Interaction between soil moisture and nitrogen dynamics in the root zone of a pear (*Pyrus communis* 'Conference') orchard

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Abstract

Nitrogen (N) is an essential macronutrient to ensure the quality of 'Conference' pears (*Pyrus communis* 'Conference'). On the one hand, excessive N fertilization results in N percolation, which contaminates the ground and surface water. Longer periods of drought, as they occurred during the last years, cause a decrease in N uptake, which results in more N percolation in winter. On the other hand, minimizing N fertilization makes it difficult to ensure pear quality. Therefore, the relation between soil moisture and N dynamics was studied. A mineral N balance, coupled to a soil water balance, was used to calculate N dynamics in the root zone. These balances were calibrated with in situ observations (soil water and N content), collected in an irrigated Belgian 'Conference' pear orchard. Alongside soil observations, fruit parameters (fruit quality, yield and phenological parameters), stem water potential (SWP) measurements and NDVI (normalized difference vegetation index) images were analysed to identify the impact of drought and to reveal impact on the crop vegetation in two contrasting soil moisture zones in the pear orchard. Although the orchard was fertilized according to good farmers practices, which was 65 kg N ha^{-1} for the entire season, the N balance indicated significant N percolation in the observation period 2019-2020 (56-75 kg N ha^{-1} year^{-1}). Total N mineralization (0-40 cm) was responsible for 63-71% of the total N supply in the root zone while fertilization accounted for only 22-28% of the total N input. The N percolation was inherently linked to high soil fertility in the pear orchard. In the drier soil moisture zone, the N percolation was estimated to be 19 kg ha^{-1} higher compared to the more humid zone, which can be explained by a lower crop N uptake due to drought.

Keywords: drought, nitrogen balance, nitrogen fertilization, nitrogen mineralization, nitrogen percolation, soil water balance, spatial variation

INTRODUCTION

N is the most important nutrient for pear growth. N uptake is strongly influenced by soil moisture. In dry periods, N uptake is limited. This causes N contamination in ground and surface water in the following winter due to N percolation. The European Commission has set up the Nitrate Directive (European Commission, 1991) to limit nitrate concentrations in ground and surface waters (limit of 50 mg NO_3^- L^{-1}). Rising nitrate concentrations in ground and surface water were observed in the last four years which could be linked to the dry growing seasons of the past years (VLM, 2020). This caused a decreasing N uptake which can lead to N percolation to ground and surface water in the following winter. If fertilization is not adjusted to dry weather conditions, ground and surface water quality will continue to deteriorate. Therefore, the relation between soil moisture and N dynamics is studied. A mineral N balance, coupled to a soil water balance is made to calculate N content in the root zone. N balances were used in previous research to study N dynamics in ornamental tree production systems (Bracke, 2020) or several agricultural crops (Ducheyne et al., 2001). The N balance is set up as a summation of incoming and outgoing N fluxes to determine the mineral

N concentration in the soil (N_{soil}) (Bracke, 2020).

