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Peat Properties and Denitrification in Cultures of Potted Ornamental Plants

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Summary

N loss by denitrification from potted plants is subject to high variability. It was suggested that variability partly resulted from characteristics of the potting medium. Thus, peat properties were investigated with regard to their influence on denitrification N loss. The wettability of peat, which depended on substrate water content, showed a strong effect on N loss. Dry substrate produced less N emissions after irrigation than moist substrate. Sieving as well as compacting peat substrate increased denitrification N loss. This was mainly attributed to decreased air capacity. While compacted peat showed increased water and decreased air capacity already before planting, sieved substrate presumably changed during cultivation. Mixing sieved peat with rice husks or wood fibres (30 Vol.%) increased air capacity as measured by the 'Quick' method. Nevertheless, observed N emissions from the mixed substrate were at least as high as from peat. It was suggested that rice husks as well as wood fibres broke down and decomposed during the cultivation period and thus lost their positive effect on substrate aeration. In all experiments denitrification N loss sensitively reflected changes in substrate properties. It was concluded that substrate properties influenced the extent of denitrification N loss and significantly contributed to its variability.

Zusammenfassung

Torfeigenschaften und Denitrifikation in getopften Zierpflanzenkulturen. N-Verluste aus Topfpflanzen-Kulturen durch Denitrifikation unterliegen einer hohen Variabilität. Es wurde vermutet, dass diese Variabilität zum Teil durch Eigenschaften des Topfsubstrats verursacht wird. Daher wurden Torfeigenschaften hinsichtlich ihres Einflusses auf N-Verluste durch Denitrifikation untersucht. Die Benetzbarkeit von Torf, die vom Substrat-Wassergehalt abhing, zeigte einen starken Einfluss auf den N-Verlust. Trockenes Substrat produzierte weniger N-Emissionen nach Bewässerung als feuchtes Substrat. Sowohl das Sieben als auch das Verdichten von Torfsubstrat erhöhte die Denitrifikationsverluste. Dies wurde zum Großteil auf eine verminderte Luftkapazität zurückgeführt. Während verdichtetes Substrat bereits vor der Bepflanzung eine erhöhte Wasser- und eine verminderte Luftkapazität zeigte, veränderte sich das gesiebte Substrat vermutlich erst während der Kultur. Das Mischen von gesiebtem Torf mit Reisspelzen oder Holzfasern (30 Vol.%) erhöhte die mittels der „Quick"-Methode bestimmten Luftkapazität. Trotzdem waren die gemessenen N-Emissionen aus dem Substratgemisch mindestens so hoch wie aus Torfsubstrat. Es wurde vermutet, dass sich sowohl Reisspelzen als auch Holzfasern während der Kulturzeit zersetzten und dadurch ihren positiven Einfluss auf die Substratbelüftung verloren. In allen Versuchen spiegelten die N-Verluste zuverlässig Veränderungen der Substrateigenschaften wider. Daraus wurde geschlossen, dass Substrateigenschaften Einfluss auf das Ausmaß der Denitrifikationsverluste haben und signifikant zu ihrer Variabilität beitragen.

Key words. horticulture – N emission – N_2O – peat substrate – pot plants – substrate physics

Introduction

N loss by denitrification is a factor which is often missing in N balances due to the difficulty in assessing it. Apart from the requirement of technical equipment and development of methodical practice, denitrification is typically subject to high variability. This variability results from a multitude of variable, environmental factors, which have an impact on the main controllers of the denitrification process, i.e. O_2 deficiency, availability of NO_3 and C, temperature and soil pH. In addition to chemical soil characteristics such as content of mineral nutrients, organic matter and pH, physical soil properties have also been shown to have an impact on denitrification, mostly by influencing water and air balance of a soil. For example, increased bulk density or soil compaction was reported to enhance denitrification in agricultural soils (BAKKEN et al. 1987; TORBERT and WOOD 1992; RUSER et al. 1998). Soil texture was suggested to affect denitrification by determining water holding capacity and air filled pore space (SEXSTONE et al. 1985; AULAKH et al. 1991).

These physical properties are also variable in horticultural substrates. The compaction of substrate is considered to be more likely a product of potting practice of horticulturists, but there are more factors influencing physical substrate properties. Although they are mostly based on white peat, substrates vary in composition and quality. Often organic components like wood fibres and, to a lesser extent, rice husks are added to improve aeration of peat substrates. Also, among peats there are differences in physical properties, depending for example on the degree of decomposition, peat origin, and particle size (MICHIELS et al. 1993; UOSUKAINEN and LÖTJÖNEN 1997). Air and water content of peat may also be affected by the degree of peat dryness before irrigation as drying of peat reduces its wettability (NIGGEMANN 1970; VALAT et al. 1991).

