Removal of Nitrogen Leaching from Vegetable Crops in Constructed Wetlands

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Abstract

Vegetable growing leads to high nitrogen emissions. In the Netherlands, nitrogen emissions can hardly be reduced by reducing fertilization without risks for yield and quality loss. An alternative measure to reduce emissions is to collect nitrate-rich drain water and remove nitrate from the drain water in constructed wetlands. This was tested in three different types of constructed wetlands at an experimental farm in the SE of the Netherlands: (1) a surface flow system (SF) planted with Common reed, (2) a horizontal subsurface flow system with Common reed (SSF-reed) and (3) a horizontal subsurface flow system filled with straw (SSF-straw). The water discharge into the wetlands is adjusted to the nitrate removal capacity of the wetlands. In- and outlet concentrations of nitrogen and other nutrients were measured every two weeks since December 2005. Collected water from pipe drains contained on average 30 mg N L^{-1}. The mean N removal was 58% in SF (1655 kg N ha^{-1} year^{-1}), 25% in SSF-reed (1447 kg ha^{-1} year^{-1}) and 63% in SSF-straw (3622 kg N ha^{-1} year^{-1}). SF and SSF-straw are functioning well. In SSF-reed, the amount of carbon seems to be insufficient to sustain nitrogen reduction. Disadvantage of SSF-straw is the negative removal rate of phosphorus (mean 16 kg ha^{-1}). With a removal rate of about 60% within the system, about 20% of the leached nitrogen from the vegetable fields could be removed: about two-third of the leached water is collected in drains and half of the nitrate-rich drain water is collected for purification. The cost effectiveness (expressed as € per kg N removed) ranged between € 52 and € 104 kg^{-1} N for SF, between € 29 and 58 kg^{-1} N for SSF-straw and between € 161 and € 322 kg^{-1} N for SSF-reed. Cost reduction is possible by combining with other functions as water storage and nature development.

INTRODUCTION

Eutrophication of freshwater lakes, rivers and coastal ecosystems is one of the main environmental issues. In many European countries, non-point pollution from agricultural sources is the largest source of nutrients emissions to surface waters. In 1991, Europe adopted the Nitrates Directive to reduce water pollution from agricultural sources. High emissions of nutrients in vegetable growing are inevitable because of inefficient nitrogen uptake (Neeteson and Carton, 2001; Thorup-Kristensen, 2001), harvest during full growth, cropping during periods with a high rainfall surplus and low risk cropping strategies because of relative high financial crop values and stringent quality requirements of retail organizations (Oerke and Dehne, 2004).

In the Netherlands, vegetable growers on sandy soils, however, are unable to meet the standards set by the Dutch government to comply with the Nitrates Directive. Over the last years, fertilizer inputs were already reduced to approximate the official recommendations. The decline in leaching, however, is small and still far above the standards of the Nitrates Directive. Model and experimental studies indicate that a further reduction of fertilizer inputs will be insufficient to reach the standards and may result in yield losses (van der Bolt et al., 2008). To be able to grow high quality vegetables within the limits set by the Nitrates Directive, post harvest measures such as catch crops and the

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removal of crop residues, or removal of leached nitrate in constructed wetlands and buffer strips should be considered (De Haan et al., 2006).

Governments in various countries promote constructed wetlands to treat agricultural water (Crumpton, 2001; Borin et al., 2001; Paludan et al., 2002; Braskerud, 2002; Dunne et al., 2005). In the Baltic States, more than 1000 wetlands were constructed between 1990 and 2000 to reduce nitrogen emissions to the Baltic Sea (e.g., Paludan et al., 2002). The government of the United States has stimulated the construction of wetlands on farmland in the Wetlands Reserve Program (Hey et al., 2005; Kadlec, 2005). In the Netherlands, there is a lack of experiences with constructed wetlands to reduce nitrogen emissions from farmland.