N input is coming from atmospheric deposition (N_{atm}), fertilization (N_{fert}), mineralization (N_{soc}) and capillary rise (N_{cap}). N losses from N percolation (N_{perc}), denitrification (N_{denit}) and N uptake (N_{pear}) are also considered: $N_{soil} = N_{atm} + N_{soc} + N_{fert} + N_{cap} - N_{perc} - N_{denit} - N_{pear}$; N_{atm}, N_{fert} and N_{pear} can be determined reliably based on field measurements and literature. N_{soc}, N_{denit}, N_{perc} and N_{cap} are strongly influenced by the in situ conditions in the soil profile and the weather and are thus more difficult to predict. N_{atm} in the region of the pear orchard is approximately 20-25 kg N ha^{-1} $year^{-1}$ (VMM, 2020). N_{fert} in Belgium ranges between 60 and 100 kg N ha^{-1} per growing season (Remy et al., 2019). According to Sanchez (2015), N demand of pear during the growing season is 60 kg N ha^{-1}. N_{soc} ranged between 30 and 186 kg N ha^{-1} $year^{-1}$ (0-15 cm) for loamy agricultural soils in Belgium (Sleutel et al., 2008). Jegajeevagan et al. (2013) found N mineralization values on sandy agricultural soils in Belgium between 116 and 214 kg N ha^{-1} $year^{-1}$ (0-30 cm). Soils with higher carbon (C) contents have higher mineralization rates (Herelixka et al., 2002). N_{denit} is around 25-35 kg N ha^{-1} $year^{-1}$ (D' Haene et al., 2003; van der Salm et al., 2007). N_{denit} and N_{soc} are positively influenced by temperature and soil moisture (D'Haene et al., 2003; Sleutel et al., 2008). N_{cap} and N_{perc} are directly linked to the soil water balance. N_{cap} depends on capillary rise (the water flux from the groundwater table to the root zone) which is influenced by the depth of the groundwater table and the saturated hydraulic conductivity of the soil (Raes et al., 2018). N_{perc} only occurs when the water content is above field capacity and is highly variable between parcels. Ducheyne et al. (2001) measured an average N_{perc} of 90 kg N ha^{-1} over 30 years on loam soils with winter wheat in Belgium when 85 kg N ha^{-1} was applied as fertilizer. N_{perc} values of 50-240 kg N ha^{-1} $year^{-1}$ are mentioned for different fruit orchards (Cui et al., 2020) but N_{fert} values in these studies reach up to 300 kg N ha^{-1} $year^{-1}$.

If the mineral N balance can predict the N content in the root zone on a reliable way, it can be used as a tool to further optimize N fertilization and to reduce N percolation to ground and surface water.

MATERIALS AND METHODS

Parcel information

The subjected orchard was situated in Vissenaken, Belgium (50.830°N, 4.909°E) and was planted with pear (*Pyrus communis* 'Conference'). Trees were planted in a free spindle system with a planting distance of 3.50×1.25 m. The orchard was equipped with irrigation drippers with a flow rate of 1.60 L h^{-1}. The distance between drippers in one row was 0.50 m. There were two contrasting zones in the orchard (A and B). Zone A had a silt loam soil texture, zone B a sand loam texture. Each zone had four observation plots. The organic C content in zone A was 1.32% and 1.01% in zone B. Zone B had a stony soil profile, zone A not. Based on these properties, zone A was considered as a more fertile zone in the orchard. During the growing season (6/04/2020-17/08/2020), 65 kg N ha^{-1} of fertilizer was applied.

Soil water balance

Soil water balance calculations are described in Janssens et al. (2011a) and were already used to optimize irrigation in 'Conference' pear orchards. This soil water balance approach is used to schedule irrigation in nearly 100 commercial orchards in Belgium under the name PWARO advisory service (http://www.bdb.be/Home/PWARO/tabid/306/language/nl-BE/Default.aspx). The soil water content in the root zone was determined on daily basis by making a summation of incoming and outgoing water fluxes. The soil water balance was calibrated with soil samples, collected with a gouge augur at a depth of 0-30 and 30-60 cm in the herbicide strip. The herbicide strip is the part of the orchard where the trees are planted and fertilizer is applied. Six soil samples were taken per plot on 8 moments throughout the growing season. Water retention characteristics were determined based upon Kopecky soil samples. The total precipitation amount in the growing season was 146 mm while the total crop evapotranspiration during the growing season was 318 mm (Allen et al., 1998). 166 mm water, provided by drip irrigation, was applied.

Mineral nitrogen balance

The mineral N balance was set up for the herbicide strip. N_{atm} resulted from a field campaign and was 20 kg N ha^{-1} year^{-1} in the region of the pear orchard (VMM, 2020). N_{cap} and N_{perc} were calculated by using the soil water balance. N_{pear} was spread over the growing season by using a S shaped curve. Mineralization calculations were determined based upon the optimal mineralization rate (k_{opt}) which was corrected for the daily soil temperature and soil moisture content (expressed as water filled pore space, WFPS = volumetric soil water content/porosity) (De Neve et al., 1996; De Neve and Hofman, 2002). This correction involves different mineralization parameters (κ, ξ, $WFPS_{opt}$, T_{opt}) which were based upon Sleutel et al. (2008). k_{opt} originated from an incubation experiment from a pear orchard in Sint-Truiden with a loamy soil. k_{opt} was adapted for the organic C content in both zones by using a linear relationship between mineralization rate and C content (Herelixka et al., 2002). Denitrification was calculated by using a pedotransfer function proposed by Herelixka et al. (2002) based on the clay content in the A-horizon. Denitrification was also adjusted for soil temperature and soil moisture content. Just as the soil water balance, the mineral N balance was calculated on a daily basis. The parameter setting which was used in the N balance is summarized in Table 1.

