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NITRATE LOSS FROM FERTILIZED CROP FIELDS: DOES SLOPE STEEPNESS MATTER?

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Abstract: Nitrogen (N) is one of the most important nutrients that plants and microbiota need. In general, under temperate conditions its availability in soil limits biological production especially on intensively cultivated crop fields. Cultivation gradually mitigates organic carbon and nitrogen content of the soil hence a continuous N supply is of crucial importance for reasonable crop production. Therefore, N fertilization is a necessity that has additional environmental effects. Most of the applied fertilizers contain inorganic N, mainly nitrate, which is soluble in water and, accordingly, mobile in the soil. Nitrate can be delivered from the soil by surface runoff or percolation to the deeper layers and the ground water. Present study aimed to compare nitrate losses triggered by the same precipitation event (40 mm h^{-1}) on different slope steepness (5 and 12%) and soil status (seedbed; sealed and crusted condition) on a Cambisol right after inorganic N fertilizer (100 kg ha^{-1}) application using laboratory rainfall simulation. Results indicated that at each precipitation event, only the first 0.5 mm runoff contained considerable amount of nitrate (~170 mg L^{-1}), while main loss was due to percolation (also ~170 mg L^{-1} but all along the percolation period). Accordingly, slope steepness (and also surface conditions) affects nitrate loss via controlling the volume of infiltrated and percolated water. Namely, the crusted steeper slope had the lowest nitrate loss, because most precipitation water was turned to runoff. Evaporation from the soil surface between the precipitations generated upward moisture movement in the profile that finally triggered a higher nitrate concentration on the surface. This N was supposed to be the reason of the increased nitrate content of initial runoff. Accordingly, nitrate loss is inversely proportional to slope steepness, although the effect is subordinate.

Introduction

Fertility is one of the most important soil properties that ensures food production for humankind. Population increase is higher than ever, which triggers more and more intensive use of soils in addition to agricultural area expansion. Soil are believed to be an infinite good, even though the danger of soil erosion and degradation increases parallel with the intensity of human activity (Barczi and Centeri 2005). FAO, in 2015, declared that soil is a non-renewable resource, hence it has been official that we have to handle the soil degradation problem. Furthermore, even brownfield regeneration is important (Frantál et al. 2013). It is essential to preserve or increase soil fertility, therefore, nutrients removed by the crops must be replaced. The best practice for fertilization (and also soil health improvement) would be the application of manure (Hati et al. 2008, Maillard et al. 2016) or green manure (cover crops) (Burger et al. 2017, White et al. 2017, Kassam et al. 2017), even though Castellano and David (2014) reported results on rapid incorporation of inorganic nitrogen fertilizers to soil organic matter (SOM). Nevertheless, mineral fertilizers recently definitely rule practice (Nishina et al. 2017).

In most circumstances available nitrogen (N) limits crop production, accordingly, this nutrient has to be replaced in the soil in the greatest amount (Shibata et al. 2017). N stored in SOM is more stable and after mobilization processes acts as a constant resource for the plants generally on a low level. Theoretically, a carbon and SOM saturated soil can provide enough N for plant growing. SOM and soil organic carbon (SOC) holding capacity of a soil is a function of the active mineral surface area and finally soil texture (Hassink 1997). Cultivation removes N from the surface of coarser particles (sand) (Gelaw et al. 2013).

N fixation from the atmosphere is performed by microorganism such as Rhizobium sp. but most of these species are associated only to some certain plants such as legumes. Accordingly, the widespread practice is the application of mineral N fertilizers, those provide a high amount of easily available N. On the other hand, easy availability means high mobility in the soil, which can trigger N loss by runoff or leaching (Zhang et al. 2016). In addition to this, NO_2^- and NO_3^- ions are harmful for water bodies. They can cause eutrophication of the surface water and even diseases reaching the groundwater and migrating to wells (Anció et al. 2016). Another main part of N loss is due to the increased biological activity of the soil, decomposing SOM that triggers higher N_2O or NH_3 and CO_2 emission to the atmosphere (Bilandžija et al. 2017, Gagnon et al. 2016, Charles et al. 2017).