MATERIAL AND METHODS

The removal of leached nitrogen in constructed wetlands was tested at the experimental farm Vredepeel in the South East of the Netherlands on a sandy soil (92% sand, 7% silt, 1% clay). The soil is drained using drain pipes (depth 100 cm, density 6 m). Only nitrate-rich drainage water, originating from vegetable crops (lettuce, leek, broccoli and beans), ornamental crops (roses and *Buxus sempervirens*) and arable crops (sugar beet and summer barley) was collected and stored in a water reservoir of 600 m^3. This comprised about half of the total amount of drainage water from 2,5 ha agricultural soil. The nitrate-rich water in the water reservoir was discharged into three different types of constructed wetlands (Fig. 1): SF, a surface flow system planted with Common reed (*Phragmites australis* (Cav.) Trin. ex Steud.), (surface area of 64 m^2 filled with local soil and 20 cm water depth); SSF-reed, a horizontal subsurface flow system with Common reed (surface area 32 m^2 filled with building sand) and SSF-straw, a horizontal subsurface flow system filled with straw (surface area 32 m^2 filled with local soil). All wetlands are lined with pvc pond liner. In- and outlet concentrations of total nitrogen, nitrate, ammonium, total phosphorus and orthophosphate were measured every two weeks at the soil lab of Wageningen University. Redox potentials were measured with single platinum shaft electrodes and a calomel reference electrode (Eijkelkamp, The Netherlands) at 15, 30 and 45 soil depth in three replicates. The wetlands were constructed in spring 2005, measurements started December 2005 (Clevering et al., 2007). Besides removal efficiency, economic perspectives and nature value of constructed wetlands were studied but not reported here.

RESULTS

Water Flow and Nitrate Concentration in Drain Water

The amount of water discharged into the wetlands was adjusted to the nitrate removal capacity of the wetlands: hydraulic load is low in winter and high in summer (Fig. 2).

Water from pipe drains contained 21 (2006) to 25 (2007) mg nitrate-N L^{-1}. Nitrate concentrations were high after vegetable crops and *Buxus sempervirens* and low after the arable crops and roses (data not shown). Collected water from pipe drains contained on average 30 mg N L^{-1} (96% nitrate) but hardly P. Total N concentrations were higher in the winter than in the summer period (Fig. 3). The N concentrations varied little before and after storage, indicating that hardly any denitrification occurred in the water reservoir.

Effectiveness Constructed Wet Lands

The mean N removal was 58% in SF (1655 kg N ha^{-1} $year^{-1}$, 25% in SSF-reed (1447 kg ha^{-1} $year^{-1}$) and 63% in SSF-straw (3622 kg N ha^{-1} $year^{-1}$, Fig. 4). The negative removal rate of phosphorus (mean 16 kg ha^{-1}) is a disadvantage of SSF-straw, because of straw mineralization in this wetland. The outlet P-load of the other two systems was negligible (data not shown).

The target outflow concentration of 3 mg N L^{-1} was reached during the summer in SF and SSF-straw (Fig. 2). Around 90% of the nitrate was removed. Values in 2007 were more variable than in 2006. In the winter season, the target value was not reached (Fig. 3). The mean daily N removal was about 4 kg N ha^{-1} for SF and SSF-reed. Very high summer values (exceeding 20 kg N ha^{-1}) were measured in SSF-straw.

Redox potentials indicated anaerobic conditions and nitrate reduction in SF and SSF-straw (<220 mV) (data not shown). In SSF-reed, however, redox potentials indicated aerobic conditions, at least in the upper part of the wetland soil (data not shown).

The mean area-based removal rate coefficient value (k_{a20}-values) of the constructed wetlands, indicating the nitrate removal rate of the systems at a constant temperature of 20°C (Kadlec and Knight, 1996), were 18, 11 and 41 m $year^{-1}$ respectively for SF, SSF-reed and SSF-straw.

Perspectives and Cost Effectiveness

The construction costs of the wetlands varied between € 86 m^{-2} for SF, € 106 m^{-2} for SSF-straw to € 233 m^{-2} for SSF-reed. Yearly costs for depreciation and maintenance are estimated to amount to 10 and 20% of the construction costs. The cost effectiveness (expressed as € per kg N removed) ranged between € 52 and € 104 kg^{-1} N for SF, between € 29 and € 58 kg^{-1} N for SSF-straw and between € 161 and € 322 kg^{-1} N for SSF-reed. Costs for loss of agricultural production and income of the farmer are not taken into account. The wetland/arable land ratio is about 0.01-0.02. However, when the water reservoir is included the ratio is about 0.05-0.09, depending on the depth of the reservoir.

DISCUSSION

Measurements indicate that the removal of N from drain water in constructed wetlands can be an effective measure to reduce nitrogen loads to surface waters. Two of the three systems are functioning very well with a high nitrate removal in the summer period. SSF-reed did not function well. Reed in the system is growing badly, probably due to malnutrition. Probably, the amount of carbon produced in this system is not enough to sustain the nitrogen reduction process. This explanation is supported by the redox measurements indicating aerobic conditions.