Table 1. Parameter setting for the N balance.

Parameter N balance	Explanation	Zone A	Zone B
κ	T° influence on N_{soc}	2.63	
ξ	Soil moisture influence on N_{soc}	10	
T_{opt} (°C)	Optimal T° for N_{soc}	37	
$WFPS_{opt}$ (%)	Optimal WFPS (= volumetric water content/ porosity) for N_{soc}	72	
k_{opt} (kg NO_3^--N ha^{-1} day^{-1})	Optimal mineralization rate	2.03	1.79
N uptake (kg NO_3^--N ha^{-1} year^{-1})	Pear N uptake	60	50

Field data and statistics

NDVI and SWP can be used to study water stress in a pear orchard (Van Beek et al., 2013). Lower SWP values indicate more water stress, higher NDVI values indicate less water stress and healthier trees (Van Beek et al., 2013; Remy et al., 2019). SWP of two shadow leaves per plot was measured using a pressure chamber at six moments spread over the growing season. NDVI was calculated based upon Sentinel 2 satellite images at seven moments throughout the growing season. Satellite images were downloaded from Terrascope (https://terrascope.be/). Images were already processed to level 2A, which means corrected for atmospheric effects. Firmness (kg 0.5 cm^{-2}) was measured by using a FTA penetrometer and plunger (8 mm diameter). N content (mg N 100 g^{-1} fresh weight fruit) of the fruit was derived from mineral analysis. Total soluble solids (TSS, °Brix) was measured using a refractometer. All fruit quality measurements (firmness, N content and TSS) were done on 20 fruits per plot and the mean value was calculated per plot. Yield parameters (yield (kg tree^{-1}), fruit weight (g), number of pears tree^{-1}, pears >65 mm (kg tree^{-1})) were derived from the total production of four pear trees per plot. On these trees, the number of flower buds were counted and fruit set was calculated. Shoot length (cm) was derived from 20 shoots per plot.

To test significant differences between both zones in SWP and NDVI, an ANOVA (significance level = 0.05) was performed in Rstudio (R Core Team, 2018). The average value of all plots per zone was taken for each day an observation was made. To compare the fruit quality, phenology and yield parameters, the Mann-Whitney U test was executed to find significant differences between both zones.

RESULTS

SWP values were lower throughout the entire growing season for zone B as compared to zone A. From the end of June until harvest (17/08/2020), SWP was significantly lower in zone B and the SWP values were below -1.5 MPa which can be considered as the water stress treshold for pear trees (Janssens et al., 2011b) (Figure 1a). NDVI values were significantly lower in zone B from mid-May until harvest and the difference between both zones increased towards the end of the growing season (Figure 1b).

