Nitrapyrin mitigates nitrous oxide emissions, and improves maize yield and nitrogen efficiency under waterlogged field

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Abstract

Aims In order to explore the effects of nitrapyrin (N-Serve) application on greenhouse gas emission, and nitrogen leaching of waterlogged maize (*Zea mays* L.) field, we investigated the effects of applying nitrapyrin on soil ammonium (NH_4^+-N) and nitrate nitrogen (NO_3^--N) content, nitrous oxide (N_2O) fluxes and warming potential (GWP_{N2O}) in a waterlogged maize field.

Methods The design included three treatments: waterlogging treatment with only urea application (V-3WL), waterlogging treatment with urea and nitrapyrin application (V-3WL+N), no waterlogging treatment applied only urea (CK).

Results Our results revealed that waterlogging lead to the increase of nitrogen leaching, resulting in the decrease of nitrogen use efficiency. The accumulated N_2O emissions increased significantly in waterlogged plots compared to control plots, and maximum N_2O emission fluxes occurred during the process of soil drying after waterlogging, resulting in the increase of GWP_{N2O} and N_2O greenhouse gas intensity ($GHGI_{N2O}$) by 299% and 504%, respectively, compared to those of CK. However, nitrapyrin application was able to reduce N_2O emissions. Nitrapyrin application was also good for decreasing GWP_{N2O} and $GHGI_{N2O}$ by 34% and 50%, respectively, compared to V-3WL. In addition, nitrapyrin application was conducive to reduce N leaching and improve N use efficiency, resulting in a yield increase by 34%, compared to that of V-3WL.

Conclusions The application of nitrapyrin helped to mitigate agriculture-source greenhouse effects and N leaching induced by waterlogging, and was an eco-friendly, high N-efficient fertilizer method for waterlogged field.

Introduction

Agriculture has become a major source of global greenhouse gas (GHG) emissions, which must be substantially reduced to minimize impacts of climate change (Godfray et al. 2010). Reactive nitrogen losses and greenhouse gas (GHG) emissions from agriculture contribute substantially to atmospheric and water pollution in China and elsewhere (Chen et al. 2014). Agriculture accounts for 10%-20% of global GHGs produced by human activities, with nitrous oxide (N_2O) accounting for 60% (IPCC 2007) of total agricultural emissions (Wang et al. 2010). In China, GHGs produced by agriculture sector are primarily N_2O (90%) and CH_4 (60%), comprising of 15% of total GHG emissions of the country (Wang et al. 2010).

Because of respiration by soil microbes, soil animals, and plant root, soil become a significant source of GHGs such as CO_2, CH_4, and N_2O. The biomass, physiology, and biochemistry of soil microbes are affected by temperature, water content, organic content, pH, redox potential, and texture of soil, among other factors, which in turn affects the rate of soil GHG emission (Wei et al. 2014; Weier 1999). Global climate change is predicted to increase the frequency and intensity of extreme precipitation events

(Fischer et al. 2013; Cohen et al. 2014; Min et al. 2011; IPCC 2014), which could dramatically alter soil GHG emissions. For example, intensified precipitation regimes would lead to higher incidences of soil waterlogging or flooding (Knapp et al. 2008) and the changes of soil hydrological cycles. N_2O, a long-lived GHG, contributes to global warming and also serves as an atmospheric tracer of anthropogenic changes to the global nitrogen (N) cycle, with a global warming potential 300 times that of CO_2 (Denman et al. 2007; Forster et al. 2007; IPCC 2013). In agricultural fields, the N_2O emissions are mainly produced by the chemical and organic N inputs (Gil et al. 2021). Globally, agricultural sectors emitted almost 60% of the total anthropogenic N_2O emissions. N_2O emission rates depend on the interaction among soil types, climate, and farm management, which influence soil microbial processes and the diffusion of gaseous N_2O to the atmosphere (Granli and Bockman 1995). Humid tropical soils are generally associated with production of large amounts of gaseous N oxides, including N_2O (Weitz et al. 2001).

