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Monitoring of nitrate leaching during flush flooding events in a coarse-textured floodplain soil

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ABSTRACT

The demand for foods in central Chile is increasing and arable land is expanding rapidly onto floodplain soils, which are being cleared for maize cultivation. After harvest, a significant amount of residual nitrogen (N) may be still present in the soil in autumn–winter, when a high risk of nitrate leaching (NL) is expected due to occasional flooding events. Determining nitrate (NO_3^-) movement through the vadose zone is essential for studying the impact of agricultural practices on surface water quality. This study focused on understanding the processes of NO_3^- leaching in a floodplain environment and compared the effectiveness of four different methods: soil coring (T0), an observation well (T1), ceramic suction cup lysimeters (T2) and a capillary lysimeter (FullStop^{TM} wetting front detector) (T3) for monitoring NL using an infiltration cylinder to simulate the conditions generated during flush flooding events during autumn–winter season in a typical coarse-textured alluvial floodplain soil. The comparison showed that T0 and T3 can be used for monitoring NL during flush flooding events during autumn–winter season in stratified coarse-textured floodplain soils, whereas T1 and T2 are not appropriate for these site conditions. A correlation was found between NO_3 and soluble salt (Cl^- concentration and EC) only in the first measurements after the dry summer period. The results of this study suggest that most of the surplus N could be leached by excessive irrigation during the crop growing season (spring–summer), while a lower amount of residual N may still be present in the soil in autumn–winter available to be lost by NL during flush flooding events. Overall the two monitored flushing events could have leached around 6% of the total NO_3–N load. There was no significant effect of sampler devices on saturated hydraulic conductivity.

1. Introduction

Maize (*Zea mays* L.) is the most important crop in the O'Higgins Region of central Chile, covering 47,419 ha during the growing season 2011–2012. It is cultivated mainly on flat soils located in alluvial terraces (Casanova et al., 2013), under furrow irrigation systems during spring–summer (September–April). However, demand for food is increasing and arable land is expanding rapidly to soils with limitations, with e.g. floodplain soils having been cleared for maize cultivation. These production systems normally use high nitrogen (N) fertilisation rates (350–560 kg N ha^{-1}), together with low irrigation efficiency (<45%). Moreover, on average 200 kg N ha^{-1} are not taken up by the maize and are susceptible to leaching if water percolates through the soil profile (Salazar and Nájera, 2011). Although it is possible for a substantial amount of applied N to be leached by excessive irrigation during the crop growing season (spring–summer) (Gehl et al., 2006), a significant amount of residual N may still be present in the soil in autumn–winter, posing a high risk of nitrate leaching (NL) during the fallow period.

Maize production in Chile is mainly located in the central zone, under Mediterranean climate conditions with most rainfall falling in autumn–winter. Thus streams have a snow-pluvial regime, where floodplain soils can be occasionally flooded following intensive rainfall events. Under these conditions, NL monitoring is a complex task, particularly on coarse-textured floodplain soils, where water movement mainly occurs under unsaturated conditions with occasionally saturated flow during flush flooding events.

Noe (2013) noted that the biogeochemistry of N cycling in floodplain soils is very sensitive to spatial and temporal variations in hydrogeomorphology, in particular floodplain wetness and sedimentation. In their natural state, floodplain soils are an effective nitrate (NO_3) sink throughout the whole year when permanent vegetation covers the area, by protecting the surface water from large nitrate (NO_3^-) inputs irrespective of season (Lewandowski

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and Nützmann, 2010). Floodplains can favour NO_3^- removal by creating sites of high denitrification when intermittent flooding provides the anaerobic conditions necessary for denitrification to occur (Fellows et al., 2011; Shrestha et al., 2012). However, during this process there may be some release of nitrous oxide (N_2O), which is a powerful greenhouse gas (GHG) and the single most important depleter of stratospheric ozone (Butterbach-Bahl et al., 2013). There is thus particular concern about the effects of land use change on floodplain soils, as the alteration in N balance may convert the floodplain into an important nonpoint source of N pollution to surrounding water ecosystems (Krause et al., 2008). For instance, the NO_3^- abatement function of the cultivated floodplain can be lost during fallow, with flood events directly moving NO_3^- down to the shallow groundwater. However, few studies have evaluated the N dynamics in floodplain soils with short hydroperiods (1–3 days of inundation) (Noe and Hupp, 2007; Huber et al., 2012), so the links between NL and water flow dynamics in these particular soils are unclear.

Monitoring and quantification of NL below the root zone can determine the contribution of agricultural practices to NO_3^- contamination of surface and subsurface water bodies, but NL is difficult to measure without disturbing the soil (Webster et al., 1993). Different methods have been employed for monitoring and quantifying NL in coarse-textured soils and different advantages and disadvantages have been reported, depending on interactions with the soil solution, the heterogeneous nature of soils, the range of water tensions and the frequency of sampling (Litaor, 1988; Fares et al., 2009). Nieminen et al. (2013) divided these methods into non-destructive and semi-destructive. Non-destructive methods involve the installation of a soil solution collector (tension lysimeters) that samples the soil solution at the same location over time, whereas semi-destructive sampling concerns zero-tension lysimeters, the installation of which can cause major, long-term changes to the soil hydrology and aeration of the sampling point. The methods can also be broadly divided into active sampler methods, such as soil coring, ceramic suction cups and observation wells, which need action by an operator to obtain a sample, and passive samplers, such as capillary lysimeters, which usually have a small cavity in the base where free water can be automatically stored for later sampling. A number of studies have compared the effectiveness of these methods for evaluating NL in coarse-textured agricultural soils (Barbee and Brown, 1986; Webster et al., 1993; Gehl et al., 2005; Zotarelli et al., 2007; Arauzo et al., 2010; van der Laan et al., 2010; Wang et al., 2012), but did not consider the dynamics of soil–water–NO_3^- interactions in floodplain soils within short hydroperiods. It is also important to evaluate how the setting of these sampling methods affects water percolation and thus the downward movement of NO_3^- in the soil profile, which can be assessed by measuring changes in saturated hydraulic conductivity (K_s).

In addition, methods based on concentration of ions can be used to study flow paths, reactions between soil and solute, and groundwater recharge (Allison et al., 1994). One of most widely used is the chloride (Cl^-) concentration profile method, because in most soils Cl^- acts as a tracer since it moves with water in the soil (Lo Russo et al., 2003; Rasiah et al., 2005; Huang et al., 2013). Some of these conservative salt concentration methods, such as Cl^- and electrical conductivity (EC), are easier to determine than NO_3^- and may be used to identify the risk of NL in coarse-textured soils.