The daily nitrogen removal of 4 kg N ha^{-1} corresponds with Kadlec and Knight (1996). Very high summer values of more then 20 kg N ha^{-1} in SSF-straw were also found by Bachand and Horne (2000). The k_{a20}-value (a measure of efficiency) of SF and SSF-reed are low compared to Kadlec and Knight (1996). They found an average k_{a20}-value of 35 m $year^{-1}$. However, our wetlands are not yet fully grown, whereas N loading is high compared to other (constructed) wetlands.

The SSF-straw system was a new tested concept for constructed wetlands and could be a cheap and interesting concept for farmers. A drawback might be that the substrate has to be replaced with fresh straw every several years. Beforehand, we estimated that in SSF-straw the amount of carbon incorporated in the straw was sufficient to sustain the nitrate reduction processes for not more than two years. Until now (three years after construction) no decline in removal efficiency is apparent. The high phosphorus release from this system, due to decomposition of straw, can be overcome by P-uptake in a combined SSF-straw / SF-system or chemical removal.

Although N removal of the constructed wetlands is high, interception of lost N from under the root zone is much lower. In the present study approx. 67% of the lost N was intercepted by the drains (Vos et al., 2006). Approx. 50% of the drain water was led through the constructed wetlands. With the removal of 60% of the N in the constructed wetlands, approx. 20% of the lost N under the root zone is removed in the wetlands.

The method to calculate cost effectiveness is still under debate. The question is how loss of agricultural income can be accounted for. Van der Bolt et al. (2008) estimated the cost effectiveness of surface flow constructed wetlands for phosphor removal (0.02 area ratio) with reed, but without liner at € 45 kg^{-1} N (range € 15-63 kg^{-1} N). The calculated cost effectiveness of SSF-straw lies within this range. However, when applied at larger scales, the costs can strongly be reduced. Constructed wetlands are cost effective when large reductions in nutrient leaching are aimed at and relative cheap source measures are already taken into account (Noij et al., 2008).

The constructed wetlands and water reservoir can be combined with other functions, such as nature development or water storage. This can reduce treatment costs considerably.

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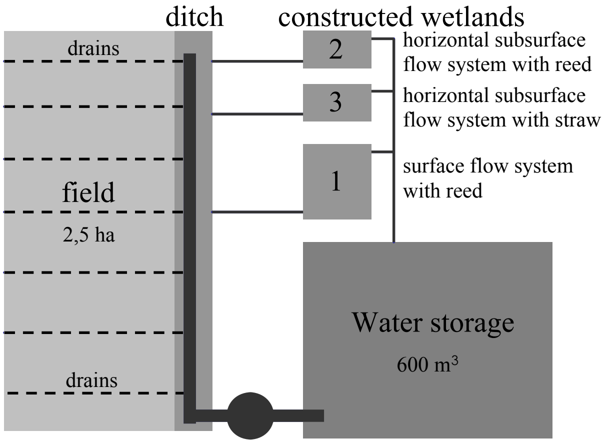
Figures



(1) Surface flow **SF** system with reed, 64 m^2. Nitrate rich water flows superficially through the wetland. Micro-organisms on stems the soil surface and in the soil convert nitrate in to nitrogen gas (denitrification).
(2) Horizontal subsurface flow **SSF-reed** system with reed, 32 m^2. Water flows horizontally through the soil. Denitrification occurs by micro-organisms in the root-zone of reed.
(3) Horizontal subsurface **SSF-straw** flow system with straw, 32 m^2. By adding straw, there is sufficient carbon available for denitrification. The wetland substrate is replaced when carbon is depleted.

Fig. 1. Design of the constructed wetlands.

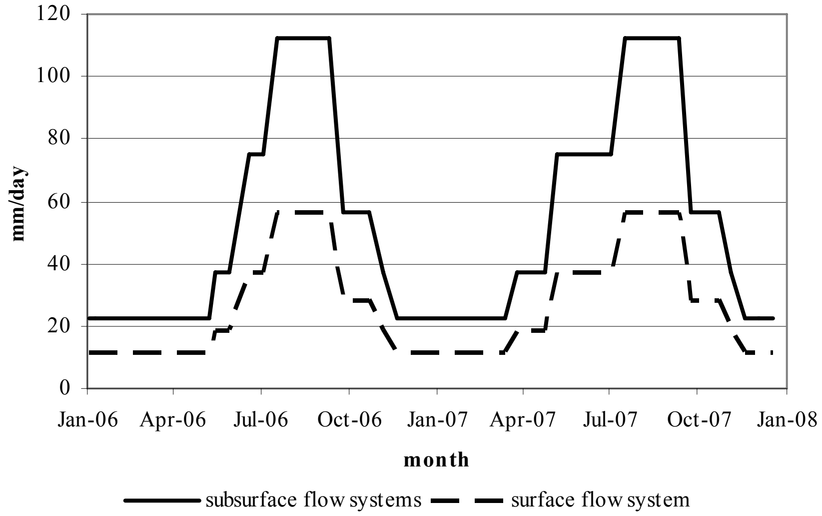


Fig. 2. Hydraulic load of the constructed wetlands (mm day^{-1}) during 2006 and 2007.