As denitrification in horticultural peat substrates proved to be primarily controlled by water and air dynamics (AGNER 2003), it was assumed that changes in physical substrate characteristics were reflected in denitrification N loss. To investigate the influence of physical substrate properties on denitrification, N emissions were measured from planted substrate in flow-through chambers (AGNER 2003). Additionally, changes in physical substrate properties which are most closely related to denitrification (pore space, air and water capacity), were surveyed by laboratory analysis (the 'Quick' method) of unplanted substrate (WREDE 2001) .

Materials and Methods

Substrates and plant material

Substrates used for experiments were commercial, full fertilized white peat substrates with and without cocopor. Additionally, some substrates were self-prepared to investigate the effects of substrate sieving and of substrate composition on denitrification and substrate properties. Sieved (5 mm) and unsieved white peat substrate was used to study the effect of substrate sieving. Sieved (5 mm) white peat substrate, a mixture of 70 Vol.% sieved white peat plus 30 Vol.% rice husks and a mixture of 70 Vol.% sieved white peat plus 30 Vol.% wood fibres were used to study the effect of substrate composition. Prior to planting, all self-prepared substrates were adjusted to pH 6 by liming with $CaCO_3$ according to the buffer curve of the substrate. The pH was measured in suspensions of 20 mL substrate in 50 mL of a 0.01 M $CaCl_2$ solution (VDLUFA 1991). Then, the substrates were fertilized with 1 g L^{-1} of a commercial full compound fertilizer containing 15 % N in form of NO_3 (4,5 %) and NH_4 (10,5 %) as well as P_2O_5 (10 %), K_2O (15 %), MgO (2 %) and trace nutrients (Flory3, Euflor).

Denitrification measurements were done with plants of *Pelargonium zonale* 'Grand Prix' and *Euphorbia pulcherrima* 'Sonora Red'. Plants were propagated by cuttings and rooted in small peat nuggets (Jiffy7) for two weeks. Then, plants were potted into 340 mL plastic pots and cultivated for at least four weeks to guarantee rooting of the substrate. During cultivation, plants were fertigated with 1 g L^{-1} of a commercial full compound fertilizer (see above) as it is common in horticultural practice.

Experimental setup

Flow-through chambers were used for measurement of denitrification from planted substrate (AGNER 2003). When (N_2+N_2O)-N loss was to be determined, substrates were pretreated for two hours with 5 Vol.% acetylene (C_2H_2) within the chambers before the start of the experiment. The C_2H_2 treatment continued until the end of each experiment, which was reached when N emissions had finally ended. C_2H_2 inhibits the reduction of N_2O to N_2 (YOSHINARI et al. 1977) and thus allows the quantification of (N_2+N_2O)-N in gas samples by measurement of N_2O. After pretreatment with C_2H_2 the planted pots were flood irrigated for two hours within the chambers with 1 L of a 150 mg NO_3-N solution. The irrigation event was defined start of the experiment. Air samples were taken with syringes topped with gauge needles from silicon tubes at the air outlet of the chambers every two to four hours until N_2O emissions ceased.

Analytical procedures

N_2O. The analysis of N_2O in all air samples was performed by gas chromatography (Chrompack 9001) with an electron capture detector (ECD) according to a method described by MOSIER and MACK (1980).

Water content. During denitrification measurement, every four to eight hours, pots were taken from the chambers and weighed. At the end of the experiment, when N emissions had finally ceased, plants were harvested, and the fresh weight of the shoot and of the rooted substrate was determined. Then the substrate was dried at 105 °C and weighed again. Water content (Vol.%) was calculated from pot volume, fresh weight of shoot, dry weight of rooted substrate, and fresh weight during the experiment.

The 'Quick' method by WREDE (2001) was used to determine total pore volume, water capacity, and air capacity of substrates. To investigate the effect of plant roots on substrate properties, test cylinders of 10 cm diameter (785 mL) were used instead of the recommended cylinders of 7 cm diameter.

Statistics. Statistical analyses were conducted using the SAS software package. Three to six and six replications per treatment were used for measurements of physical substrate properties and denitrification, respectively.