It is important to note that a key step in assessing the impact of residual N in coarse-textured cultivated floodplain soils on water quality would be to monitor and quantify its NL potential through a suitable technique that allows soil solution samples to be taken during flush flooding events. Fares et al. (2009) concluded that accurate sampling and analysis of the soil solution can provide

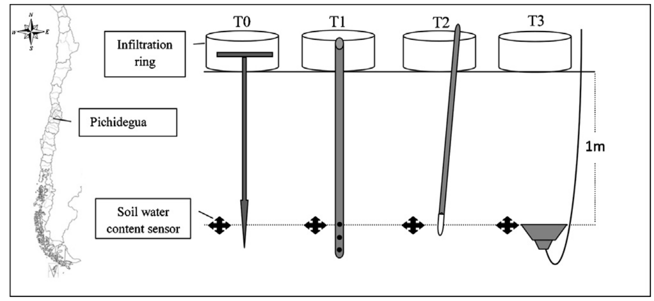

Fig. 1. Location of the Pichidegua experimental site in central Chile and method layout in a microplot.

an early warning of potential groundwater contamination. Thus best management practices to enhance water quality in floodplain soils should be evaluated in terms of minimising the risk of NO_3^- contamination along waterways in the O'Higgins Region of central Chile.

The overall aim of the present study were to understand the processes of NO_3^- leaching in a floodplain environment and to evaluate four different methods: soil coring, an observation well, ceramic suction cup lysimeters and a capillary lysimeter (FullStop^{TM} wetting front detector) for monitoring NL using an infiltration cylinder to simulate the conditions generated during flush flooding events during autumn-winter season in a typical coarse-textured alluvial floodplain soil. Specific objectives were: (i) to evaluate if conservative salt measurements, such as Cl^- and electrical conductivity (EC), may be used to identify the risk of NL; (ii) to quantify the NL during flush flooding events using FullStop^{TM} wetting front detector and (iii) to evaluate the effects of the sampler devices installation on water percolation by measuring K_s in a typical coarse-textured alluvial floodplain soil.

2. Materials and methods

2.1. Site description

The study site was located in the Pichidegua commune, O'Higgins Region (34°22′S, 71°25′West, altitude 124 m a.s.l.) in central Chile (Fig. 1). The soil was prepared using a disc plough in September 2011 and maize was sown in October 2011 and harvested in early April 2012. The grain yield was 15 Mg ha^{-1} and maize stalks were removed from the experimental area. During the growing season, 470 kg N ha^{-1} were applied as urea and compound fertiliser (N–P_2O_5–K_2O: 25–10–10), and a N balance estimated 200 kg N ha^{-1} surplus were available for NL. This study was carried out during autumn–winter (April 2012–August 2012) after harvest of the maize, when the field was fallow.

The climate in the study area is classified as temperate with dry, warm summers, corresponding to Csb according to the Köppen–Geiger system (Peel et al., 2007). The mean annual temperature at the site is 14.1 °C and mean annual precipitation is 696 mm (Santibañez and Uribe, 1993). The rainfall distribution is strongly seasonal, with 75% falling in the winter months. The experimental field was located near the Tinguirica river (300 m north), where occasional flooding events with short hydroperiods occur during intensive precipitation events in winter. Climate data (i.e. precipitation, temperature, etc.) were obtained from a weather station located 2 km north-east of the experimental site, which also provided the weather data needed to calculate reference evapotranspiration (ETo) according the FAO Penman–Monteith combination equation (Allen et al., 1998).

Table 1
Soil properties at the experimental site in O'Higgins Region of central Chile.

Soil horizon	Depth (cm)	Soil properties[a]								
		Db ($Mg\ m^{-3}$)	Textural class[b]	Clay (%)	AWC (%)	SOM (%)	TN (%)	pH_{water}	EC ($dS\ m^{-1}$)	CEC ($cmol_{(+)}\ kg^{-1}$)
A_p	0–15	1.35	L	10.06	11.91	1.47	0.039	6.93	1.59	9.65
A_2	15–39	1.36	SL	8.05	9.11	1.24	0.015	6.90	1.04	10.64
B_{w1}	39–73	1.32	SL	16.10	6.27	1.18	0.015	6.90	0.89	10.15
B_{w2}	73–103	1.31	L	18.12	28.18	1.35	0.024	6.80	1.32	10.94
C	103–132	1.46	S	6.03	0.19	0.44	0.002	7.27	0.80	10.49
C_g	132–155	1.31	LS	16.10	5.10	0.71	0.023	7.29	0.59	10.94

[a] Db: bulk density; AWC: available water content. SOM: soil organic matter; TN: total nitrogen; EC: electrical conductivity; CEC: cation exchange capacity.
[b] L: loamy; SL: Sandy loam; LS: Loamy sand; S: sandy.

Table 2
Description of the four methods compared in the field.

Method	Description	Sampling time (min)
T0	Soil coring	0 and 240
T1	Observation well	0, 5, 15, 30, 60, 120, 180 and 240
T2	Ceramic suction cup	0, 5, 15, 30, 60, 120, 180 and 240
T3	FullStop™ wetting front detector	0, 5, 15, 30, 60, 120, 180 and 240

2.2. Soil characterisation

Cartographically, the soil comprises undifferentiated alluvial terraces with sandy loam surface texture, moderately deep, nearly level, with excessive internal drainage and occasional flooding (CIREN, 2002). Soil samples were collected from the mineral soil horizons for chemical and physical characterisation, including properties such as: pH in water (1:2.5), electrical conductivity (EC) in saturated extract, soil organic matter (SOM), total nitrogen (NT) according to Sadzawka et al. (2006) and cation exchange capacity (CEC) according to Dewis and Freitas (1970) (NaOAc 1 N, pH 8.2). Soil physical properties were determined according to Sandoval et al. (2012). The results of these analyses are summarised in Table 1. Based on the soil description and the analytical results (Table 1), the soil was classified as a Typic Xerochrept (Inceptisol). Moreover, in each method cumulative infiltration (CI) and soil infiltration rate were measured using a single-ring infiltrometer cylinder of 50 cm diameter (Bouwer, 1986) and the values used to estimate the saturated hydraulic conductivity (K_s).

2.3. Experimental design and methods

There were six microplots (5 m × 2 m) within 1 ha, where in each microplot all the sampling method (Table 2) were 1 m apart (see Fig. 1). Each sampling method was evaluated once per microplot in six different dates (Table 3), during the study period to evaluate the temporal variation in water content in the soil profile and its effects on NL. All the methods in each microplot were evaluated on the same day to avoid additional experimental errors related to different water content in the soil. These sampler devices were put in place three months before the start of measurements in order to minimise all disturbances to the soil profile during installation.