N fertilizer application is a necessity but many environmental circumstances must be taken into account to do so such as i.) current need of vegetation; ii.) available N content of the soil; iii.) hydrological properties of the field; iv.) proximity of surface waters. However, more and more research focuses on the efficiency improvement of N use (Caires et al. 2016); Lassaletta et al. (2014) and Snyder et al. (2014) estimated that still half of the applied N amount was lost. Loss by leaching usually triggered by extreme hydraulic conditions such as both intense rainfalls and droughts that inhibits nitrate uptake by plants within the same growing season (Izsáki 2010). Since these extreme hydraulic conditions are non-predictable and out of control, one of the most suitable method for measuring their effects is rainfall simulation. The application of rainfall simulators has several benefits, including high accuracy replicability and almost *in situ* conditions for extreme precipitation and hydraulic conditions (Centeri et al. 2011, Szabó et al. 2017a,b).

The objective of this study was to identify main N losses by runoff and percolation from recently tilled crop field. Within this general purpose the special goal was to estimate the role of slope steepness and soil status in this process.

Materials and methods

The investigated soil is the uppermost permanently cultivated layer of a calcaric Cambisol (IUSS, WRB 2015) located at N47.238759°; E19.642499° between Albertirsa and Ceglédbercel, Hungary. The sampled arable land (circa 3ha) is within 50 m distance to the Gerje stream (Figure 1). The surface is flat; the ground water depth is 150–200 cm. No N fertilization was applied on this field in the previous 5 years. The recently tilled soil was sampled on the spring of 2016 and delivered into the lab for rainfall simulation investigations. The sample was a composite of nine subsamples from the cultivated layer along a circle of 3m in diameter.

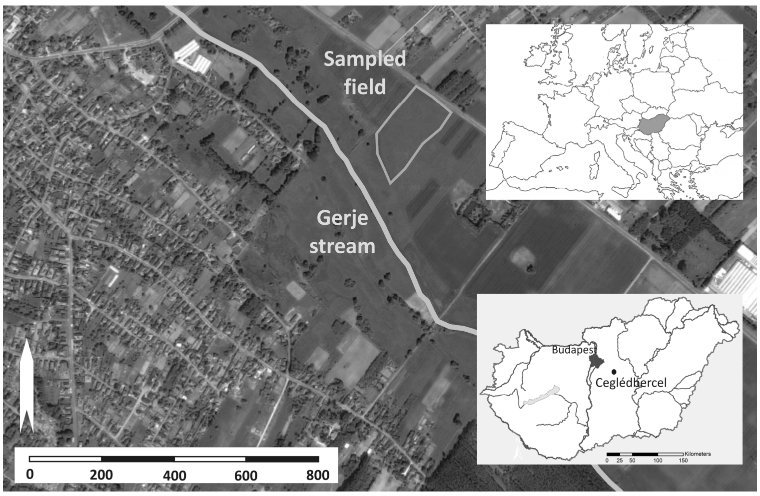

Figure 1 Location of the studied crop field

2. ábra A vizsgált szántóföld elhelyezkedése

Particle size distribution was measured by laser diffractometry (Fritsch Analysette Microtec 22, Centeri et al. 2015); SOC and TN were determined by a carbon-nitrogen analyzer (Tekmar Dohrman Apollo 9000N; Buurman et al. 1996). Ammonium lactate soluble potassium (AL-K) and ammonium lactate soluble phosphorus (AL-P) were determined by a flame photometer (Sherwood 410) (Burt et al. 2004).

We used the ELTE Rainfall simulator equipment (Zámbó and Weidinger 2006; Jakab et al. 2016). The investigated plot size is 100 cm in length, 50 cm in width and 20 cm in depth. Rainfall intensity was set to a constant of 40 mm h^{-1} and permanently monitored with rain gauges (Szabó et al. 2015). Intensity fluctuation was below 10% all along the measurements. Slope steepness were adjusted to 5 and 12% since these values are the boundaries of soil protection measurements in Hungary (Stefanovits et al. 1999). Rainfalls were created using deionized water. The total amount of surface runoff and leached water was collected and measured.