Results

Effect of substrate moisture before irrigation on denitrification

Denitrification N loss was measured from pots of *E. pulcherrima* that contained dry (20 Vol.% H_2O) or moist (55 Vol.% H_2O) peat substrate before irrigation. Emissions from the formerly dry peat were very low in comparison to those from moist peat (Fig. 1). In spite of the rather long irrigation period of 2 hours, the dry substrate reached a much lower water content than the moist substrate. Obviously the water repellency caused by drying of the peat prevented water

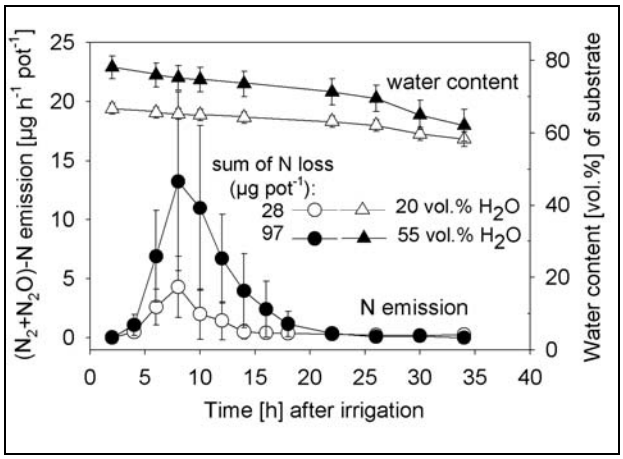


Fig. 1. (N_2 +N_2O)-N emissions and water content of sieved peat substrate planted with *E. pulcherrima* with different substrate moistures before irrigation (5 Vol.% C_2H_2).

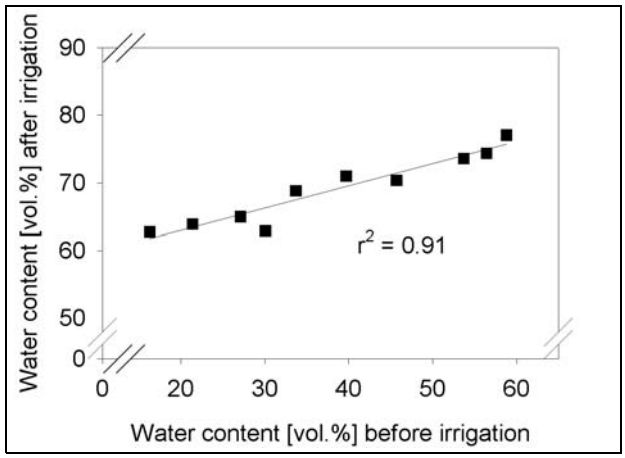


Fig. 2. Relationship of water content before and after flood irrigation (2 h) of a peat substrate planted with *P. zonale*.

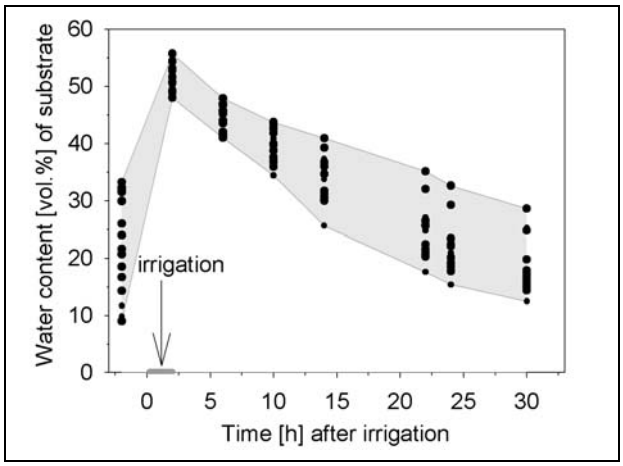


Fig. 3. Water content of a peat substrate planted with *P. zonale* before and after flood irrigation (2 h).

