Spatial and temporal distribution of the root system and root nutrient content of an established Miscanthus crop

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Abstract

Although a high biomass yield is obtained from established Miscanthus crops, previous studies have shown that fertilizer requirements are relatively low. As little information on the role of the Miscanthus roots in nutrient acquisition is available, a study was conducted to gather data on the Miscanthus root system and root nutrient content. Therefore in 1992, the root distribution pattern of an established Miscanthus crop was measured in field trials using the trench profile and the auger methods. Also, in 1994/1995, seasonal changes in root length density (RLD) and root nutrient content were monitored three times during the vegetation period.

The trench profile method showed that roots were present to the maximum depth measured of 250 cm. The top soil (0–30 cm) contained 28% of root biomass, while nearly half of the total roots were present in soil layers deeper than 90 cm. Using the auger method, we found that RLD values in the topsoil decreased with increasing distance from the centre of the plants. Below 30 cm, RLD decreased markedly, and differences in root length in the soil between plants were less pronounced. The total root dry weight down to 180 cm tended to increase from May 1994 (10.6 t ha\(^{-1}\)) to November 1994 (13.9 t ha\(^{-1}\)) and then decreased again until March 1995 (11.5 t ha\(^{-1}\)). Nutrient concentrations in the roots decreased with increasing depth. The concentrations of N (0.7–1.4\%) and K (0.6–1.2\%) were clearly higher than those of P (0.06–0.17\%). The mean values for N, P and K contents of the roots of all three sampling dates in 1994/1995 were 109.2 kg N ha\(^{-1}\), 10.6 kg P ha\(^{-1}\) and 92.5 kg K ha\(^{-1}\).

Although our results showed that RLD values for Miscanthus in the topsoil are lower than for annual crops, the greater rooting depth and the higher RLD of Miscanthus in the subsoil mean that nutrient uptake from the subsoil is potentially greater. This enables Miscanthus crops to overcome periods of low nutrient (and water) availability especially during periods of rapid above-ground biomass growth. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Auger method; Miscanthus; Root length density; Root nutrient content; Root system; Trench profile method

1. Introduction

Over the last few years, the cultivation of non-food crops has been promoted in Europe to replace fossil energy sources. Miscanthus × giganteus (Greef and Deuter, 1993; hereafter called Miscanthus), a herbaceous perennial originating from East Asia, is an interesting option because of its fast growth rate and high yield level under European conditions (Nygaard Nielsen, 1988; Schwarz et al., 1995; Greef, 1996). However, the fertilizer requirement of an established Miscanthus crop has been found to be rather small. Results from several field experiments have shown either
Table 1

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>N (mg/kg soil)</th>
<th>P (mg/kg soil)</th>
<th>K (mg/kg soil)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–15</td>
<td>2500</td>
<td>44</td>
<td>154</td>
</tr>
<tr>
<td>15–30</td>
<td>2190</td>
<td>24</td>
<td>84</td>
</tr>
<tr>
<td>30–45</td>
<td>1940</td>
<td>18</td>
<td>57</td>
</tr>
<tr>
<td>45–60</td>
<td>760</td>
<td>4</td>
<td>28</td>
</tr>
<tr>
<td>60–75</td>
<td>500</td>
<td>4</td>
<td>32</td>
</tr>
<tr>
<td>75–90</td>
<td>380</td>
<td>4</td>
<td>26</td>
</tr>
<tr>
<td>90–105</td>
<td>410</td>
<td>4</td>
<td>26</td>
</tr>
<tr>
<td>105–120</td>
<td>490</td>
<td>5</td>
<td>35</td>
</tr>
<tr>
<td>120–135</td>
<td>550</td>
<td>4</td>
<td>35</td>
</tr>
<tr>
<td>135–150</td>
<td>500</td>
<td>4</td>
<td>28</td>
</tr>
<tr>
<td>150–165</td>
<td>550</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>165–180</td>
<td>600</td>
<td>5</td>
<td>37</td>
</tr>
</tbody>
</table>

*Total soil N according to Kjeldahl digestion.

† P and K extraction with CAL.