Excessive rainfall or irrigation can also lead to high rates of nitrate (NO_3^-) leaching from soils, resulting in the losses of reactive N from maize fields. Waterlogging also restrict nutrient absorption and use by maize roots, leading to a substantial reduction of N efficiency (Ren et al. 2016). Nitrification inhibitors can effictively suppress the oxidation of ammonium (NH_4^+) to NO_3^-, and thus reducing N loss from soils and improving N uptake by crops (Di and Cameron 2006). The companion of nitrification inhibitors with N fertilizer has been applied as an agronomic practice to reduce N leaching and lessen N_2O and NO emissions (Di and Cameron 2006; Wu et al. 2017). Nitrapyrin (2-chloro-6-(trichloromethyl) pyridine) is similar to other customarily used nitrification inhibitors, such as dicyandiamide (DCD) and 3,4-dimethylpyrazole phosphate (DMPP), and has been customarily applied to crop fields to inhibit NO_3^- leaching with great success (McCarty 1999; Abbasi and Adams 2000; Chen et al. 2010; Niu et al. 2018). The application of nitrapyrin can reduce N leaching by inhibiting the release of soil N_2O by 49% and 24%, respectively, compared with urea and urea-ammonium nitrate application during maize growth period (Burzaco et al. 2013; Martins et al. 2017), suppressing the oxidation of ammonium (NH_4^+) to NO_3^-, and maintaining N in the form of NH_4^+ in soil for a longer period (Bremner et al. 1981; Bronson et al. 1992). The effectiveness of nitrification inhibitors on N_2O emissions depends on environmental parameters, such as waterlogging, heat, cold, and so on (Menéndez et al. 2012; Wu et al. 2017; Shi et al. 2016; Parkin and Hatfield 2010). Nitrification inhibitors affect N_2O emissions more effectively under higher soil moisture levels by increasing the abundance of denitrifying genes (narG, nirK, and nosZ) (Barrena et al. 2017; Borzouei et al.2021; Dawar et al. 2021). Our previous studies revealed that nitrapyrin application was able to alleviate waterlogging damages by increasing the grain production capacity of fertilizer N of summer maize, and facilitating maize recovery (Ren et al. 2017a). Moreover, the application of nitrapyrin can lead to higher yields in waterlogged summer maize by optimizing the absorption and relocation of N, which effectively improves N use efficiency (NUE) and N harvest index (Ren et al. 2017a, b). Over the years, N-Serve has been used primarily to reduce N_2O emissions and improve NUE in crops (Monge-Muñoz et al. 2021), especially in poorly or excessively drained soils. However, little research has been conducted on the role of nitrapyrin in mitigating the effects of waterlogging on GHG emissions and nitrogen leaching. In this study, we conducted a field experiment to measure the effects of nitrapyrin application and waterlogging on N_2O emissions and the content of soil NO_3^--N and NH_4^+-N in maize field. The results of this study will help in developing strategy to reduce GHG emissions and nitrogen leaching in waterlogged maize.

Materials And Methods

Plant materials and experimental location

A field experiment was conducted at the experimental farm (36°10’N, 117°04’E, 151 m a.s.l.) maintained by the State Key Laboratory of Crop Biology of Shandong Agricultural University, China in 2016 and 2017. This region was characterized by a temperate continental monsoonal climate with mean annual temperature of approximately 13°C, frost-free period of 195 days, and annual precipitation of 697 mm, which occurred mainly from June to August. The 0–20 cm top-soil of the experimental field consisted of brown loam, which contained 10.7 g kg^{-1} organic matter, 0.9 g kg^{-1} total N, 50.7 mg kg^{-1} available phosphorus (molybdenum-antimony [Mo-Sb] colorimetry), and 86.2 mg kg^{-1} available potassium (Flame photometry). Denghai605 (DH605), a commonly grown maize (*Zea mays* L.) hybrid, was used for this experiment. Maize seeds were sown on June 16 at a density of 67,500 plants ha^{-1}.