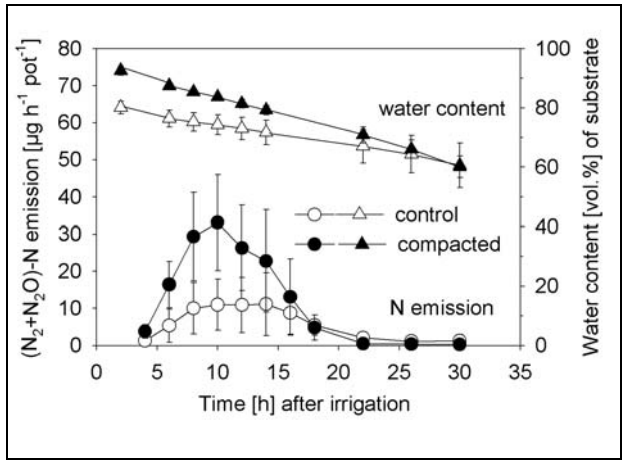


Fig. 4. (N_2 +N_2O)-N emissions and water content of substrate planted with *P. zonale* as affected by compaction, which increased bulk density by 1/3 following irrigation (5 Vol.% C_2H_2).

uptake, and thus reduced denitrification to a large extent. This suggestion was confirmed when potted and planted substrate with water contents ranging from 16 to 59 Vol.% was flood-irrigated (Fig. 2). The positive relationship of water content before and after irrigation was very clear and showed that dry substrate would reach a lower mean water content after irrigation than moist substrate. Thus, differences in water content were not nullified by an irrigation period of two hours but they persisted and even increased with time (Fig. 3).

Effect of substrate compaction on denitrification

N emission from compacted peat substrate was up to three times higher than from the uncompacted substrate (Fig. 4). The compacted substrate reached a higher water content after irrigation than the control substrate. This was expected, since compaction increased the water capacity of unplanted substrate in the laboratory analysis (Fig. 5). Although the water content of the compacted substrate remained at a higher level throughout the denitrification experiment, the duration of denitrifying activity in both treatments was the same. These apparently contradictory observations could be ascribed to the fact that the crucial factor controlling denitrification was not the mean water content but the highest water content in the substrate layer at the pot bottom (AGNER 2003). It was suggested that by the time denitrification ended, the water content of the denitrifying substrate volume was the same in compacted and uncompacted substrate. The higher mean water content of the compacted substrate was due to the higher water content in the upper substrate layers, which did not contribute to denitrification. In total, the compacted substrate produced twice as much N loss (Table 1). In contrast to higher (N_2+N_2O)-N emissions, the compacted substrate emitted less N_2O than the control substrate (Table 1). The N_2O:N_2 ratio of the control substrate was more than four times higher than that of the compacted substrate.

Table 1. Sum of (N_2+N_2O)-N and N_2O-N emissions from compacted and uncompacted substrate planted with *P. zonale* following irrigation (0 or 5 Vol.% C_2H_2).

Treatment	(N_2 +N_2O)-N emission [mg pot^{-1}]	N_2O-N emission [mg pot^{-1}]	N_2O:N_2 ratio
control	0.15 ± 0.08	0.06 ± 0.02	0.68
compacted	0.31 ± 0.12	0.04 ± 0.02	0.15

Data represent mean values of six replications ± standard deviation.

Effect of substrate sieving (5 mm) on denitrification

N emissions from sieved white peat substrate were higher than emissions from unsieved substrate (Fig. 6). While the duration of denitrifying activity was similar in both treatments, N emissions from the sieved substrate reached a higher maximum and started to decrease later than emissions from the unsieved substrate. Although the course of N emissions showed obvious differences, water contents of the substrates were about the same. Also, further investigations showed that sieving had no significant effect on air and water capacity of unplanted peat, which was also used for denitrification studies (data not shown).

Effect of substrate composition on denitrification

To investigate the effect of substrate composition on denitrification, measurements were conducted with pots of *P. zonale* grown in sieved peat mixed with rice husks (Fig. 7a) and in sieved peat mixed with wood fibres (Fig. 7b). In both cases, control treatments consisted of sieved peat. Addition of rice husks or wood fibres led to about the same N loss as from peat substrate. In contrast to this, measurement of air and water capacity from unplanted, freshly mixed substrate showed that addition of both wood fibres and rice husks, increased air capacity and decreased water capacity relative to plain peat (data nor shown). In the case of rice husks, it was observed after denitrification measurement that the outer appearance of the husks had changed during the cultivation period, which lasted about 12 weeks in this experiment.

Effect of planting on substrate characteristics

Laboratory measurements of pore volume, air and water capacity were done with unplanted substrate, while denitrification was measured from planted substrate. As treatment effects on denitrification N loss did not always correspond to those on substrate air capacity, the question was whether planting altered substrate characteristics and thus limited transferability of results from laboratory to greenhouse, and vice versa.