The NL was calculated using nitrate–nitrogen (NO_3–N) concentration at 100 cm, determined in soil samples (T0) or in the soil solution (T1, T2 and T3). It was assumed that NO_3^- which moved below 100 cm corresponded to NL losses, because at this depth NO_3^- was too distant from the main maize root system and in coarse-textured soils the capillary rise and upward flow mass of NO_3–N is negligible (Fuentes et al., 2014).

In each method, the test began (time 0 min) with the application of a constant water column (20–30 cm) using a single-ring infiltration cylinder, which was kept during 4 h (240 min): (i) to simulate the conditions that may occur during flooding events, (ii) to quantify the amount of NL that occurs during this short flushing event and (iii) to estimate K_s.

In soil coring (T0), a 50 mm diameter soil auger was used for sampling at 0.25 m increments to a soil depth of 1.25 m at time 0 min and time 240 min. At time 0 min, soil samples were collected 0.5 m away from the perimeter of the ring infiltrometer, while at time 240 min soil samples were collected at the centre of the ring infiltrometer.

The observation well (T1) comprised a PVC tube (35 mm diameter) placed vertically with nine holes (1 mm diameter) at equal spacings between 1 and 1.25 m soil depth, where an extraction tube connected with a syringe was used to collect water samples.

The ceramic suction cup lysimeter (T2) comprised a PVC tube (15 mm diameter) with the ceramic cup. For the installation of T2, a hole was drilled with an auger with a diameter slightly larger than that of the cup without soil smearing, which was set vertically at a 15–25° angle to avoid preferential flow. It was connected to a portable pressure bomb applying 70 kPa vacuum with an extraction

Table 3
Soil water changes in each microplot during the study period.

Microplot	Date	Parameter[a]				
		W_i over 0–0.25 m (mm)	W_i over 0–1.00 m (mm)	ΔW over 0–1.00 m[b] (mm)	CI (mm)	DP[c] (mm)
1	7 June	83	318	48	222	174
2	27 June	82	321	52	183	131
3	17 July	65	273	100	237	137
4	24 July	74	225	129	126	−3
5	7 August	100	456	32	75	43
6	21 August	98	371	30	77	47
Mean ± σ[d]		84 ± 12	327 ± 73	65 ± 37	153 ± 65	88 ± 63

[a] W_i: initial soil water content; ΔW: amount of water being added or removed; CI: cumulative infiltration; DP: deep percolation
[b] Obtained from auger soil coring in T0 at t0 min and t240 min.
[c] Calculated using Eq. (2).
[d] Mean ± standard deviation (σ) (n = 6).

tube for collecting soil solution samples only during the sampling period.

The capillary lysimeter FullStop™ wetting front detector (T3) comprised a funnel-shaped container at the bottom filled in with filter sand, where an extraction tube connected the storage volume to the surface and soil solution samples were removed with a syringe (Fig. 1). The T3 was buried at 1 m depth from a pit dug to a depth of 1.5 m. A small hole was dug horizontally to 0.5 m between 1 m and 1.3 m depth in the side of the pit, the T3 was inserted and the pit was completely filled with the same soil. Therefore the soil column above the T3 was undisturbed. In addition, in T3 the storage volume was empty before the ring infiltration cylinder was positioned and thus only the leachate generated between 0 min and 240 min during the test was collected.

In the surface soil of methods T1, T2 and T3, the ring infiltrometer was set in a position that kept the soil solution samplers in the centre. Samples were collected in each microplot for all methods at different sampling times between 0 min to 240 min (see Table 2).

Decagon soil water sensors (ECH2O EC-5) were set in each method in the six microplots at 1 m depth and connected to a datalogger to record the variation in water content two days before and during the tests. In addition, in T0 the soil water content was determined on the soil samples collected at 0 min and 240 min after drying at 105 °C for 48 h. Multiplying volumetric water content by the depth interval was used to calculate the water content to a depth basis. Thus using the values from T0 for each microplot, the amount of water (mm) in separate depth layers and the 0–1 m soil layer was calculated for each date.

2.4. Measurements

Soil solution samples were chilled on ice in coolers and delivered to the Laboratory of Soil and Water Chemistry at the Faculty of Agricultural Sciences, University of Chile, where they were stored and analysed within 24 h. Water samples were filtered using syringe nitrate-free filters (0.45 μm), which gave a clear filtrate in which NO_3–N was measured by the NO_3 chromotropic acid method using a Hach kit (NitraVer® X Reagent Set Cat. No. 26053-45 USA) and a UV–Vis spectrophotometer (Hach DR5000, USA). Electrical conductivity (EC) and chloride (Cl^-) ion concentration were determined using titration with silver nitrate in soil water solution according to Chilean standards (Sadzawka, 2006).

The soil samples were dried at room temperature crushed using a porcelain mortar and sieved through a 2-mm mesh. Soil NO_3–N was measured by the KCl extraction and steam distillation method, and Cl^- and EC in saturated extract according to Sadzawka et al. (2006).

Deep percolation (DP) was calculated using a water balance equation for the microplot area over 0–1 m depth, which can be represented as:

$$\mathrm{DP} = \mathrm{CI} - \frac{\Delta W}{\Delta t} + U - \mathrm{ETc} - \mathrm{SR} \qquad (1)$$

where ΔW is the amount of water added or removed over 0–1 m depth based on the T0 measurements at 0 min (initial soil water content of soil before infiltration) and 240 min (final soil water content of soil after infiltration), Δt is the time (240 min), CI is the cumulative infiltration during 240 min measured with the ring infiltrometer, U is upflux of shallow groundwater into the root zone (capillarity), ETc is the crop evapotranspiration rate and SR is surface runoff. The last three variables in equation 1 (U, ETc and SR) can be neglected because the groundwater level was significantly deeper than the root zone ($U = 0$), during the test there was a permanent water column over the soil (ETc = 0) and when using a ring infiltrometer $SR = 0$. Using these assumptions, Eq. (1) simplified to:

$$\mathrm{DP} = \mathrm{CI} - \frac{\Delta W}{\Delta t} \qquad (2)$$

In T0, the N leaching (NL) from soil samples taken from 0 to 1 m depth was calculated using a modified Burns equation (Matus and Rodríguez, 1994) as:

$$\mathrm{NL} = A\left(\frac{\mathrm{DP}}{\mathrm{DP} + (W \times \mathrm{Db})}\right)^z \qquad (3)$$

where NL is the amount of N leached (kg NO_3–N ha^{-1}) below the root zone z (cm), A is the amount of NO_3–N (kg NO_3–N ha^{-1}) in soil to depth z, W is the soil water content (g g^{-1}), Db is the soil bulk density (Mg m^{-3}) and DP is the cumulative deep percolation below depth z (cm).