Rainfall is created by a single Lechler 460.788 full cone nozzle on 21 kPa pressure which provides a constant 40 mm h^{-1} intensity (KE=18 J m^{-2} mm^{-1}) (Salles et al. 1999). During the rainfalls the total amount of runoff and percolated water were collected and measured.

NH_4NO_3 fertilizer (100 kg ha^{-1} N) was applied on both slope steepness before the simulations. Nitrate concentration was measured from runoff and percolated water using the spectrophotometric method of Cataldo et al. (1975) by a Jenway 6705 UV-VIS spectrophotometer at 414.4 nm. A measurement without fertilizer application was carried out; first, in order to measure runoff and leaching NO_3^- amounts to be the control. Three simulations were applied at both slope steepness: i.) at seedbed soil condition with intact fertilizer on the surface; ii.) one week later on a sealed surface; iii.) an additional week later on a crusted surface.

Results and discussion

Soil was described as clay loam with less than 1 % SOC content (Table 1). Total nitrogen was around 0.05% that resulted a high (19) carbon-nitrogen ratio indicating the dominance of less polymerized, more mobile low molecular weighted SOM. N content of this type of SOM, however, was in organic form is much more available for mineralization than polymerized ones (De Clercq et al. 2015), even though Filep and Rékasi (2011) found no correlation between dissolved organic and inorganic N in Hungarian soils.

Table 1 Main properties of the investigated soil SOC: soil organic carbon; TNb: total nitrogen, EC: electric conductivity, AL-: Ammonium lactate soluble
1. táblázat A vizsgált talaj főbb tulajdonságai SOC: szerves talajszén, TNb: összes nitrogén, EC elektromos vezetőképesség, AL-: ammónium-laktát oldható, clay: agyag, silt: iszap, sand: homok

pH_{dw}	pH_{KCl}	$CaCO_3$	SOC	TNb	EC	AL-K	AL-P	Mg^{2+}	clay	silt	sand
		m m^{-1}	mg kg^{-1}	mg kg^{-1}	µS cm^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	<6 µm	6-20	20<
7.98	7.51	2.9	9788.4	515.4	197.3	6.65	804.6	25.6	27.5	34.3	38.2

On 5% slope steepness runoff intensity was the highest under seedbed condition, while sealing and crust formation did not trigger increase in runoff (Figure 1). This phenomenon was the result of an earthworm created burrow at the lower edge of the plot. Using this drain line, some parts of the surface runoff was leached down and resulted an increase in percolated water volume. The efficiency of this drain has increased during the investigation since under seedbed condition it took almost 1000 sec to start the percolation after the occurrence of runoff, while this value decreased to 300 and 200 sec concerning the second and third precipitation respectively (Figure 2).