Test cylinders with planted peat substrate were cultivated in a greenhouse for eight weeks. After this period pore volume, water and air capacity showed only few differences between planted substrate and the unplanted control treatment (Fig. 8). Plant roots increased the dry weight of the substrate by about 7 % and reduced shrinking of the substrate, as determined by measurement of substrate surface distance from the cylinder edge, from 9 % in unplanted substrate to 7.8 % in planted substrate (data not shown).

All in all, changes in physical substrate properties by planting were considered small enough to transfer laboratory results obtained with unplanted substrate to planted substrate of greenhouse experiments.

Discussion

Effect of substrate moisture on denitrification

Denitrification N loss from dry peat was not even 1/3 of that from moist peat (Fig. 1) since N emission rates were much lower and the denitrifying activity ended sooner. This was attributed to the lower water content that was reached by the dry substrate after irrigation compared to the moist substrate (Fig. 1). As a decrease

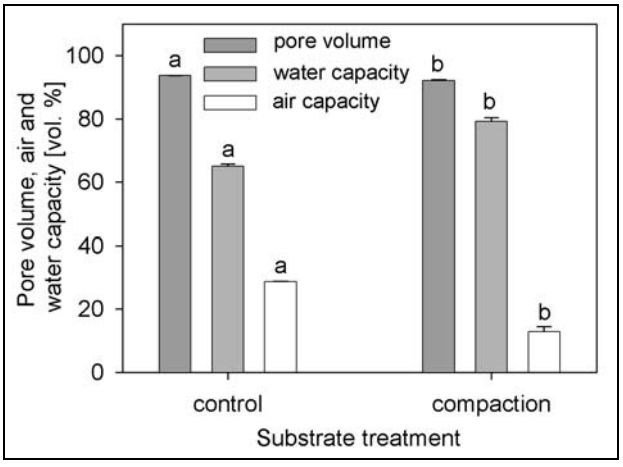


Fig. 5. Pore space, air and water capacity of unplanted peat substrate as affected by compaction which increased bulk density by 1/3.

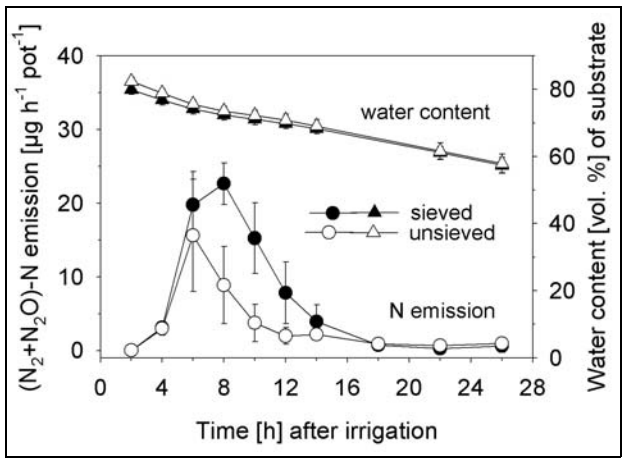


Fig. 6. (N_2 +N_2O)-N emissions from sieved (5 mm) and unsieved substrate planted with *P. zonale* following irrigation (5 Vol.% C_2H_2).

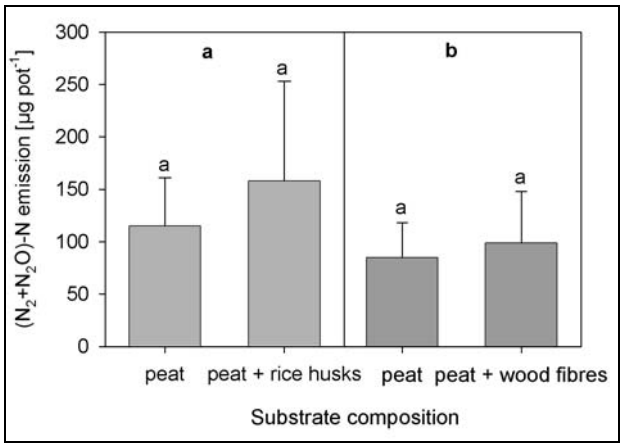


Fig. 7. (N_2+N_2O)-N emissions from sieved peat and from mixtures of 30 Vol.% rice husks or wood fibres and 70 Vol.% sieved peat planted with *P. zonale* (5 Vol.% C_2H_2).