Experimental design

Each plot measured 4 × 4 m^2 and was surrounded by four 4 × 2.3 m^2 polyvinyl chloride (PVC) boards, which acted as water barriers. Each PVC board was buried 2.0 m below the soil surface, with the remaining 0.3 m above ground. In waterlogged plots, the water level was maintained at 2 ~ 3 cm above soil surface for 6 days starting when maize plants were at the third leaf stage (V3). After 6 days, all water was drained from soil surface. Two treatments were tested in this experiment: waterlogging treatment with urea application only (V-3WL), and waterlogging treatment with urea and nitrapyrin application (V-3WL + N). Control plots (CK) were not waterlogged but applied only urea. Each treatment had three replicates, and treatments were randomly applied to plots in the field. Fertiliser was applied 210 kg ha^{-1} N (urea with 46% N), 84 kg ha^{-1} phosphorus pentoxide (P_2O_5; calcium superphosphate with 17% P_2O_5) and 168 kg ha^{-1} potassium oxide (K_2O; muriate of potash with 60% K_2O) at the beginning of experiment. For nitrapyrin treatment, 2,550 mL ha^{-1} nitrapyrin was mixed uniformly with urea, and incorporated into the soil via ploughing.

Soil N_2O fluxes measurements

Soil N_2O fluxes were estimated using a static-chamber method (Gao et al. 2019). These gas fluxes were measured between 8:00 am and 11:00 am daily from the first day of waterlogging to the last day of soil drying using closed-chamber every other day. The closed chamber (length 0.35 m× width 0.35 m× height 0.2 m) was enclosed by plastic sheets. The exterior of chamber was insulated using sponge material and aluminum foil, and an air vent was installed in the middle of chamber. A pedestal was placed under chamber, and the base was sealed using water to ensure that the external environment did not affect the interior of chamber when gases samples were collected. Gas samples (50 mL) were collected using glass syringes from chamber headspace at 0, 10, 20, and 30 min after placing the chamber on the soil. Concentrations of N_2O in gas samples were detected using an Agilent GC7890 gas chromatograph (Agilent, Santa Clara, CA, USA).

N_2O flux was calculated as:

$$J = \frac{dc}{dt} \times \frac{M}{V0P} \times \frac{TH}{P0T0}$$

1

where J is flux (mg m^{-2} h^{-1}), *dc/dt* is the change in gas concentration (c, mg m^{-3}) against time (t, hour). M is the molar mass (mg mol^{-1}) of each gas, P is atmospheric pressure (KPa), T is the absolute temperature (K) during sampling, H is the height (m) of headspace in chamber, and $V0$, $T0$ and $P0$ are the gas molar volume (m^3 mol^{-1}), absolute air temperature (K), and atmospheric pressure (KPa), respectively, under standard conditions.

N_2O warming potential (GWP_{N2O}, kg CO_2-eq m^{-2}) was calculated by multiplying the N_2O emission fluxes by radiative forcing potentials. The equation is as follows:

$$GWP_{N2O} = fN_2O \times 273$$

2

where fNO_2 is NO_2 emission flux.

N_2O greenhouse gas intensity ($GHGI_{N2O}$, kg kg^{-1}) represented the comprehensive greenhouse effect of each treatment and was calculated as follows (Mosier et al. 2006; Qin et al. 2010):

$$GHGI_{N2O} = \frac{GWP_{N2O}}{Y}$$

3

where Y (kg ha^{-1}) is the grain yield of summer maize for each treatment.

Soil NH_4^+-N and NO_3^--N content

Soil samples were divided into three layers from 0 to 90 cm, each one with a height of 30 cm. Soil sample of each layer was placed by an earth drill into a Ziploc bag at the sixth leaf stage (V6), tasseling stage (VT) and physiological maturity stage (R6) (Gao et al. 2019). Soil NH_4^+-N and NO_3^--N were extracted with

1 *M* KCl, and filtered through a 0.45-μm membrane filter to remove insoluble particulates. The content of soil NH_4^+-N and NO_3^--N were measured by AA3 Continuous Flow Analytical System (Zhu et al. 2015). Three replicate soil samples were collected in each treatment.

Nitrogen efficiency

Five representative plant samples were obtained from each plot at the physiological maturity stage (R6). Samples were dried at 80^{o}C in a force-draft oven (DHG-9420A, Bilon Instruments Co. Ltd, Shanghai, China) to constant weight and weighed separately. Total N was measured using the Kjedahl method. Nitrogen use efficiency (NUE, kg kg^{-1}), N partial factor productivity (NPFP, kg kg^{-1}), and nitrogen harvest index (NHI, %) were calculated to investigate the performance of agricultural management practices, using the following equations:

$$NPFP = \frac{Y}{NA}$$

4

$$NUE = \frac{Y}{TN}$$

5

$$NHI = \frac{GN}{TN}$$

6

where *NA* (kg N ha^{-1}) is N applied, TN (kg ha^{-1}) is total N uptake by plant, GN (kg ha^{-1}) is grain N amount.