A recent study on the nutrient requirements of Miscanthus (Himken et al., 1997) has shown the importance of below-ground rhizomes in storage and mobilization/remobilization of nutrients. Although rhizomes are first formed in July, roots originating from these rhizomes do not grow before shooting starts the following year. Koike et al. (1975) reported that rhizomes and associated shoot bases begin to shoot in late April/early May. About a month after the start of shoot elongation, roots begin to grow. The roots of a rhizome are only active during the year the rhizome sends up shoots, and regrowth of roots associated with older rhizomes is negligible. The maximum shoot biomass is found in September, coincident with anthesis, and almost all above-ground plant material dies before early November. However, root growth continues until late October (Midorikawa et al., 1997).

Little information exists on the role of the roots in nutrient acquisition for a Miscanthus crop. Therefore, this study focused on the root system of Miscanthus. The aims were (1) to characterize the root distribution pattern of an established Miscanthus crop and (2) to obtain information about total root weight and nutrient content of Miscanthus roots.

2. Material and methods

2.1. Study site and trial set-up

The study site was a Eutric fluvisol (sandy loam; pH 7.1) located near the Rhine valley (N 51° 31’, E 6° 42’) in Western Germany. The soil nutrient status is summarized in Table 1. Further details on soil characteristics and cropping history have been reported by Himken et al. (1997). Miscanthus was planted at a rate of 10,000 plants ha⁻¹ in May 1989 on a farmer’s field following a wheat crop. After a 3 year establishment period, the plant density had declined to 9260 plants ha⁻¹ due to low frost resistance. In 1992 and 1994/1995, root studies were performed on the plots receiving 90 kg N ha⁻¹ [for more details see Himken et al., 1997].

2.2. Root measurements

Rooting patterns of Miscanthus were estimated using two methods: the trench profile method and the auger method (Böhm, 1979). In May 1992, a trench (200 cm wide), oriented perpendicular to the plant rows, was dug down to a depth of 250 cm. To expose the roots for counting, a 5 mm soil layer was removed from the trench wall by water using a hand sprayer (Böhm and Köpke, 1977). A transparent plastic sheet with a 50 × 50 mm grid was fixed to the wall, and all visible roots regardless of their thickness were marked on the sheet. The number of marks on the sheet were counted for each 5 cm soil layer. To calculate the root length density (RLD), these values were converted, taking into account a soil volume of 450 cm³ (180 cm width × 5 cm depth of the soil layer × 0.5 cm thickness of the sprayed soil layer).

The root distribution was determined using the auger method (Böhm, 1979) in June 1992 and
three times in the 1994/1995 vegetation period (May 1994, November 1994, March 1995). The field was subdivided into four blocks and from each block five plants were chosen at random for root sampling. Soil was sampled from the 0–90 cm and 90–180 cm soil layers using 10 cm and 8 cm diameter augers, respectively. The cores were positioned (i) at the centre of the plant (p1 = area effected directly by the rhizome), (ii) at the mid-way point between the rhizomes of four plants (p3 = area with smallest influence from the plants) and (iii) mid-way between p1 and p3 (p2 = area with average conditions) (Fig. 1). Cores were cut into 15 cm segments. It was not possible to measure roots in the 0–15 cm layer at position p1 due to the presence of rhizome material in the cores. The soil samples from the same position and depth of each replicate were bulked and stored at 4 °C for a maximum of 2 weeks, until roots were washed from the soil and collected in a sieve (0.25 x 0.25 mm mesh). After weighing the cleaned roots, a subsample was taken and stored at −5 °C until determination of root length (RL) was possible. RL was measured by a modified line intersection method (Newman, 1966 modified according to Tennant, 1975) using a 1.5 x 1.5 cm grid. The root length density (RLD; cm cm⁻³) was then calculated taking the respective soil volume into account (Garay and Wilhelm, 1983). In the 1994/1995 examination, the rest of the subsample from each depth, position and replicate was dried, weighed again, dried and ground.

Total root dry weight (RDW; kg ha⁻¹) was calculated, assuming that each of the three sampling positions (p1–p3) was representative for a specific area (a1 = 1104 cm², a2 = 8592 cm², and a3 = 1104 cm²; Fig. 1).

For analysis of the nutrients in the roots, a weighed sample from the four replicates was mixed and homogenized. N, P and K contents were determined following Kjeldahl digestion using an automated continuous flow system (Holz, 1974). N and P were determined colorimetrically, and K was analysed with a flame photometer. The total nutrient content was defined as the product of RDW and nutrient concentration in the roots.