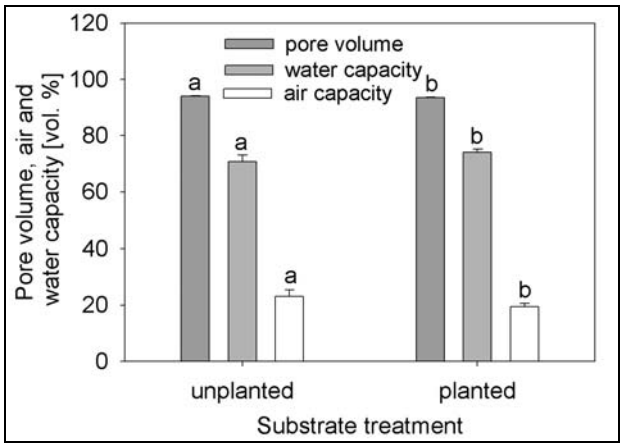


Fig. 8. Pore volume, air capacity, and water capacity of unplanted and planted unsieved peat substrate after eight weeks of cultivation.

in water filled pores corresponds to an increase in air filled pores, it is very likely that denitrification in drier substrate was repressed by oxygen availability.

The effect of substrate moisture on water content after irrigation was confirmed by experimental results which prove a close positive relationship between water content of peat substrates before and after irrigation. The problem of water repellency of dried peat has often been described in the literature (NIGGEMANN 1970; VALAT et al. 1991; MICHEL et al. 1999). It is reported to be related to chemical (humic polymers) as well as physical (shrinkage, adhesion) characteristics of peat. Hydrophobia after drying was also described for soils, where it is generally related to soil organic matter (MA'SHUM et al. 1988; WALLIS and HORNE 1992; ELLIES et al. 2003). Nevertheless, its effect on denitrification has not received much attention in the literature.

As differences in water content were shown to provoke differences in denitrification N loss, it was considered most important to conduct denitrification measurements only with substrates of homogenous water content at the beginning of irrigation.

Effect of substrate compaction on denitrification

Denitrification N loss from compacted substrate was significantly higher than from uncompacted substrate (Fig. 4, Table 1). In contrast to this, N_2O-N emissions were lower from compacted than from uncompacted substrate. The increase of gaseous N loss in compacted substrate was due to higher water and lower air content. This was confirmed by laboratory measurement, where compacted substrate proved to have decreased air capacity and increased water capacity relative to the control, whereas total porosity remained nearly unchanged (Fig. 5).

Reduction of air filled pores is a common consequence of soil or substrate compaction. RICHARD et al. (2001) analysed pore size distribution of agricultural soils and showed that the total porosity was relatively little affected by soil compaction, because the amount of macropores destroyed was mostly compensated for by an increase in micropores. The same was stated by KOOISTRA and TOVEY (1994). In their review on soil compaction and soil aeration, STEPNIEWSKI et al. (1994) presented many examples of reduced soil aeration due to compaction.

Lack of oxygen is one of the crucial prerequisites for denitrification, and consequently the promoting effect of soil compaction on denitrification has been repeatedly reported with regard to agricultural soils. TORBERT and WOOD (1992) investigated the effect of soil compaction on N loss and observed a more than 3-fold increase in N loss when the soil bulk density was increased from 1.4 to 1.8 Mg m^{-3} soil. They suggested that soil compaction reduced O_2 diffusion by restricting the continuity of air-filled pores and reducing the number of larger pores. Soil compaction by tractor traffic was found by BAKKEN et al. (1987) to cause 2 to 4-fold higher N emissions relative to uncompacted soil. Apart from observing increasing N loss with increasing soil compaction, WALENZIK and HEINEMEYER (1990) found that the emission of N_2O also increased with compaction but that the ratio N_2O:N_2 decreased. The increased reduction of N_2O in compacted soils may be related to the lower diffusion coefficient of gases at high bulk density. When the escape of N_2O from the site of reduction to the atmosphere is delayed, the chance for reduction to N_2 is increased (SMITH 1980). In general, it is assumed that the proportion of N_2O decreases when conditions for denitrification, like oxygen deficiency, become more favourable (TIEDJE 1988).

Effect of substrate sieving on denitrification

The positive effect of sieving on total denitrification N loss from peat substrate (Fig. 6) could not be explained by an increase in substrate water content since the water content of sieved and unsieved substrates was nearly the same after irrigation, and also throughout the experiment. However, emissions from the sieved substrate lasted longer and reached a higher peak. This indicated increased oxygen deficiency in the sieved relative to the unsieved peat substrate. But water content in substrate layers within the pot showed no difference

between sieved and unsieved substrate (data not shown). Also, water and air capacity of the unplanted peat substrate used for denitrification measurement showed no change after sieving (data not shown).