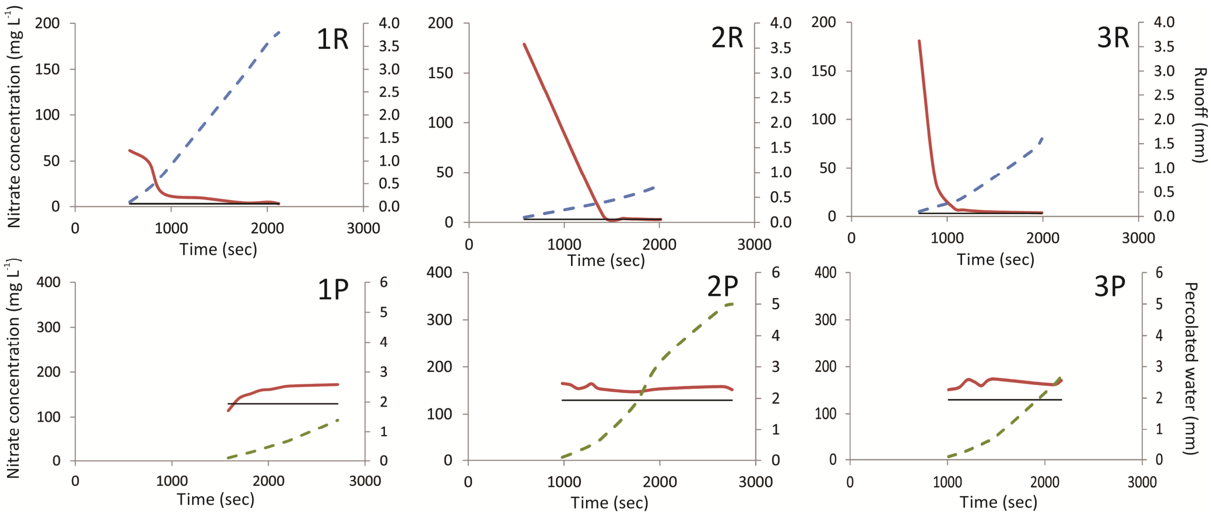

Figure 2 Runoff and percolated water volumes and their nitrate concentration on 5% slope steepness 1: seedbed condition; 2: sealed soil due to the first precipitation; 3: crusted soil due to the first two precipitations; R: runoff; P: percolation; thin black line indicates control values without fertilizer

2. ábra Az átszivárgó és a felszínen lefolyó víz mennyiségének és nitrát koncentrációjának alakulása 5% lejtés mellett 1: magágy állapot; 2: az első eső által megtömörített talaj; 3: két eső által kérgesített talaj; R: felszíni lefolyás; P: mélybeszivárgás; fekete egyenes: a nitrogéntrágyázás nélküli kontroll érték

For nitrate content the control runoff and percolated values without fertilizer application showed considerable difference. Percolated water had one order higher values, even though nitrogen fertilizer has not applied for the original in situ soil for ten years. This is in accordance with the high electric conductivity value of the soil and suggests that some N was initially in inorganic form within the soil. However, N mineralization is presumed to be a slow process, Osterholz et al. (2016) reported data on 14.5 kg inorganic N ha^{-1} d^{-1} production in the uppermost 20 cm, which is quite high and without plant uptake can be a source of N loss.

Regarding nitrate concentration of runoff, always the first ~0.5 mm runoff got the highest values (Figure 2). In each case the first sample had the highest nitrate concentration followed by a rapid decrease to the control as it was also reported by Garcia-Díaz et al. (2017), however, their nitrate values were two orders lower. The very first runoff sample right after the fertilizer application, however, showed just a small increase compared to the following ones. This might be due to the effect of fertilizer dissolution that needs time. The temporal length of decrease stage was also mitigated. On seedbed condition nitrate concentration reached the control value at 1600 sec, while it only took 1200 sec on the crusted surface. The highest measured values in runoff were in accordance with those of the percolated water. Contrarily, there was no relevant change in nitrate concentration of percolated water with time. This relatively constant percolated nitrate concentration was very close to the control value and to the highest initial value of surface runoff. Although it was extremely high, Janssons et al. (2009) measured quite similar values in percolated water after long drought period.

In general, the same tendencies were recorded under 12 % slope steepness (Figure 3).