The NL values for methods T1, T2 and T3 over 0–1 m soil depth were calculated using the cumulative deep percolation obtained from Eq. (2) and the mean NO_3–N concentration obtained from each method as:

$$\mathrm{NL} = A \times \mathrm{DP} \times 10 \qquad (4)$$

where NL is expressed in kg NO_3–N ha^{-1}, A is the concentration of NO_3–N (mg NO_3–N L^{-1}) in water samples, DP is expressed in (m) and 10 is a conversion unit factor.

In addition, the FullStop™ wetting front detectors were used to obtain soil solution samples in each microplot ($n = 6$) within 48 h after flush flooding events during the study period to estimate NL below the root zone using Eq. (4).

2.5. Statistical analysis

For individual comparisons between two methods or variables, the t-test for paired samples was used at $p < 0.05$. The General Linear Model procedure was used to correlate overall NO_3–N measurements with Cl^- and EC. Analysis of variance (ANOVA) at $p < 0.05$ was used to test the significance of differences sampler devices installation on K_s. All data from soil analyses were statistically analysed using Minitab Version 15.0 Software.

3. Results and discussion

3.1. Climate conditions and sampling

During the study period precipitation amounted to 307 mm, which was 44% lower than in a normal year as has been recorded by INIA (1989) in the zone (Fig. 2). In the period there were only four intensive precipitation events: 25–27 May (91 mm); 12–13 June

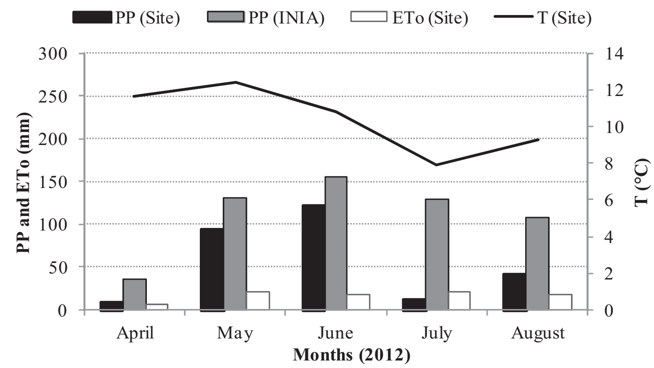

Fig. 2. Monthly precipitation (PP (Site)), reference evapotranspiration (ETo (Site)) and temperature (T (Site)) at the field site during the study period, and historical mean monthly precipitation (PP (INIA)) in the zone (INIA, 1989).

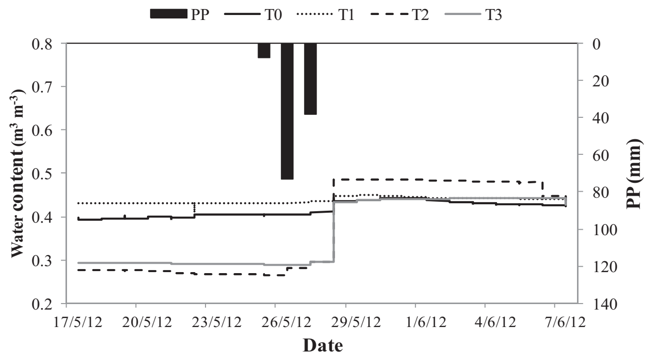

Fig. 3. Hourly volumetric soil water content at 1 m depth, measured using Decagon sensors in all methods (see Table 2) in microplot 1, and daily precipitation (PP), 17 May–7 June.

(47 mm); 16–17 June (34 mm); and 28 June–1 July (32 mm). Cumulative reference evapotranspiration (ETo) was 84.9 mm and mean air temperature was 10.4 °C.

It is important to note that the experimental area was flooded for 8 h on 26 May and for 4 h on 13 June, reaching a maximum floodwater level of approximately 0.5 and 0.3 m, respectively, according to a depth pole in the field. In the days prior to the first flooding event on 26 May, the soil water content (measured using sensors at 1 m depth) showed high variability, ranging from 0.28 to 0.43 $m^3\ m^{-3}$ (Fig. 3). However, after the intensive precipitation event on 25–27 May (91 mm) and the first flooding on 26 May, the soil water content was more homogeneous between methods, ranging between 0.42 and 0.44 $m^3\ m^{-3}$ at the first measurements on 7 June.

In addition, the water content sensors at 1 m indicated that immediately after the first flooding event the soil profile was saturated (see Fig. 3). After that, the water content at 1 m during the study period ranged between 0.45 and 0.49 $m^3\ m^{-3}$, very close to saturated conditions (data not shown).

3.2. Soil water dynamics

The soil water content was measured in method T0 on six different dates during the study period (Table 3). In method T0, the initial soil water content ($t0$, 0 min) ranged between 65 and 100 mm and showed a negative correlation with cumulative infiltration (CI) values ($R^2 = -0.61$, $p = 0.066$). This confirms that when the initial soil is wet, CI is lower than when the initial soil is dry. Deep percolation (DP) was observed in five of the six dates and showed a broad range (43–174 mm). In date 4, the DP was near zero because of the low initial soil water content (225 mm) of the 0–1 m soil layer before infiltration, so most infiltrating water was stored over 0–1 m depth. The latter can be seen in Fig. 4, where in contrast to the other dates, in date 4 the soil was particularly dry over 0.5–0.75 m depth due to lack of precipitation during July.

Additionally, 30 PVC monitoring wells at 0–100 cm soil depth interval were located on the experimental area for water sampling. However, during the study period it was not available water on the wells because watertable did not reach this sampling depth interval.

3.3. Evaluation of methods for monitoring nitrogen leaching

Although four methods for monitoring NL were set up in the field, with six replicates per method, it was only possible to obtain samples from the soil coring (T0) and FullStop™ wetting front detector (T3) methods. In addition, in microplot 4 there was no DP (Table 3), and consequently zero NL was assumed for that particular day. Multiplying DP obtained from T0 measurements

Table 4
Nitrate leaching (NL) from the 0–1 m soil layer in the soil coring (T0) and FullStop™ wetting front detector (T3) methods and cumulative precipitation (PP) during the study period.

