be found in the literature (Arundale et al., 2015; Hodgson et al., 2011; Meehan et al., 2013; Vrije et al., 2002). The nutrient concentrations are in the range of Himken et al. (1997). However, when comparing 15 studies of Mxg Cadoux et al. (2012) found higher N and K, and a narrower range of P concentrations.

4.1 | Impact of cutting height on biomass yield

The results of the study enabled the impact of increasing cutting height on the biomass yield of fractions 1–4 to be quantified. On average, 270 kg ha^{-1} are lost per 1 cm increase in cutting height. This is equivalent to 0.83% of the total aboveground yield potential. Although a yield decline with increasing cutting height is logical and to be expected, to our knowledge, this is the first time it has been quantified over 40 cm in multiple genotypes. Kahle et al. (2001) assessed harvested biomass and harvest residues (mainly stubble) on the field and found that they accounted, on average, for 16.5% (range: 8.2%–31.8%) of total standing biomass yield potential. However, Kahle et al. (2001) did not specify the exact cutting height; it was merely given as between 12.4 and 22.4 cm. Assuming an average cutting height close to the arithmetic mean of these two values, the yield loss per cm was 0.96% of the total yield, which is in line with the 0.86% in our study. Fernando (2017) separated shoots into 50 cm fractions and found that the lowest 50 cm contributed 30% of the total aboveground biomass yield, which is equivalent to a 0.6% yield decline per 1 cm higher cutting height. However, the field trial in the Fernando study was located in Portugal where, with irrigation, a yield exceeding 20 t DM ha^{-1} and a shoot height of over 350 cm were achieved. Total biomass yield and shoot height presumably influence the yield proportion accumulated in the lower parts of the shoots. Lesur-Dumoulin et al. (2016) compared commercial yields harvested using standard agricultural machinery with a scientific hand-harvest of randomly chosen plots located within the same field. They reported an average reduction of 20% for the commercial harvest. While the scientific hand-harvest was performed at a cutting height of 10 cm, that of the commercial machine harvest was highly variable within the field and not further defined.

As expected, the present study found the highest yield losses in the lowest part of the shoots (fraction 1) due to the slight tapering of stem diameter with height. The approximate average yield decline with increasing cutting height was as follows: fraction 1: 0.96% cm^{-1}; fraction 2: 0.86% cm^{-1}; fraction 3: 0.77% cm^{-1}; and fraction 4: 0.71% cm^{-1}. A similar decline in yield proportion with increasing shoot height was found by Fernando (2017) for the whole shoot. If leaf-fall is incomplete, for example, due to very mild winter conditions or lodging of the crop, the proportion of yield in the upper shoot could be larger. We assumed that, due to the colder winter and higher precipitation, leaf-fall was more complete in 2018 than in 2015. This, and the difference in age, could explain the higher yield proportions of the lower shoot fractions in 2018. However, leaf mass needs to be analysed separately in future research. A correlation between biomass distribution and number of stems per plant was not found. Cutting height most likely not only has an effect on yield but also on soil organic matter and soil biodiversity due to differences in the biomass left on the field.

Our results reveal the importance of maintaining a constant cutting height in scientific trials comparing yields from different treatments. For commercial harvests, a lower cutting height is recommended to minimize biomass losses within the limits imposed by the available harvest technology and in-field ground conditions, including evenness and slopes. Similar observations were reported by Monti et al. (2009) for harvest losses in commercially harvested switchgrass. However, cutting heights should be high enough to avoid harvesting litter from leaves and stem tops that have come into contact with the ground, as these have high ash concentrations unfavourable for biomass quality. For commercial harvests, we recommend a cutting height between 15 and 25 cm.

4.2 | Impact of cutting height on dry matter and ash content

The results of our study showed that DM content, and therefore moisture content, can be significantly influenced by cutting height. In general, DM content increases with shoot height, and thus, the overall DM content of the harvested biomass can be manipulated by cutting height. Bruce et al. (2005) also reported a lower moisture content in higher plant parts. One reason for this is the higher proportion of leaves in the upper plant parts, which have a higher surface-to-mass ratio and therefore dry more quickly than stems. Additionally, leaves have a higher DM content than stems (Jensen et al., 2017). The microclimate within the crop also affects drying, since the lower parts of the plants are shaded by upper parts, are less exposed to wind (Kath-Petersen, 1994) and frost, and the ambient air has a higher humidity due to soil moisture.

In practice, the aim is to harvest biomass at a moisture content below 20% to ensure safe storage (prevent self-heating) and avoid post-harvest losses through microorganism growth and mould formation. Up to now, the moisture content of miscanthus biomass is mainly managed by delaying harvest time to spring, but even March is in many cases still too early to achieve a sufficient dry matter content (Iqbal & Lewandowski, 2014; Lewandowski & Heinz, 2003). In addition, a delayed harvest leads to yield losses (Iqbal et al., 2017). In particular for late-ripening genotypes and climates with mild winters, delaying the harvest is not sufficient to reduce the moisture content to below 20% (Nunn et al., 2017). In such environments, mowing to a swath for drying before baling is preferred over direct chipping (Meehan et al., 2013, 2014). However, in continental Europe, direct chipping of the standing crop in spring is the most common harvest practice where the biomass is used locally. The choice of cutting height can contribute to managing the dry matter content of the harvested biomass. The harvest must be completed before shoots emerge from the rhizome to avoid damage to following year's crop. These aspects determine the harvest window, a key factor in harvest cost calculations involving the deployment of expensive machinery. This study showed that the dry matter content of the harvested biomass can be significantly increased by a higher cutting height, on account of the bottom-to-top moisture gradient. This is particularly the case with wet conditions before harvest. Although the 2017–2018 winter was colder than that of 2014–2015—which generally promotes the maturation process of miscanthus biomass (Nunn et al., 2017)—the moisture content was higher in 2018 due to rain events in the days immediately before harvest. In such cases, raising the cutting height could minimize the drying time necessary to achieve the target <20% moisture, but at the expense of yield.