Crop yield

To determine maize yield and ear traits, 30 ears were harvested at the physiological maturity stage (R6) from three rows at the center of each plot. All kernels were air-dried, and grain yield was measured at 14% moisture, the standard moisture content of maize in storage or for sale in China (GB/T 29890 – 2013).

Data analysis

Analysis of variance (ANOVA) was performed according to the general linear model procedure of SPSS (Ver. 17.0, SPSS, Chicago, IL, USA). The least significant difference (LSD) between the means was estimated at the 95% confidence level. Unless otherwise indicated, significant differences are at $P \leq 0.05$. LSD was used to compare adjacent means arranged in order of magnitude.

Results

Grain yield

Waterlogging significantly decreased grain yield. Grain yield of V-3WL was 31% lower than that of CK across years. However, the application of nitrapyrin was beneficial to increase yields in waterlogged plots, with grain yield being 34% higher in V-3WL + N treatment than that in V-3WL treatment. In addition, the kernel number and 1000-grain weight were significantly increased by 19 and 9% for V-3WL + N, respectively, compared to those of V-3WL across years (Table 1).

Table 1
Effects of applying nitrapyrin on grain yield and its components under waterlogged field

Year	Treatments	Harvest ear number (ears ha^{-1})	Grains number (per ear)	1000- grains weight (g)	Grain yield (kg ha^{-1})
2016	V-3WL	61906c	447b	318c	8795c
	V-3WL + N	64407b	582a	341b	12803b
	CK	66908a	588a	351a	13821a
2017	V-3WL	62822b	490c	277b	9915c
	V-3WL + N	64038a	527b	309a	12141b
	CK	65724a	553a	311a	13159a

V-3WL, waterlogging treatment with urea application only; V-3WL + N, waterlogging treatment with urea and nitrapyrin application; CK, not waterlogged but applied only urea

Values fallowed by a different small letter within a column are significantly different at 5% probability level. Differences among treatments were calculated for each particular year

N_2O emissions

The three treatments during summer maize season showed significant temporal variation in N_2O emissions. N_2O emission increased significantly after waterlogging, and maximum N_2O was recorded during the process of soil drying. The N_2O emission fluxes in CK, V-3WL + N, and V-3WL ranged from 8.9 to 514.1, 19.6 to 2666.5, and 40.0 to 3699.5 μg m^{-2} h^{-1}, respectively. The variation trends of N_2O fluxes in the two waterlogging treatments were similar, while the treatment with nitrapyrin decreased significantly. After waterlogging, the cumulative emission flux of N_2O increased significantly, showing a trend of V-3WL > V-3WL + N > CK (Fig. 1).

Likewise, waterlogging significantly increased GWP_{N2O} and $GHGI_{N2O}$. However, after the addition of nitrapyrin, the GWP_{N2O} and $GHGI_{N2O}$ were significantly decreased, V-3WL + N decreased by 34% and 50%, respectively, compared with V-3WL treatment (Fig. 2).

Soil NO_3^--N and NH_4^+-N concentrations

Soil N was rapidly leached in waterlogged soil due to high levels of soil moisture. The two-year average results showed that NO_3^--N concentration in the top (0–30 cm) soil layer in V-3WL treatment was 40% lower than that in CK soil at V6 stage, whereas NO_3^--N concentrations in the mid (30–60 cm) and deep (60–90 cm) soil layers were 22% and 15% higher in V-3WL treatment, respectively, compared to that in CK (There was no significant difference between V-3WL and CK treatment in 60-90cm soil layer in 2017). When nitrapyrin was applied, the transformation of NH_4^+-N to NO_3^--N was inhibited. The NO_3^--N concentrations in V-3WL + N treatment increased by 14% in the top soil layer, and decreased by 12% and 31% in the mid and deep soil layers, respectively, compared to V-3WL. At VT, the NO_3^--N concentration of the waterlogging treatment in the 0–30 cm and 30–60 cm soil layers was lower than CK. In 2017, the NO_3^--N concentration of V-3WL treatment in each soil layer at R6 stage was significantly higher than that of V-3WL + N, while there was no significant difference between the two waterlogging treatments in 2016 (Fig. 3).