Block	Cumulative PP (mm)	NL	
		T0[a] ($kg\ NO_3$–$N\ ha^{-1}$)	T3[b] ($kg\ NO_3$–$N\ ha^{-1}$)
1	123	10.57	1.69
2	263	7.28	1.74
3	307	5.99	0.00[c]
4	307	0.00[c]	0.00[c]
5	307	0.02	0.00[c]
6	307	0.06	0.00[c]
Mean ± σ[d]		3.99 ± 4.59	0.57 ± 0.89

[a] Calculated using Eq. (3).
[b] Calculated using Eq. (4).
[c] Not detected.
[d] Mean ± standard deviation (σ) ($n = 6$).

Table 5
Comparison of soil nitrate–N (NO_3–N) concentration at different depth intervals at time 0 min ($t0$) and time 240 min ($t240$) in the soil coring (T0) method.

Soil depth (cm)	Nitrate concentration	
	$t0$ ($mg\ NO_3$–$N\ kg^{-1}$)	$t240$ ($mg\ NO_3$–$N\ kg^{-1}$)
0–25	7.66 ± 2.26	4.04 ± 2.74*
25–50	4.62 ± 3.46	3.73 ± 2.29
50–75	4.00 ± 3.19	4.01 ± 4.26
75–100	6.06 ± 3.37	2.67 ± 3.16*
100–125	4.60 ± 2.46	2.73 ± 2.31

* Indicates significant difference between values within the row ($p < 0.05$, t-test, $n = 6$).

(Table 3) by the NO_3–N concentration obtained from soil coring (T0) and the FullStop™ wetting front detector (T3) gave the NL loads ($kg\ NO_3$–$N\ ha^{-1}$) (Table 4). Non-detectable values were set at zero, under the assumption that non-detection accurately reflected conditions of no DP and hence no NL losses. Variability in NL estimates when different methods are used for monitoring and quantifying NL are attributable to a number of factors, such as: (i) T0 collects samples from smaller areas than T3, which may greatly increase spatial variability in T0 and/or potential fluctuations between measurements (Zotarelli et al., 2007); (ii) inundation of soils leads to anaerobic conditions, so accumulation of water in the bottom of the funnel-shaped container of T3 might enhance the denitrification process, resulting in underestimation of potential NL; (iii) in T3 the high water application may have resulted in a dilution effect; and (iv) some preferential flow path leaching of NO_3^- pulses can be missed by some methods (i.e. T0) when small sample size is not able to capture a representative sample of the pore network responsible for percolation (Wang et al., 2012).

It is also important to note that in T0 the results suggested that the first infiltrating water after the dry summer period in microplot 1 found a higher amount of NO_3–N available for transport, after which NO_3–N concentrations gradually decreased in the other dates due to natural NL caused by accumulated precipitation percolating through the soil profile (see Table 4). Similarly, Baldwin and Mitchell (2000) reported that the re-wetting of desiccated floodplain soils can result in an initial flush of available N.

Fig. 5 shows the NO_3–N concentration in T0 over 0–1.25 m soil depth at six different microplots (dates) at time 0 min ($t0$) and 240 min ($t240$) ($n = 6$). There were significant differences ($p < 0.05$, t-test) at 0–25 cm and 75–100 cm (Table 5). These results confirm that during the 240 min test in T0, there was movement of NO_3–N from the topsoil to below the root zone.

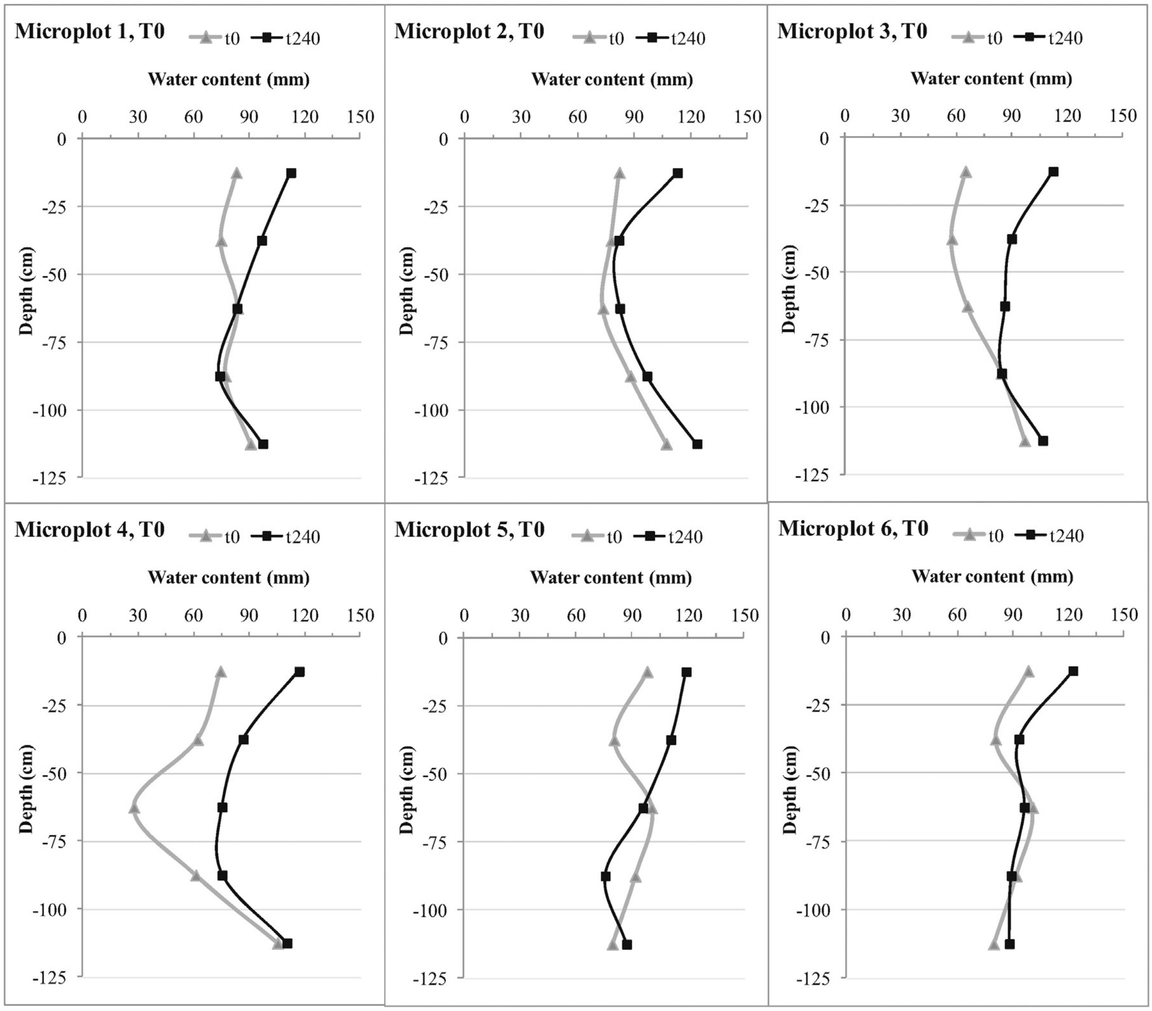

Fig. 4. Changes in soil water content (mm) at 25 cm increments to a soil depth of 125 cm in the soil coring (T0) method on six different microplots (see Table 3) at time 0 min (*t*0) and 240 min (*t*240).