2.3. Data analysis

A statistical evaluation was only possible for RLD and RDW, because nutrient concentrations in the roots were measured in pooled samples. Differences in RLD and RDW between soil depth and sampling dates were analysed using the Tukey HSD test at the 5% level.

3. Results

3.1. Root distribution

The root distribution determined using the trench profile method in 1992 is shown in Fig. 2. Roots were visible down to a depth of 250 cm. The top soil (0–30 cm) contained 28% of the counted roots. About a quarter of the roots were found in the 30–90 cm soil layer. Nearly half of the total counted roots were present in the deeper soil layers. In general, the number of roots...
3.2 Root length density

Using the auger method in June 1992, RLD was found to be highest for the two top soil layers (0–15 cm and 15–30 cm; Fig. 3). With increasing distance from the centre of the plant, RLD decreased for these soil layers. Below 30 cm, the density of roots decreased clearly for all three sampling positions, and horizontal differentiation was less pronounced (tendency for higher RLD values at p3 in comparison to p2 and p1). At a soil depth of 135–165 cm, markedly higher values in 1994/1995, with the exception of the 75–105 cm soil layer, in which RDW was higher than in the layers above or below (Table 2). The total RDW in the soil profile down to 180 cm increased from 0.6 t ha$^{-1}$ in May 1994 to 13.9 t ha$^{-1}$ in November and then decreased to 11.5 t ha$^{-1}$ in March 1995, reaching nearly the same level as in spring the previous year. The increase in RDW from May 1994 to November 1994 was mainly due to increases in the 0–15, 15–30 and 30–45 cm soil layers because changes in deeper soil layers were much smaller.

There were no significant differences in RLD between the three sampling dates in 1994/1995. Nevertheless, the total RL for the soil profile — calculated using RLD data and the representative areas (a1–a3) for each sampling position (Fig. 1) — increased from 3.6 km m$^{-2}$ in May 1994 to 4.9 km m$^{-2}$ in March 1995 (Fig. 4).

3.3 Root dry weight

As with RLD values, RDW tended to decrease with sampling depth for all three sampling dates in 1994/1995, with the exception of the 75–105 cm soil layer, in which RDW was higher than in the layers above or below (Table 2). The total RDW in the soil profile down to 180 cm increased from 0.6 t ha$^{-1}$ in May to 13.9 t ha$^{-1}$ in November and then decreased to 11.5 t ha$^{-1}$ in March 1995, reaching nearly the same level as in spring the previous year. The increase in RDW from May 1994 to November 1994 was mainly due to increases in the 0–15, 15–30 and 30–45 cm soil layers because changes in deeper soil layers were much smaller.
However, the decrease in RDW over winter was also due to a loss of dry weight in deeper soil layers up to 120 cm.

### 3.4. Content of mineral nutrients in the roots

The nutrient concentrations in the roots were similar for the three sampling dates in 1994/1995, and the concentrations of N (0.7–1.4%) and K (0.6–1.2%) were clearly higher than those of P (0.06–0.17%). The N, P and K concentrations in the roots tended to decrease with increasing soil depth (data not shown).

### Table 3

<table>
<thead>
<tr>
<th>Nutrient content (kg ha⁻¹)</th>
<th>May</th>
<th>November</th>
<th>March</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>94.0</td>
<td>124.6</td>
<td>108.9</td>
</tr>
<tr>
<td>P</td>
<td>7.6</td>
<td>13.2</td>
<td>11.0</td>
</tr>
<tr>
<td>K</td>
<td>75.0</td>
<td>118.5</td>
<td>85.9</td>
</tr>
</tbody>
</table>

The nutrient contents (N, P and K) in total root dry matter of Miscanthus.

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**Fig. 4.** Root length density (RLD) obtained with the auger method for the 0–180 cm soil profile for three sampling dates in the 1994/1995 growing period (P1, P2 and P3 indicate the different sampling positions; see Fig. 1).
The contents of N, P and K, defined as the product of dry matter and mean nutrient concentration, were also fairly similar throughout the vegetation period of the *Miscanthus* crop (Table 3). The mean values for the N, P, and K contents of the roots of all three sampling dates were 109.2 kg N ha$^{-1}$, 10.6 kg P ha$^{-1}$ and 92.5 kg K ha$^{-1}$.