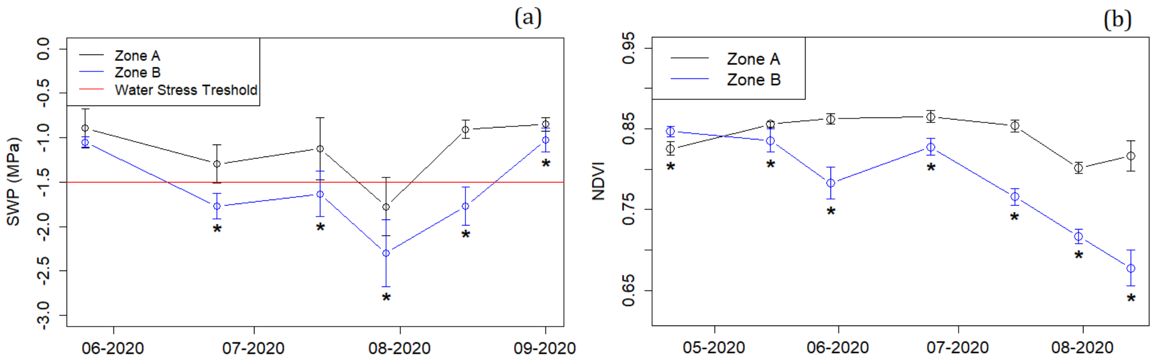

Figure 1. (a) SWP (MPa) for both zones during the growing season. (b) NDVI for both zones during the growing season (* indicates a significant difference between different zones, $p<0.05$).

The soil water balance for both zones was calibrated using the soil moisture samples. In the calibration, rooting depth was set to 0.40 m and the irrigation dose was scaled up with 45% (Figure 2). This scaling is necessary to account for interactions between the grass strip and the root zone of the trees (Janssens et al., 2011b).

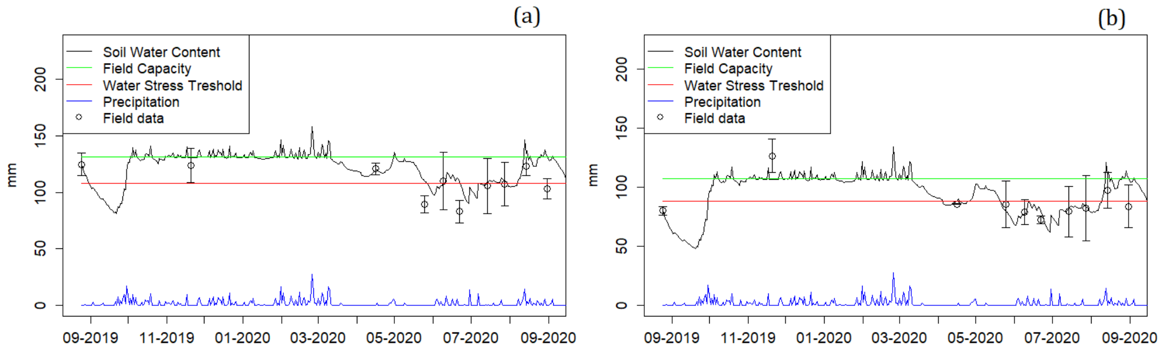

Figure 2. a) Soil water balance for zone A (RMSE = 14.68 mm, NSE = -0.13); b) Soil water balance for zone B (RMSE = 11.04, NSE = 0.41).

The soil water balance showed a longer period of water stress for zone B since the soil water content was below the water stress threshold from the end of May until the beginning of August. The soil water content in zone A was only below the water stress threshold from mid-June until mid-July (Figure 2). The higher level of water stress was confirmed by observations of SWP and NDVI (Figure 1). The calculations agreed better with the observations for zone B as indicated by the lower RMSE and higher NSE score for zone B (Figure 2). A negative NSE indicates that the mean of the field data are a better predictor than the simulated values (Krause et al., 2005). Pear N content and firmness did not differ significantly between both zones (Table 2). Pears of zone B had a significantly higher TSS. Pear trees in zone A had a significantly higher shoot length but significantly lower amount of flower buds as compared to zone B. The fruit set, yield and number of pears tree^{-1} were significantly higher in zone A. The fruit weight and the pear yield >65 mm did not differ significantly between both zones (Table 2).

Table 2. Fruit quality parameters at harvest, phenological and yield parameters. Significant differences are indicated in bold.

Fruit parameter[a]	Zone A	Zone B
N content (mg 100 g^{-1} fresh weight fruit)	48.75±4.93 a	44.98±2.95 a
Firmness (kg 0.5 cm^{-2})	6.30±0.14 a	5.98±0.15 a
TSS (°Brix)	**10.51±0.77 a**	**13.08±0.58 b**
Shoot length (cm)	**42.83±3.10 a**	**24.77±1.57 b**
No. flower buds	**144.38±28.20 a**	**237.94±19.10 b**
Fruit set (fruits/100 clusters)	**151.04±18.98 a**	**61.17±4.88 b**
Yield (kg $tree^{-1}$)	**30.84±0.51 a**	**20.19±1.10 b**
Fruit weight (g)	146.79±11.26 a	139.95±9.83 a
No. pears $tree^{-1}$	**213.13±17.16 a**	**145.36±14.87 b**
Pears >65 mm (kg $tree^{-1}$)	7.01±2.38 a	3.23±2.38 a

[a]Different letters indicate a significant difference (Mann-Whitney U test, $p<0.05$).