It was not possible to obtain sample volumes using the observation well (T1) and ceramic suction cup (T2) methods. Although T2 is considered a suitable technique for monitoring NL in non-structured soils (Webster et al., 1993), in our study it was not possible to obtain sample volumes in the stratified coarse-textured soil profile (≤18% clay). In contrast, Poss et al. (1995) found that ceramic suction cups were reliable and accurate for monitoring NL on a fairly homogeneous soil containing a moderate amount of clay (≥23%). Zotarelli et al. (2007) noted that ceramic suction cup performance in coarse-textured soils can be erratic unless the soil is close to or above field capacity. Although soil water sensors showed that the soil at 1 m depth was very close to saturated conditions (>0.45 $m^3\,m^{-3}$) for most of the time in the present study, the upper soil horizons were under unsaturated conditions (<0.30 $m^3\,m^{-3}$) according to measurements in T0. Similarly, Litaor (1988) in a review of soil solution samplers noted that inherent soil heterogeneity affects soil water retention and thus causes non-uniform and irregular solution flow from the soil to the sampler. Results of T1 and T2 methods suggest that these methods need soil saturated conditions for a proper sampling procedure. However, other studies found that the T2 method can be used for measuring NL under non-saturated conditions (Díez et al., 1997; Arregui and Quemada, 2006; Vázquez et al., 2006; Gabriel et al., 2012a). In our study in the T2 method the suction was applied only during the sampling period (240 min), therefore there was not a continue soil solution flow mass to T2 before the suction began, which suggest that the sampling period was not enough for collecting soil solution samples. However, it is important to note that maintenance of continue vacuum may increase monitoring cost.

In addition, in a stratified coarse-textured soil profile during flush flooding events (240 min) water probably moves downward following preferential flow pattern. In T3 method the soil volume sampled or radius of influence of the sampler method was higher than in the other method. Therefore T3 method collected a more representative soil solution which moves downward either preferential or matrix flow. It is important to note that T0 may be used at any time independent of the soil water content after a flooding event, but its volume of soil that can be sampled to accurately estimate NL is considerably lower than T3. Therefore in T0 there is more uncertainty than in T3 for estimating NL.

In our study although method T0 had higher mean NL values than T3 (Table 4), the difference was not significant ($p > 0.05$, *t*-test) and both methods would be accurate to derive estimates of N leached. It is clear that soil moisture and hydraulic properties usually exhibit a large spatial variability, which may affect the downward movement of solutes in the soil profile (Merz and Plate, 1997; Djurhuus et al., 1999 Zotarelli et al., 2007). The later may induce a high variability in the NL estimates and generate lack of significance when different methods for monitoring NL are been compared.

In T0 and T3 methods the average NL per simulated flood event was low (<4 $kg\,N\,ha^{-1}$) that suggest that most of the N surplus

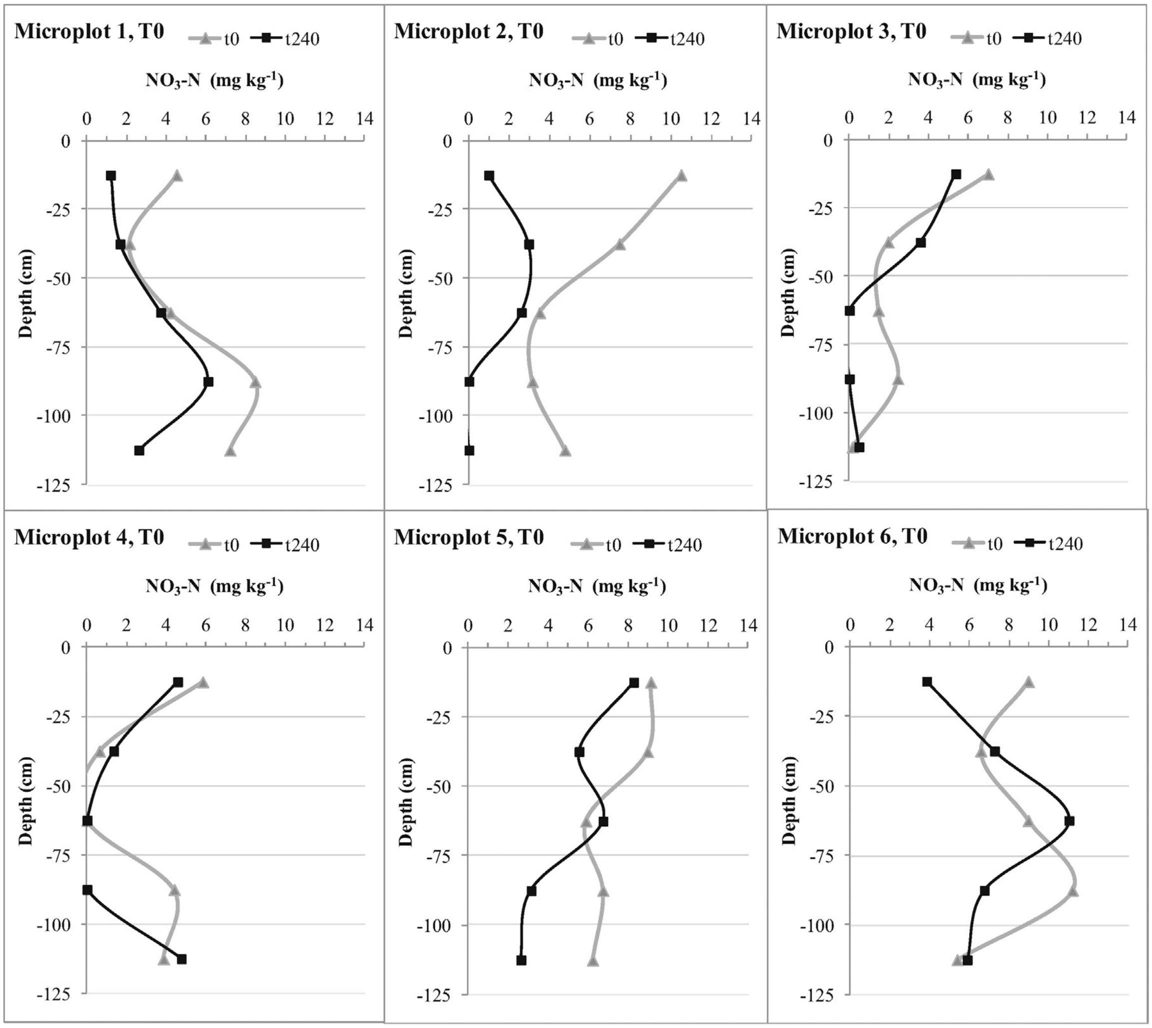

Fig. 5. Changes in nitrate–nitrogen (NO_3–N) concentration with depth (0–1.25 m) in the soil coring (T0) method on six different microplots (see Table 3) at time 0 min (*t*0) and 240 min (*t*240).