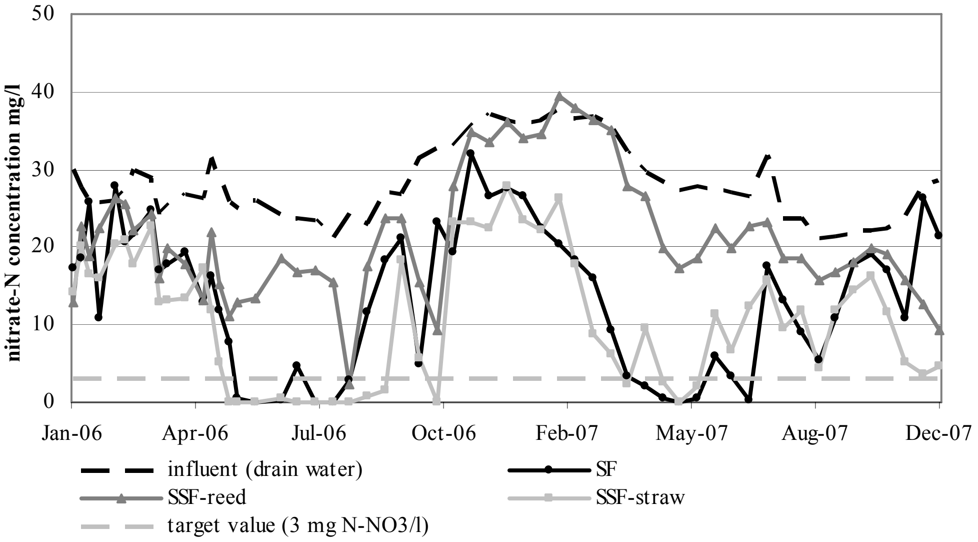


Fig. 3. Nitrate-N concentrations in inflow and outflow and target value for effluent.

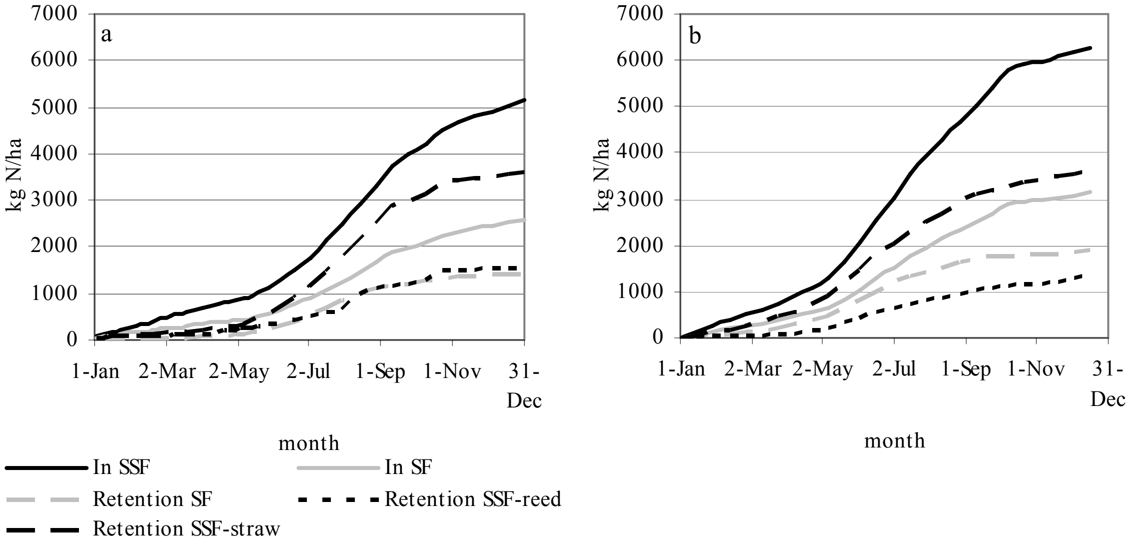


Fig. 4. Cumulative load and retention of nitrogen in kg N ha^{-1} wetland in the three constructed wetlands in 2006 (a) and 2007 (b).