Previous results showed a higher level of water stress in zone B (Table 2; Figures 1 and 2). Since NDVI at harvest was 17% lower in zone B as compared to zone A, N uptake was assumed to be 17% lower in zone B (Table 1; Figure 1b). In contradiction to the soil water balance, the N balance agreed better to the field data for zone A as compared to zone B (Figure 3).

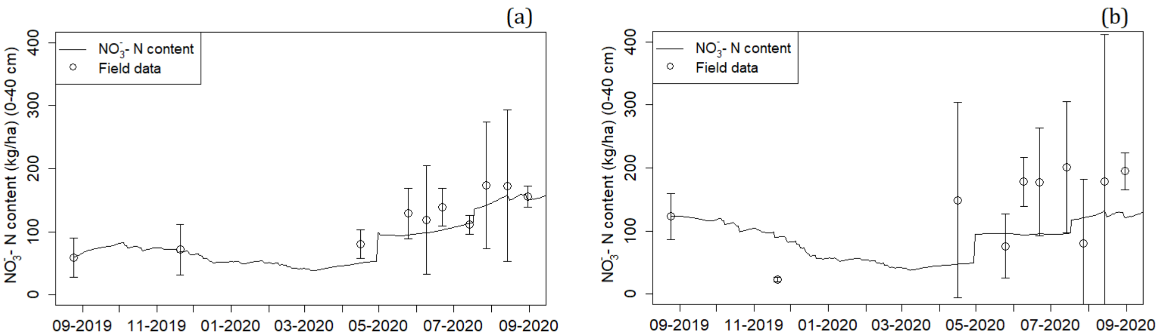

Figure 3. a) Nitrogen balance for zone A (RMSE = 22.53 kg NO_3^--N ha^{-1}, NSE = 0.66); b) Nitrogen balance for zone B (RMSE = 70.23 kg NO_3^--N ha^{-1}, NSE = -0.51).

This is clearly visible in the values of the goodness of fit parameters with a high RMSE value of 70.23 kg NO_3^--N ha^{-1} and a negative NSE for zone B. In general, the simulations underestimated the NO_3-N content in both zones during the summer months. High variability of the field data in zone B made it hard to achieve a good fit between simulations and observations (Figure 3b).

Mineralization values (0-40 cm) were relatively high compared to literature values but these values are calculated for the upper 15 or 30 cm of the soil profile while in the current study, mineralization was considered homogeneously over the entire root zone (Table 3). Denitrification values were plausible while N percolation values for the herbicide strip were high.

DISCUSSION

The aim of this research was to set up a mineral N balance to study N dynamics in the root zone of a 'Conference' pear orchard.

The significant higher level of water stress in zone B can be partly explained by the stony soil profile: pear tree roots in zone B can take up less water due to the presence of stones which causes faster soil water depletion. The higher level of water stress in zone B is also reflected in the fruit quality, phenological and yield parameters. Silt loam soils (zone A) have also a better water holding capacity as compared to sand loam soils (zone B) which results in a difference in water stress level between both zones.

Table 3. Mineralization, denitrification and N percolation (kg NO_3^--N ha^{-1} $year^{-1}$) for both zones. Literature values are mentioned in italic. The N balance was set up for the herbicide strip.