applied when the soil was cropped with maize was leached during crop irrigation. It is important to note that in the area maize is irrigated in average with 15.000 m^3 during cropping season in spring-summer, divided in 10 surface irrigation events, when most of water (>45%) is lost due to surface runoff and deep percolation. Thus these results suggest that most of the surplus N could be leached by excessive irrigation during the crop growing season (spring–summer), while a lower amount of residual N may still be present in the soil in autumn–winter. It is important to note that this study was carried out during a dry winter, thus it is possible that most N–NO_3 was accumulated in the topsoil during the study period, as is shown in Fig. 7, which usually occurs in soils under Mediterranean conditions (Gabriel et al., 2012a). Therefore NL was restricted before methods evaluations on each microplot, and during the test that simulate a short hydroperiod (240 min) the water percolating did not leach the N–NO_3 downward 1 m.

3.4. Flush flooding events

It was also possible to obtain soil solution samples from the FullStop^{TM} wetting front detectors located in each microplot ($n = 6$) within 48 h after the flush flooding events on 26 May and 13 June. Assuming that DP was similar to that calculated for 7 June (Table 3), which fell between these two flooding events when in T0 the soil was artificially flooded for 4 h, and considering the duration of the flood events on 26 May and 13 June (8 h and 4 h, respectively), the amount of NL below the root zone can be calculated using Eq. (4) (see Table 6). Although NO_3–N concentration was higher on 26 May than on 13 June, which suggests that the first flush flooding event found more NO_3–N available to leach below the root zone, there were no significant differences ($p > 0.05$, *t*-test) between these dates. However, the time duration of the flooding event strongly determined the amount of NO_3–N lost in the coarse-textured floodplain soil studied, where NL was estimated to be around 10 kg NO_3–N ha^{-1} for an 8 h event. Assuming that there was a surplus of 200 kg N ha^{-1} during maize cultivation, overall the two flushing events could have leached around 6% of the total NO_3–N load. Similarly, Huber et al. (2012) in a NL study on short hydroperiod floodplain soils in Switzerland found that during flooding, those soils could contribute up to 11% of the total NO_3–N annual load in groundwater.

3.5. Relationships between measurements of soluble solutes

To make an overall assessment of the available measurements in methods T0 and T3, NO_3–N, chloride (Cl^-) and electrical conductivity (EC) measurements were integrated into a single data set per method for regression analyses. In both T0 and T3, NO_3–N values did not show a clear correlation with Cl^- and EC measurements ($R^2 < 0.2$). However, when the NO_3–N values measured in microplot

Table 6
Estimated NO_3–N leaching (NL) during two flush flooding events.

Date	NO_3–N[a] (mg L^{-1})	Duration (h)	DP[b] (mm)	NL[c] (kg NO_3–N ha^{-1})
26 May	1.60 ± 0.82	8	348	10.56
13 June	1.28 ± 0.86	4	174	2.23

[a] Mean ± standard deviation (n = 6).
[b] Deep percolation (DP) for the 8 h flood event on 26 May was assumed to be double the DP calculated for 7 June (174 mm).
[c] Calculated using Eq. (4).

1 of T0 were compared with the corresponding Cl^- and CE values, there was a close correlation with EC (R^2 = 0.57) and a weak correlation with Cl^- (R^2 = 0.18) (Fig. 6).

In T3, the NO_3–N values in microplot 1 showed a strong correlation with both Cl^- (R^2 = 0.90) and EC (R^2 = 0.71) (Fig. 7). Although in these correlations there were found an outlier point that heavily influenced the high R^2 values, in both cases these outliers corresponded to the first measurements (microplot 1) after the summer period.

Similarly, the NO_3–N values obtained using the FullStop™ wetting front detectors (n = 6) after the first flooding event indicated a close correlation with Cl^- (R^2 = 0.61) and EC (R^2 = 0.49) (Fig. 8).

These results suggest that the first measurements after the dry summer period found higher concentrations of soluble salts in the topsoil (Salazar et al., 2011), but after the first precipitation and flooding event highly soluble salts such as Cl^- were already leached or diluted in the soil profile, giving a slower downward movement of NO_3–N ions. The results of our study suggest that Cl^- and EC measurements may be used to identify the risk of NL in coarse-textured soils during autumn-winter only for the first important percolation event after the summer period. However, these trends may change depending of crop rotation and water management. For instance, Gabriel et al. (2012b) in a study with cover crops in a Mediterranean zone in Spain (average annual precipitation of 345 mm) collected soil solution samples at 120 cm depth using ceramic cups. They found that NO_3–N did not correlate (r < 0.2, n = 62) either EC or

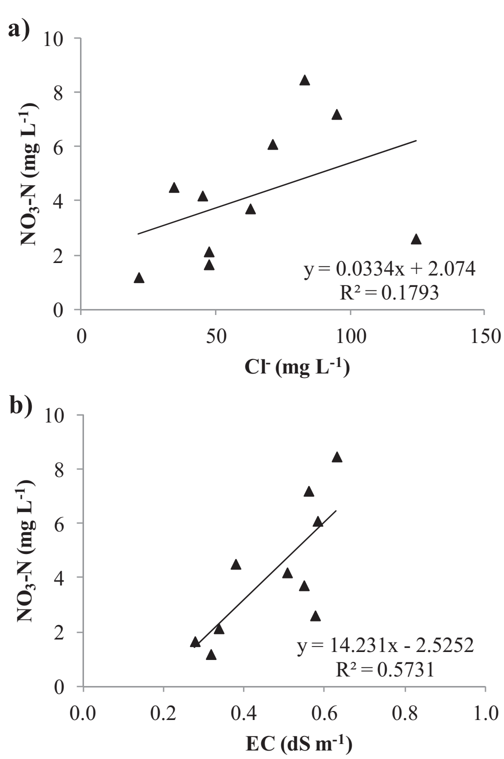

Fig. 6. Correlation between nitrate–N (NO_3–N) and (a) chloride (Cl^-) and (b) electrical conductivity (EC) in the soil solution in Block 1 of the T0 method (n = 10).