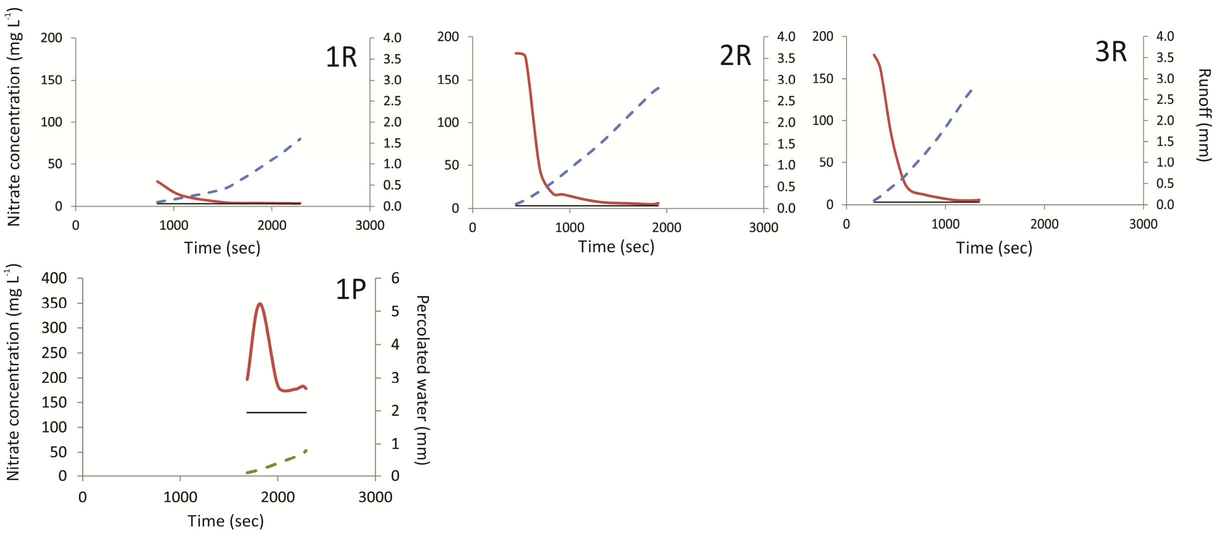

Figure 3 Runoff and percolated water volumes and their nitrate concentration on 12% slope steepness 1 – seedbed condition; 2 – sealed soil due to the first precipitation; 3 - crusted soil due to the first two precipitations; R – runoff; P – percolation; thin black line indicates control values without fertilizer

3. ábra Az átszivárgó és a felszínen lefolyó víz mennyiségének és nitrát koncentrációjának alakulása 12% lejtés mellett 1: magágy állapot, 2: az első eső által megtömörített talaj, 3: két eső által kérgesített talaj, R: felszíni lefolyás, P: mélybeszivárgás, fekete egyenes: a nitrogéntrágyázás nélküli kontroll érték

In this case the role of crust development on the surface was quite clear. Runoff has started earlier, while its intensity became higher along the repeated precipitation events. The initially high runoff concentration fell to the control value more rapidly with the development of crust again, even though, this process was ruled by the leaching depth and velocity of the fertilizer. Here the first 0.5 mm runoff has relevantly higher nitrate concentration as it was the case on 5 % slope steepness. The main difference was about percolation. At the beginning of percolation, a standard concentration of ~ 190 mg L^{-1} was dropped to over 350 mg L^{-1}; this high value, however, was still below the potential concentration. The rest of the percolated water had the same standard N concentration (Figure 3). Due to crust formation and sealing infiltration and, therefore, percolation were inhibited for the following two precipitations that resulted no percolated water during them.

The first precipitation was fallen to a soil surface where concentrated solid fertilizer spheres were distributed. Since no soil loss occurred most of the solid particles were believed to settle down into the micro basins of the seedbed surface. Low amount of runoff generated N loss was due to moderate dissolution velocity. From the infiltration of this first precipitation nitrate got a disperse distribution all along the soil and could be delivered by diffusion and moisture movement. After the end of the rainfall surface evaporation sucked pore water from the deeper horizons to the surface therefore nitrate concentration gradually increased there as it was also hypothesized by Øygarden et al. (2014). This increased and precipitated inorganic N value of the surface would be lost by the first 0.5 mm of runoff at the beginning of the next precipitation event. During this event nitrate moved downwards again but there was no increase in percolated water concentration compared to the control. Although relevant amount of nitrate loss was associated with percolation, there was no evidence that fertilizer reached the bottom of the monolith.

Total porosity of the soil was about 50%, while field capacity could be 30%. Since the investigation is on 100 dm^3 soil means 30 L pore water reserved in the monolith against gravitation before the evaporation loss. Theoretically, this 30 L pore water should contain the total amount of dissolved fertilizer after the first rainfall because no significant nitrate loss was measured. Since nitrate in the fertilizer took 77% by mass the applied value was 15.4 g nitrate per plot, which resulted around 0.5 g L^{-1} concentration in the pore water. The percolated water volume of 9.5 mm under 5 % slope steepness contained 0.2 g L^{-1} concentration independently from fertilizer application. Although there were weeks between the repeated precipitations, N concentration in the percolated water remained exactly the same compared to the end of the former rainfall. This value could be the recent solubility value in the soil. That suggested, once the nitrate reached its diffuse distribution in the soil layer:

i.) it was located and stored in the capillary pores;

ii.) fast percolation via macro pores would not trigger high N loss since the "clear" rainwater did not mix with high concentration capillary water (contrarily, N concentration in percolated water is high, therefore, in accordance with the results of Meisinger et al. (2015) leaching affects capillary pores as well);

iii.) N loss is determined by the volume of percolated water (of course, in addition to the above processes most nitrate would be uptaken by the microbiome and plants).