	Zone A	Zone B
Mineralization (0-40 cm) (kg NO_3^--N ha^{-1} $year^{-1}$)	211.9	149.6
	(30-186 (0-15 cm) - Sleutel et al., 2008) (116-214 (0-30 cm) - Jegajeevagan et al., 2013)	
Denitrification (0-20 cm) (kg NO_3^--N ha^{-1} $year^{-1}$)	26.6	23.4
	(25-35, clay soils up to 80 – D'Haene et al., 2003; van der Salm et al., 2007)	
N percolation (kg NO_3^--N ha^{-1} $year^{-1}$)	112.6	150.8
	(50-100 in loam region Belgium Ducheyne et al., 2001)	

N percolation was calculated to be very limited during the growing season. The high standard deviations of the field data from the N content is remarkable, certainly for zone B. The N content was calculated as an average of four plots in the same zone. Since there was a lot of variation between the N content of the four plots in one zone, the standard deviation was also high. Possibly, a part of the applied mineral fertilizer was not well absorbed in the soil when soil samples were taken since samples were collected in a dry period. This high spatial variation in N content over the orchard is consistent with previous research (Długosz and Piotrowska-Długosz, 2016).

The mineral N balance was set up for the herbicide strip (where N fertilizer was applied). In the adjacent grass strips, no fertilizer was applied so N percolation could be assumed to be negligible. The mineral N balance consisted of seven N processes. The mineralization parameters (κ, ξ, $WFPS_{opt}$, T_{opt}, k_{opt}) were not determined for this orchard which is a source of uncertainty in the calculation. κ, ξ, $WFPS_{opt}$, T_{opt} were based upon Sleutel et al. (2008) who investigated mineralization in loamy soils in Flandres.

k_{opt} was derived from another nearby silt loam pear orchard with a correction for C content according to Herelixka et al. (2002). The rooting depth was also unknown and is known to have an effect on soil water balance modelling (Janssens et al., 2015). A lot of assumptions were made to calculate the mineralization process, based on literature, which had a high influence on the calculations of the total N content. However, the simulations followed the trend of the field data. Moreover, literature values for N mineralization (Sleutel et al., 2008; Jegajeevagan et al., 2013) confirmed that the high mineralization values were plausible. Due to the higher C content in zone A, mineralization in zone A was higher as compared to zone B. The N input by mineralization (212 and 150 kg NO_3 -N ha^{-1} $year^{-1}$ for zone A and B) was more than double of the N input by fertilization (65 kg NO_3^--N ha^{-1} $year^{-1}$). Denitrification values agreed with literature (D'Haene et al., 2003; van der Salm et al., 2007) and were higher for zone A since denitrification was corrected for clay content which was higher in zone A. N percolation was high in both zones (113 and 151 kg NO_3^--N ha^{-1} $year^{-1}$ for zone A and B). If the assumption is made that half of the orchard consists of herbicide strip (where N percolation occurs) and the other half consists of grass strip (with no assumed N percolation), then the global N percolation of the whole orchard is half of the N percolation of the herbicide strip. Even then, N percolation would be around 56 kg and 75 NO_3^--N ha^{-1} $year^{-1}$ for the entire orchard. When N percolation is 60 kg NO_3^--N ha^{-1} $year^{-1}$ and around 300 mm water $year^{-1}$ percolates from the root zone to the groundwater, there would be a groundwater concentration of 20 mg NO_3^--N L^{-1} or 89 mg NO_3^- L^{-1}. However, the Nitrate Directive imposes a maximum concentration of 50 mg NO_3^- L^{-1} (European Commission, 1991). Although the orchard was fertilized according to good farming practices which are based on N fertilization experiments (Janssens, 2015), N percolation was high. Since N input by fertilization was only 22-28% of the total N supply in the root zone, the high N percolation was inherently linked to high soil fertility in the pear orchard. Even with fertilizer reductions, which have an impact on fruit quality and fruit yield (Raese, 1998; Janssens, 2015), N percolation will still be significant.

CONCLUSIONS

When field data about soil moisture and N content are collected over a long period, soil water and N balances can be further adapted and calibrated. This way, the soil moisture and N content predictions will become more reliable. By doing this, the N balance can become an important tool to monitor the N content in the root zone and to facilitate fertilization decisions which can avoid excessive N fertilization and N percolation to the ground and surface water.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support from VLAIO (HBC.2016.0782). Eric Gomand is thanked for giving the opportunity to carry out this research in his pear orchard.

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