4. Discussion

The distribution and growth of roots from annual crops and trees have been intensively investigated (e.g. Kutschera, 1960; Bohm, 1978), whereas the root patterns of perennial plants like *Miscanthus* are not well known. There is no generally acceptable method for estimating root systems of herbaceous perennials. The main difficulties are separation of the current year’s roots from roots that were established in the preceding years as well as the differentiation between live and dead roots. Furthermore, translocation of nutrients and carbohydrates from the below-ground plant parts of herbaceous perennials in spring to form new shoots and vice versa relocation from the shoots to the root/rhizome system at the end of the growth period may cause mass changes without any shedding or formation of new tissues.

Up to now, investigations concerning the rooting system of *Miscanthus* have only been done in natural plant communities in East Asia (Kayama et al., 1969, 1972; Yamane and Sato, 1971; Midorikawa et al., 1975). In such systems, the interaction of the roots of other plant species on the rooting pattern of *Miscanthus* has to be taken into consideration.

The present study was conducted on a well-established *Miscanthus* crop in the 4th and 6th year after planting to give a general view of the spatial and temporal root distribution and of the nutrient content of *Miscanthus* roots.

4.1. Methods comparison

Several methods have been proposed to examine the spatial and temporal variability of plant root systems (e.g. Bohm, 1979). Both methods used in our experiments have their advantages and disadvantages: qualitative analysis of root distribution is easier with the trench profile, but the auger method can give a more accurate quantitative analysis and is more suited to periodic sampling (Perry et al., 1983).

RLD values obtained in the soil depth up to 135 cm with the trench profile method in 1992 were 1.3–2.6 times lower than the values determined by the auger method (Table 4). RLD below 135 cm was much lower for the trench profile method. This is in agreement with Kücke et al. (1995), who found that RLD data for cereals and sugar beets obtained with the trench profile method were four- to tenfold lower than the values calculated with the auger method. The better correspondence of RLD data obtained with the auger and trench profile methods in our investigation may be due, at least in part, to the fact that *Miscanthus* is a perennial crop with less pronounced spatial variability, and *Miscanthus* roots are more visible because the root diameter is greater.

4.2. Rooting pattern of *Miscanthus*

The trench profile method was used to get a first impression of the vertical and horizontal

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>RLD (cm cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15–30</td>
<td>0.424</td>
</tr>
<tr>
<td>30–45</td>
<td>0.247</td>
</tr>
<tr>
<td>45–60</td>
<td>0.199</td>
</tr>
<tr>
<td>60–75</td>
<td>0.159</td>
</tr>
<tr>
<td>75–90</td>
<td>0.097</td>
</tr>
<tr>
<td>90–105</td>
<td>0.132</td>
</tr>
<tr>
<td>105–120</td>
<td>0.136</td>
</tr>
<tr>
<td>120–135</td>
<td>0.131</td>
</tr>
<tr>
<td>135–150</td>
<td>0.084</td>
</tr>
<tr>
<td>150–165</td>
<td>0.070</td>
</tr>
<tr>
<td>165–180</td>
<td>0.084</td>
</tr>
<tr>
<td>180–200</td>
<td>0.118</td>
</tr>
</tbody>
</table>

* RLD calculated with measured root length per foil unit.

† Average of RLD at p1, p2 and p3.
distribution of the Miscanthus root system. Roots were present at the maximum depth of 230 cm investigated in this study, which is comparable to the rooting depth of perennial crops like alfalfa but more than the rooting depths of other arable crops like maize or sugar beet (Kutschera, 1960).

In contrast, Yano and Kayama (1975) reported a maximum rooting depth of 120 cm in a semi-natural grassland community dominated by Miscanthus in northeastern Japan. A possible explanation for this disagreement are different soil conditions (e.g. soil compaction layers, water holding capacity, nutrient availability), which are known to have a great effect on root growth (e.g. Geisler and Maarufi, 1975).