Nevertheless, other observations reported in the literature might explain the high denitrification N loss of the sieved relative to the unsieved substrate. PRASAD and O'SHEA (1999) reported that the particle size of peat decreased with increase of the degree of its breakdown. During an incubation period of 15 months, they observed decreases in airspace and volume reductions, especially in substrates of finer particle size. MICHIELS et al. (1993) observed higher shrinkage of fine substrate than of coarse substrate during nine-month exposition to ebb/flood irrigation. Thus, possibly sieved and unsieved substrate changed differently during the cultivation period, although the initial values for pore volume and air capacity were the same. This could explain the difference in denitrification N loss. Additionally, TORBERT and WOOD (1992) concluded that within the same level of water-filled pore space changes in pore structure could contribute to an increase in anaerobic microsites. They related this to compacted soils, but it may also apply to sieved substrate.

Effect of substrate composition on denitrification

Denitrification N loss of the mixes peat/wood fibres and peat/rice husks was about the same as that of plain peat (Fig. 7a, b). This was surprising, since at planting the substrate mixes had a significantly higher air capacity than the plain peat substrate, while the total pore volume was the same for all substrates (data not shown). However, during denitrification measurement the substrate mixes showed the same water content as plain peat, indicating that air capacity was no longer higher. This was probably due to decomposition of the material. For wood fibres a breakdown during cultivation was repeatedly reported. This led to loss of volume, decrease in air capacity, and increase in water capacity (FISCHER et al. 1993; LEINFELDER et al. 1995; PRASAD and O'SHEA 1999; REST et al. 2002). For rice husks a change in the outer appearance during cultivation was observed, which was presumably caused by decomposition.

Thus, the effect of substrate components on denitrification seemed to depend on their stability during the cultivation period. Breakdown or decomposition of growing media is likely to favour denitrification by decreased air capacity and increased carbon availability, which accelerates oxygen consumption.

Conclusions

This study showed that substrate properties influenced denitrification N loss from potted plants. The main parameters, which affected denitrification, were related to substrate air and water content. Additionally, it was suggested that substrate components like rice husks and wood fibres promoted denitrification by supplying decomposable organic carbon. Substrate properties depended on the one hand on the raw material, i.e. on substrate composition and particle size. On the other hand, substrate properties were altered by potting practice (compaction) and cultivation (drying, shrinkage, decomposition). Denitrification N emissions proved to be sensitive even to comparably small changes in substrate properties such as they are to be expected in common pot plant production. This contributes to explaining the high variability of N emissions that was usually observed during denitrification measurement with potted plants (AGNER 2003).

References

AGNER, H. 2003: Denitrification in cultures of potted ornamental plants. PhD-thesis. Fachbereich Gartenbau, Universität Hannover, Germany. http://edok01.tib.uni-hannover.de/edoks/e01dh04/377337625.pdf

AULAKH, M. S., J. W. DORAN, D. T. WALTERS and J. F. POWER 1991: Legume residue and soil water effects on denitrification in soils of different textures. Soil Biol. Biochem. **23**, 1161–1167.

BAKKEN, L. R., T. BØRRESEN and A. NJØS 1987: Effect of soil compaction by tractor traffic on soil structure, denitrification, and yield of wheat (*Triticum aestivum* L.). J. Soil Sci. **38**, 541–552.

ELLIES, A., K. H. HARTGE, R. MacDONALD and C. RAMIREZ 2003: Organische Substanz und Benetzbarkeit von Bodenproben – eine Interpretation. J. Plant Nutr. Soil Sci. **166**, 120–123.

FISCHER, P., E. MEINKEN and F. KALTHOFF 1993: Holzfaserstoffe im Test. GbGw **26**, 1220–1222.

KOOISTRA, M. J. and N. K. TOVEY 1994: Effects of compaction on soil microstructure, pp. 91–111 In: SOANE, B. D. and OUWERKERK, C. v. (eds): Soil compaction in crop production. Elsevier Science B. V., Amsterdam.

LEINFELDER, J., S. HARTMANN and R. RÖBER 1995: Für Zierpflanzen im Topf geeignet. DeGa **22**, 1305–1307.