At V6 stage, the NH_4^+-N concentration in the 0–30 cm, 30–60 cm and 60–90 cm soil layers of the V-3WL + N was significantly increased, which was 77%, 28% and 54% higher than the V-3WL treatment, respectively. However, at VT, the NH_4^+-N concentration in the deep soil layer of the V-3WL treatment was significantly higher than that of the other treatments, which increased by 26% and 27% compared with CK and V-3WL + N, respectively. Obviously, the NH_4^+-N concentration of each soil layer at R6 showed a similar trend of V-3WL > V-3WL + N > CK (Fig. 4).

Nitrogen efficiency

Nitrogen accumulation was significantly reduced after waterlogging. The total N accumulation was 24% lower than of CK across years. Moreover, nitrogen partial factor productivity (NPFP), nitrogen use efficiency (NUE), and nitrogen harvest index (NHI) was 31, 5, and 17% lower than those of CK, respectively. However, nitrapyrin application effectively alleviated the reduction of N accumulation and N efficiency induced by waterlogging. The total N accumulation, NPFP, NUE, and NHI of V-3WL + N was increased by 14, 34, 10, and 12% across years, respectively (Table 2).

Table 2
Effects of applying nitrapyrin on nitrogen accumulation and nitrogen efficiency under waterlogged field

Year	Treatment	Nitrogen accunulation (g p^{-1})	Nitrogen partial factor productivity (NPFP, kg kg^{-1})	Nitrogen use efficiency (NUE, kg kg^{-1})	Nitrogen harvest index (NHI)
2016	V-3WL	2.75c	41.88c	51.66c	0.57c
	V-3WL + N	3.05b	60.97b	59.34a	0.63b
	CK	3.70a	65.81a	55.83b	0.69a
2017	V-3WL	3.09c	47.21c	51.03b	0.52c
	V-3WL + N	3.63b	57.81b	53.73a	0.59b
	CK	3.97a	62.66a	52.69 a	0.63a

V-3WL, waterlogging treatment with urea application only; V-3WL + N, waterlogging treatment with urea and nitrapyrin application; CK, not waterlogged but applied only urea

Values fallowed by a different small letter within a column are significantly different at 5% probability level. Differences among treatments were calculated for each particular year

Discussion

Soil moisture could affect the microbial species, quantity and activity that decomposing soil organic matter by affecting soil aeration condition, and then affecting the decomposition rate of organic matter, and the production and diffusion rate of greenhouse gases (Zhang et al. 2011). Soil N_2O was largely produced from microbial nitrification and denitrification, which were affected by environmental conditions such as soil temperature, moisture content, organic matter content, and pH (Sahrawat and Keeney 1986; Granli and Bockman 1995). Of these factors, soil moisture content had the greatest effect on N_2O emission (Davidson 1991). An increase in soil moisture, such as from natural (e.g., rainfall) and artificial (e.g., irrigation) processes, resulted in short-term increases in N_2O emissions, and thus lower N acquisition and NUE by crops (Ren et al. 2017a). Maximum N_2O flux was reached at 84–86% water-filled pore space (WFPS), which represented the percentage of soil saturation by water. At less than 70% WFPS, soil N_2O flux, mostly produced by nitrification, increased with increasing soil moisture content and application of N fertilizer (Abbasi and Adams 2000). Conversely, when WFPS was more than 70%, N_2O was mostly produced by denitrification (Wolf and Russow 2000; Bateman and Baggs 2005; Ruser et al. 2006). Our previous results indicated that waterlogging limited plant growth and lowered grain yield by decreasing both NUE and N fertilizer recovery efficiency in summer maize (Ren et al. 2017a, b). In this present study, we found that soil N_2O fluxes were significantly increased after waterlogging (Fig. 1). The maximum N_2O flux was recorded during the process of soil drying, similar to observations by Jie et al. (1997) for paddy fields. This was probably because the water layer covering soil surface reduced soil permeability and promoted denitrification. When soil was waterlogged, gaps among soil particles were completely filled with water. Under this condition, N_2O accumulated in the soil and did not revert back to gaseous N (N_2). However, N_2O was released from the soil as soil gradually dried. Thus, waterlogging leaded to increased N_2O emissions from our experimental plots and decreased the NUE of maize crop. On a broader spatial scale, waterlogging could increase the rate of N_2O emissions, leading to an increased contribution to greenhouse effect from agricultural activities with a significant increase of GWP_{N2O} and $GHGI_{N2O}$ by 299% and 504%, compared to those of CK, confirming that waterlogging contributed significantly to greenhouse effect. However, the application of nitrapyrin had been shown to improve the absorption and use of N fertilizer and N distribution in grains, which increased NUE of summer maize grown under waterlogged conditions (Ren et al. 2017a), and enhanced total N accumulation and N fertilizer recovery efficiency (Tables 1 and 2). Nitrapyrin could reduce N losses through leaching and gas diffusion by inhibiting soil nitrification (Borzouei et al., 2021; Dawar et al. 2021). In this study, the application of nitrapyrin resulted in lowered N_2O emissions, decreasing GWP_{N2O} and $GHGI_{N2O}$ by 34% and 50%, respectively. Visibly, nitrapyrin could reduce the effect of waterlogging on soil GHG emissions and help to lower the contribution from agricultural activities to greenhouse effect.