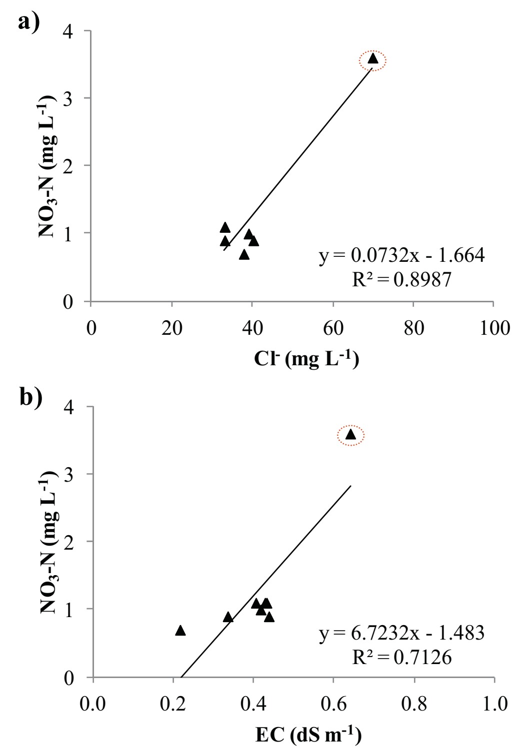

Fig. 7. Correlation between nitrate–N (NO_3–N) and (a) chloride (Cl^-) and (b) electrical conductivity (EC) in the soil solution in Block 1 of the T3 method (n = 8). Red circle shows outlier point. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

CL^- concentrations in soil solutions, which may be related to the effects of cover crops in the water balance. In other study in an arid zone of China (average annual precipitation of 150 mm), Feng et al. (2005) evaluated the relation between NO_3–N and salt (EC) concentrations in soils under different crop systems by collecting soil samples at 0–150 cm depth interval using soil auger. They found that NO_3–N and salt moved as a solution in the upper layers downward simultaneously. However, in contrast to our study, in the case of the study of Feng et al. (2005) the sites had irrigation during the autumn that might have continuously introduced salts to the soil.

3.6. Effects of the sampler devices on K_s

Although methods that involved insertion of sampler devices (T1, T2 and T3) had lower mean K_s values than in T0 (Table 7), these differences were not significant (p > 0.05, ANOVA). These results suggest that device installation had not impact on water percolation. The later may be partially explained by the carefully procedure follow during device setting to avoid compacting the soil surface, because the device installation was carried out when the soil was mostly dry at later summer. In contrast, Webster et al. (1993), in a comparison of soil coring, ceramic suction cup and monolith lysimeter methods for measuring NL, concluded that discrepancies between these methods were attributable to soil disturbance

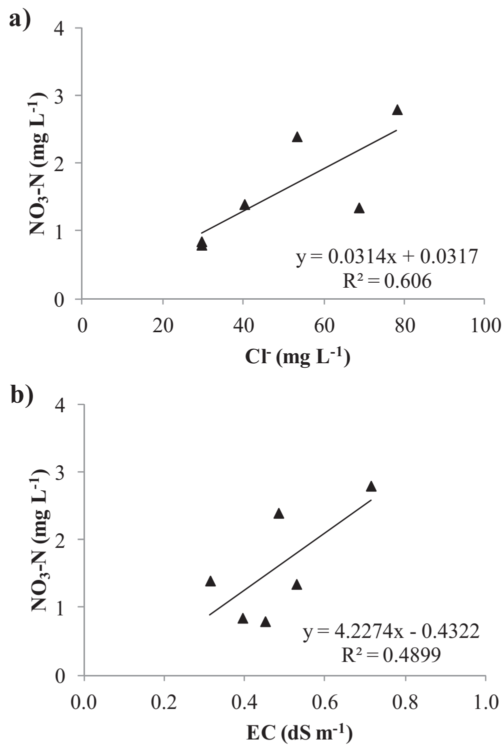

Fig. 8. Correlation between nitrate–N (NO_3–N) and (a) chloride (Cl^-) and (b) electrical conductivity (EC) in the soil solution after the first flooding event in the T3 method ($n = 6$).

Table 7
Saturated hydraulic conductivity (K_s) of soil measured in each method.

Method	K_s[a] ($cm\,h^{-1}$)	C_v[b] (%)
T0	2.39 ± 1.39	58
T1	1.21 ± 0.89	74
T2	1.45 ± 1.03	71
T3	1.27 ± 1.49	118

[a] Mean ± standard deviation ($n = 6$).
[b] C_v is the coefficient of variation ($n = 6$).

during device installation. In this case, the negative impact may be related to the effects of sampler devices on the ability of soil modified during device insertion to transmit water when subjected to a hydraulic gradient.

Other possible explanation to the lack of significant device effect on the mean K_s values could be the high coefficient of variation ($C_v > 58\%$) in K_s measurements which was found in each method. This was related to the high spatial variability in this physical parameter even within small areas in coarse-textured soils (Djurhuus et al., 1999). Similarly, Johnston et al. (2009) in a study in Australia demonstrated that K_s in coastal floodplains can be very high and extremely variable within individual sites. Therefore as Onsoy et al. (2005) pointed out, spatially variable vadose zone flow conditions must be accounted for to better estimate potential NL.

4. Conclusions

This evaluation of different methods showed that soil coring (T0) and FullStop™ wetting front detectors (T3) are seen as promising methods to provide measurement of nitrate leaching (NL) during flush flooding events during autumn-winter season in stratified coarse-textured floodplain soils. It was not possible to obtain sample volumes using the observation well (T1) and ceramic suction cup (T2) methods, indicating that these methods are not appropriate for the study site conditions.

The results of this study suggest that most of the surplus N could leached by excessive irrigation during the crop growing season (spring–summer), while a lower amount of residual N may still be present in the soil in autumn–winter available to be lost by NL during flush flooding events. Overall the two monitored flushing events could have leached around 6% of the total NO_3–N load.

The chloride (Cl^-) and electrical conductivity (EC) measurements may be used to identify the risk of NL in coarse-textured soils during autumn-winter only for the first important percolation event after the dry summer period.

The ring infiltrometer procedure used simulated the conditions generated during occasional flush flooding and allowed the effects of the sampler devices on K_s to be evaluated. Methods that involved insertion of sampling devices into the soil (T1, T2 and T3) had not impact on water percolation.

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