MA'SHUM, M., M. E. TATE, G. P. JONES and J. M. OADES 1988: Extraction and characterization of water-repellent materials from Australian soils. J. Soil Sci. **39**, 99–110.

MICHEL, J. C., L. M. RIVIÈRE and M. N. BELLON-FONTAINE 1999: Characterisation of the wettability of organic substrates (peat and composted bark) by adsorption measurements. Acta Hort. **481**, 129–135.

MICHIELS, P., R. HARTMANN, and C. COUSSENS 1993: Physical properties of peat substrates in ebb/flood irrigation system. Acta Hort. **342**, 205–219.

MOSIER, A. R. and L. MACK 1980: Gas chromatographic system for precise, rapid analysis of nitrous oxide. Soil Sci. Soc. Am. J. **44**, 1121–1123.

NIGGEMANN, J. 1970: Versuche zur Messung der Benetzungsfähigkeit von Torf. Torfnachrichten **20**, 14–17.

PRASAD, M. and J. O'SHEA 1999: Relative breakdown of peat and non-peat growing media. Acta Hort. **481**, 121–128.

REST, M., B. SCHÄFER, and E. GRANTZAU 2002: Masseverlust bei Holzfasern bei der Lagerung unter Gewächshausbedingungen, Verband der Landwirtschaftskammern, Rheinischer Landwirtschafts-Verlag, Bonn.

RICHARD, G., I. COUSIN, J. F. SILLON, A. BRUAND and J. GUÉRIF 2001: Effect of compaction on the porosity of a silty soil: influence on unsaturated hydraulic properties. European Journal of Soil Science **52**, 49–58.

RUSER, R., H. FLESSA, R. SCHILLING, H. STEINDL and F.

BEESE 1998: Soil compaction and fertilizer effects on nitrous oxide and methane fluxes in potato fields. Soil Sci. Soc. Am. J. **62**, 1587–1595.

SEXSTONE, A. J., N. P. REVSBECH, T. B. PARKIN and J. M. TIEDJE 1985: Direct measurement of oxygen profiles and denitrification rates in soil aggregates. Soil Sci. Soc. Am. J. **49**, 645–651.

SMITH, K. A. 1980: A model of the extent of anaerobic zones in aggregated soils, and its potential application to estimates of denitrification. J. Soil Sci. **31**, 263–277.

STEPNIEWSKI, W., J. GLINSKI and B. C. BALL 1994: Effects of soil compaction on aeration properties. In: SOANE, B. D. and OUWERKERK, C. v. (eds): Soil compaction in crop production. Elsevier Science B. V., Amsterdam, 167–188

TIEDJE, J. M. 1988: Ecology of denitrification and dissimilatory nitrate reduction to ammonium. In: ZEHNDER, A. J. B. (ed.): Biology of anaerobic microorganisms. Wiley, New York, 179–244

TORBERT, H. A. and C. W. WOOD. 1992: Effects of soil compaction and water-filled pore space on soil microbial activity and N loss. Commun. Soil Sci. Plant Anal. **23**, 1321–1331.

UOSUKAINEN, H. and P. LÖTJÖNEN 1997: Sphagnum classification and the influence of the different spaghnum species on horticultural peat properties. International Peat Society, Amsterdam, the Netherlands, 31–35.

VALAT, B., C. JOUANY and L. M. RIVIERE 1991: Characterization of the wetting properties of air-dried peats and composts. Soil Sci. **152**, 100–106.

VDLUFA 1991: Bestimmung des pH-Wertes. Die Untersuchung von Böden. VDLUFA-Verlag, Darmstadt.

WALENZIK, G. and O. HEINEMEYER 1990: Time course of gaseous N-losses from compacted soil cores. Mitteilgn. Dtsch. Bodenkundl. Gesellsch. **60**, 373–378.

WALLIS, M. G. and D. J. HORNE 1992: Soil water repellency. Adv. Soil Sci. **20**, 91–146.

WREDE, A. 2001: Untersuchungen zur Ermittlung der Kennwerte des Luft- und Wasserhaushalts von Kultursubstraten. PhD-thesis. Fachbereich Gartenbau, Universität Hannover, Germany. http://edok01.tib.uni-hannover.de/edoks/e01dh01/331191490.pdf

YOSHINARI, T., R. HYNES, and R. KNOWLES 1977: Acetylene inhibition of nitrous oxide reduction and measurement of denitrification and nitrogen fixation in soil. Soil Biol. Biochem. **9**, 177–183.

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