The leaching of soil N, which was exacerbated by waterlogging, resulted not only in fertilizer losses but also in serious environmental problems (Ashraf and Rehman 1999; Jackson 2004). Our previous study showed that waterlogging limited root growth and development, lowering the ability of plant to absorb N, and decreased plant NUE by increasing soil N leaching in the form of NO_3^- (Ren et al. 2016). At the early waterlogging stage, soil moisture content was very high, and soil N would be leached at high rates. At V6 stage, NH_4^+-N and NO_3^--N concentrations were lower in the top soil layers and higher in the mid and deep soil layers in waterlogged soil compared to non-waterlogged soil (Fig. 3). By contrast, NH_4^+-N concentrations in waterlogged soil with nitrapyrin (V-3WL + N treatment) were higher in all soil layers compared to concentrations in waterlogged soil without nitrapyrin (V-3WL treatment), whereas NO_3^--N concentrations in the mid and deep soil layers were lower in V-3WL + N treatment compared to those in the V-3WL treatment (Fig. 4). This result might be due to the presence of nitrification inhibitors, which prevented the transformation of NH_4^+-N into NO_3^--N. As soil dried, soil moisture content returned to baseline levels, and the process of soil N leaching slowed. However, the disorder of root growth and development caused by waterlogging leaded to reduced ability to absorb N (Ren et al. 2016) and accumulation of N around root rhizosphere. Therefore, NH_4^+-N concentrations in the top soil layers of waterlogged plots were higher than that of control plots when plants were at VT and R6 stages. These results showed that nitrogen uptake and NUE of summer maize were reduced in waterlogged soils. However, nitrification inhibitors could reduce N leaching rates and improve N absorption and use efficiency in plants, thus mitigating waterlogging damages on N leaching and N use efficiency.

Overall, the application of nitrapyrin to waterlogged fields can help to reduce N loss and GHG_{N2O} flux and increase grain yield (Fig. 5). Nitrapyrin, an eco-friendly and N-efficient fertilizer companion, was useful for waterlogged soil conditions by helping to decrease N leaching and reduce the agricultural contribution to greenhouse effect.

Conclusion

In our study, waterlogging significantly decreased crop yield and increased the cumulative emission flux of N_2O, warming potential and greenhouse gas intensity. Nitrapyrin application not only helped to increase grain yield and N efficiency of maize grown in waterlogged soil, but also reduced $GHGI_{N2O}$ and GWP_{N2O} of waterlogged soil as well as the contribution to greenhouse effect from agricultural sources.

Declarations

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Authors' contributions B.Z.R. and Z.T.M. Data curation, Writing-original draft; J.W.Z. Conceptualization, Methodology; P.L. Supervision; B.Z. Methodology, Formal analysis. All authors contributed critically to the manuscript and gave final approval for publication.

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Availability of data and material All data are included in the manuscript, and upon the request form the correspondence authors.

Code availability Not applicable.

Conflict of interest The authors declare that they have no conflict of interest.