Overall, the results of our study confirm other findings (summarized by Bohn (1979) and Köpke (1981)) that root density is highest in the topsoil. Nevertheless, in the sub-soil (30–90 cm) and in the deeper subsoil layers (>90 cm), Miscanthus has many more roots than other arable crops. This can be explained by the fact that Miscanthus as a perennial crop builds up a root system at depth, which can be used for more than one vegetation period. In contrast, annual plants like winter wheat need about 2 months after the start of the growing period to explore the soil profile down to 90 cm (Bohn, 1978).

As expected, rooting density decreased with increasing distance from the centre of the plant (Figs. 3 and 4). A higher rooting density within the rows rather than between rows has also been reported for annual crops such as maize and soybeans (Mengel and Barber, 1974; Arya et al., 1975; Tardieu, 1988a,b). Nevertheless, for Miscanthus, these differences could only be found in the topsoil (0–30 cm). In deeper soil layers, distribution of roots is independent of the position of sampling. This could be due to the overlapping of root systems from neighbouring plants in deeper soil layers.

In comparison to RLD in the topsoil reported for annual crops (e.g. 2.6–5 cm cm$^{-3}$ for maize; Taylor and Klepper, 1973; Mengel and Barber, 1974; Smika and Klute, 1982; Fusseder, 1985), the RLD values found for Miscanthus were relatively low (0.5–2.3 cm cm$^{-3}$). However, the RLD of Miscanthus was greater in deeper soil layers. For example, at the 150 cm soil depth, the RLD for the Miscanthus crop was 0.1–0.3 cm cm$^{-3}$ (Fig. 4) in contrast to the RLD values of 0.04–0.13 cm cm$^{-3}$ of winter wheat reported by Kuhlmann et al. (1989) and 0.01–0.05 cm cm$^{-3}$ of maize reported by Wiesler and Horst (1994). The presence of relatively high RLD values in the subsoil and the ability to explore the subsoil for nutrients can help to explain why an established crop of Miscanthus requires relatively low external inputs of nutrients (Himken et al., 1997).

### 4.3. Root dry weight

Comparing the start and end of the growing period, there were only small variations in RDW. Almost similar trends were observed for rhizome dry matter in this field experiment (Himken et al., 1997). The highest RDW values in the top- and subsoil layers in our study measured at the end of the growing period in November 1994 are in agreement with the results of Yano and Kayama (1975), who found a maximum RDW in natural Miscanthus communities in late October. The results therefore indicate that root growth of Miscanthus continues at least one more month after anthesis (Bohm, 1978).

As expected, rooting density decreased with contrast to annual crops, in which the highest root distribution and root dry weight are attained at increasing distance from the centre of the plant (Midorikawa et al., 1975). These results are in contrast to annual crops, in which the highest root distribution and root dry weight are attained at anthesis (Bohm, 1974; Mengel and Barber, 1974).

The RDW for the Miscanthus crop under study is equivalent to about half of the maximum above-ground dry matter production of an established crop and in the same order of magnitude as rhizome dry matter (Himken et al., 1997).

### 4.4. Nutrient content

Nutrient concentrations in roots have been reported to vary with soil nutrient status (Van Praag et al., 1988; Burke and Raynal, 1994). The decrease in nutrient concentration in the roots appears to be related to the decrease in nutrient content in the soil. Similar results were found by Raspe et al. (1989) for N, P and K concentrations in roots of a 100 year old Picea abies stand in the Black Forest, Germany. One possible reason is...
inadequate washing of the roots, especially in the topsoil, where much higher soil N, P, and K contents were found (Table 1). Overall, a significant amount of nutrients found in the total biomass is located in the roots. In comparison to N, P, and K contents in shoots (Himken et al., 1997), nutrient contents in roots are in the same order of magnitude, whereas nutrient contents in rhizomes are twofold higher. This gives a clear indication that storage of nutrients in below-ground plant parts is an important nutrient pool for Miscanthus.

5. Conclusions

Our results show that RLD in the topsoil for Miscanthus is lower than for annual crops such as winter wheat and sugar beets. However, much greater rooting depth enables Miscanthus crops to potentially take up nutrients (and water) from the subsoil and thereby overcome periods of low nutrient (and water) availability in the topsoil, especially during periods of rapid above-ground biomass growth. Furthermore, such an extensive rooting system is likely to reduce losses of nutrients (especially nitrate) due to leaching throughout the year.

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References