Conclusion

Rainfall simulation was found to be an applicable tool for N movement in soils; 0.5 m^2 plot size can be representative under steady environmental circumstances. Taking fast changing biological effects such as bioturbation into account, this plot size is not enough to be independent from that sort of influence.

Runoff delivered nitrate loss is of a lower degree compared to percolation. Only the first 0.5 mm runoff contains considerable volume. Therefore, -at least within the above mentioned circumstances- heavy rainstorms and a huge amount of runoff induces less nitrate loss than repeated moderate rainfalls with low amount of runoff. Since main N loss is due to percolated water it is crucial to create and maintain the water holding capacity of the soil. In this study N loss was found to be less on steeper slopes because of the inhibited infiltration that would trigger higher runoff and soil loss values and even drought because of the missing moisture. Results suggested that temporal N loss is the result of complex processes where slope is just one parameter which can be hardly determined as a single variable. Therefore, much more measured data are needed to gain more general conclusions.

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MŰTRÁGYÁZOTT SZÁNTÓK NITRÁT VESZTESÉGE: MIT BEFOLYÁSOL A LEJTÉS?

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Kulcsszavak: felszíni lefolyás, bemosódás, mesterséges esőztetés, talajoldat, párolgás

Összefoglalás: A nitrogén (N), mint alapvető makro tápelem nélkülözhetetlen mind a növények mind a mikrobióta számára. A mérsékelt égövben és különösen az intenzíven művelt területeken a biológiai produkciót a talajból felvehető N mennyisége korlátozza. Az intenzív talajművelés fokozatosan csökkenti a talaj szervesszén és N tartalmát ezért a gazdaságos növénytermesztés szempontjából a tápanyagutánpótlás létkérdés. A leggyakrabban alkalmazott N trágyák szervetlen nitrogént leginkább nitrátot tartalmaznak, mely vízben jól oldódik ezért a talajban kimondottan mozgékony. Következésképpen a kijutatott nitrát mennyiség kisebb-nagyobb hányada nem hasznosul, hanem a felszíni lefolyás által távozik a területről vagy a mélybeszivárgó víz által jut el a talajvízbe. Jelen munka arra keresi a választ, hogy azonos csapadékok (40 mm h^{-1}, laboratóriumi esőszimulátor) eltérő lejtőhajlás (5 és 12%) és talajállapot (magágy, tömörödött és kérges) mellett, közvetlenül nitrát műtrágyázás (100 kg ha^{-1}) után milyen nitrát veszteségeket okoznak. Minden csapadékeseménynél csak a felszínről lefolyó víz első fél mm-ben mértünk megnövekedett nitrát koncentrációt (~170 mg L^{-1}) ugyanakkor a jelentős nitrát veszteséget (szintén ~170 mg L^{-1}, azonban az átszivárgó víz teljes mennyiségében az átszivárgás egész időtartama alatt) a mélybeszivárgó vízmennyiség okozta. Következésképpen a lejtő meredeksége (és a felszín állapota) a talajba, ill. az azon átszivárgó víz mennyiségének szabályozásán keresztül határozza meg a nitrátveszteség mértékét. Azaz a meredek, kérges lejtőn mértük a legkisebb nitrát veszteséget, mert a minimális beszivárgás miatt a csapadékjelentős része a felszínen folyt le. A csapadékok között a talajfelszín párolgása felfelé irányuló vízmozgást indukált a talajban, ami ismét a felszínre emelte a már bemosódott nitrát egy részét. Feltehetőleg e felszíni, kicsapódott nitrát mennyiség okozza a következő csapadék kezdeti felszíni lefolyásában mért magas koncentrációt. A talaj nitrát vesztesége és a terület lejtése tehát fordítottan arányos, habár az összefüggés gyenge.