The ash content followed no clear trend. As ash contents are higher in leaf than in stem fractions (Baxter et al., 2014; Iqbal et al., 2015; Jensen et al., 2017; Lewandowski & Kicherer, 1997; Meehan et al., 2013), the variations between years are likely to be due to differences in the leaf–stem ratio. A lower cutting height will increase the proportion of stem and reduce ash in the harvested biomass, provided the harvester does not also collect leaf litter.

4.3 | Impact of cutting height on nutrient concentration and removal

Genotype and year were found to alter the distribution of elemental concentrations of the individual fractions harvested at different cutting heights. In 2015, N and Ca concentrations were higher in the upper shoot fractions than the lower ones. This was the reverse in 2018 with higher N concentrations in the lower fractions than the upper ones. This indicates complex interactions between environmental conditions and ripening prior to harvest. The weather conditions at the time of ripening in 2014–2015 and 2017–2018 were quite distinct. The first frost occurred later in the autumn of 2014 than in 2017. The timing of the first frost is important because it can terminate the physiologically active translocation of nutrients and carbohydrates from the shoots to the rhizome in autumn (Iqbal & Lewandowski, 2014; Purdy et al., 2015). Ripening thereafter is a more passive process involving leaching and desiccation, which depends on low temperatures combined with low air humidities. For this reason, we expected a higher nutrient concentration in the lower part of the plant, but our data did not validate this hypothesis. Cadoux et al. (2012) found the concentrations of the non-leachable elements N, P and Ca in the harvested biomass to depend on the leaf–stem ratio, which correlates negatively with the amount of rainfall. N and Ca concentrations are higher in leaves than in stems (Beale & Long, 1997; Lewandowski & Kicherer, 1997), which explains the high N and Ca values in the upper plant part in 2015, and lower values in 2018. As the precipitation in the 2017–2018 winter was higher and the first frost occurred more than a month earlier than in 2014–2015, the number of leaves lost was higher. For P, lower concentrations were observed in 2015 than in 2018. This is an interesting observation since there was no P fertilization. One possible explanation could be a more complete relocation to the rhizomes in the 2014–2015 season due to warmer weather in autumn or an accumulation of P in the crop over the years. Of the nutrients analysed, only K is leached from standing biomass (Jørgensen, 1997; Tukey, 1970). Iqbal and Lewandowski (2014) found that leaching also occurs in standing miscanthus, since the stability of the cell walls is lost during the ripening process and rain leaches minerals from the plant material (Eichert & Fernández, 2012). However, contrary to our expectations, neither the higher amount of precipitation nor the early frost in the winter of 2017–2018 led to a lower K concentration. The same phenomenon was observed by Iqbal and Lewandowski (2014). The hypothesis that lower shoot parts have a higher K concentration because the upper plant parts protect them from the rain was also not proven. The reason for both phenomena could be that the K concentration is not only determined by leaching but also by internal relocation mechanisms (Beale & Long, 1997; Cadoux et al., 2012; Himken et al., 1997). Iqbal et al. (2017) concluded that the K concentration is more influenced by internal relocation mechanisms than by leaching. They analysed the nutrient concentration from the same field trial from August 2014 to March 2015 and found a decline in K from August 2014 to January 2015, but no difference between January and March 2015, when the aboveground plant parts were killed by frost.

The results show that leaving a higher amount of biomass on the field reduces the nutrient removal by a similar proportion to the reduction in yield, except for Ca, where 80% is accumulated in the biomass above 45 cm. The nutrient removal decreases on average by 0.8% N, 0.8% P, 0.9% K and 0.5% Ca per 1 cm increase in cutting height in the lowest 40 cm of the shoot and is therefore for Ca under-proportional compared to the yield decline. Harvesting at a cutting height of 25 cm instead of 5 cm lowers the nutrient removal from the field on average by 4.1 kg N ha^{-1}, 1.4 kg P ha^{-1}, 10.0 kg K ha^{-1} and 1.5 kg Ca ha^{-1}. Nutrient offtakes in this study were generally relatively low compared to other sites harvested around the same time (Christian et al., 2008; Himken et al., 1997). Comparing different studies mainly from Europe, Cadoux et al. (2012) found on average higher N and K offtakes (in kg ha^{-1}), but P offtakes within the same range. Ca offtake was low for all genotypes at 3–10 kg ha^{-1}; a slightly broader range than reported by Christian et al. (2008). Overall, we found that cutting height has a limited impact on nutrient removal. Therefore, we conclude that lower cutting heights, which help minimize the yield gap, do not compromise biomass quality or increase nutrient offtakes.

5 | CONCLUSION

With each 1 cm increase in cutting height, average yield was reduced by 0.83%. For example, by raising the harvest height from 10 to 30 cm, average yield losses would be 2 t DM ha^{-1}. In contrast to yield, cutting height had less impact on biomass quality and nutrient removal. The largest quality impacts were found to be with moisture content, especially if there was insufficient drying time between the last rain event and harvest. Cutting height can therefore be used—within certain limits—to manipulate the moisture content under suboptimal harvest conditions. This could widen the harvest window, especially for harvests made by forage harvesters directly chipping the standing crop. Nutrient removal was not affected by cutting height and is no reason for raising it. However, low-cutting grass mowers could inadvertently collect mineral-rich leaf litter, which would both lower biomass quality and reduce litter for mineralization needed to build up soil organic carbon.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

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

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