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Figures

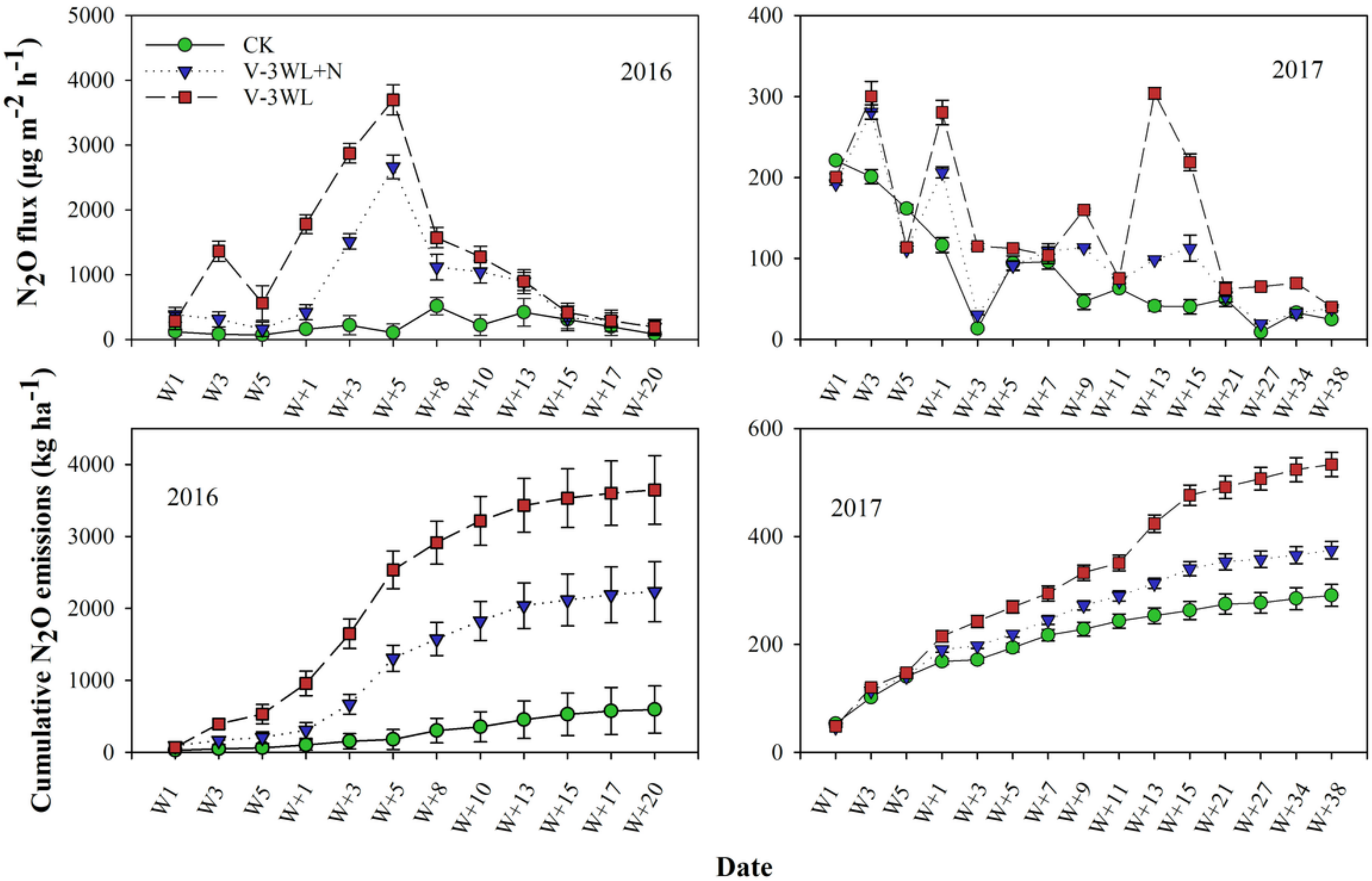

Figure 1

Effects of applying nitrapyrin on soil N_2O emission flux under waterlogged field

V-3WL, waterlogging treatment with urea application only; V-3WL+N, waterlogging treatment with urea and nitrapyrin application; CK, not waterlogged but applied only urea

Wn, waterlogging duration; W+n, the day after waterlogging

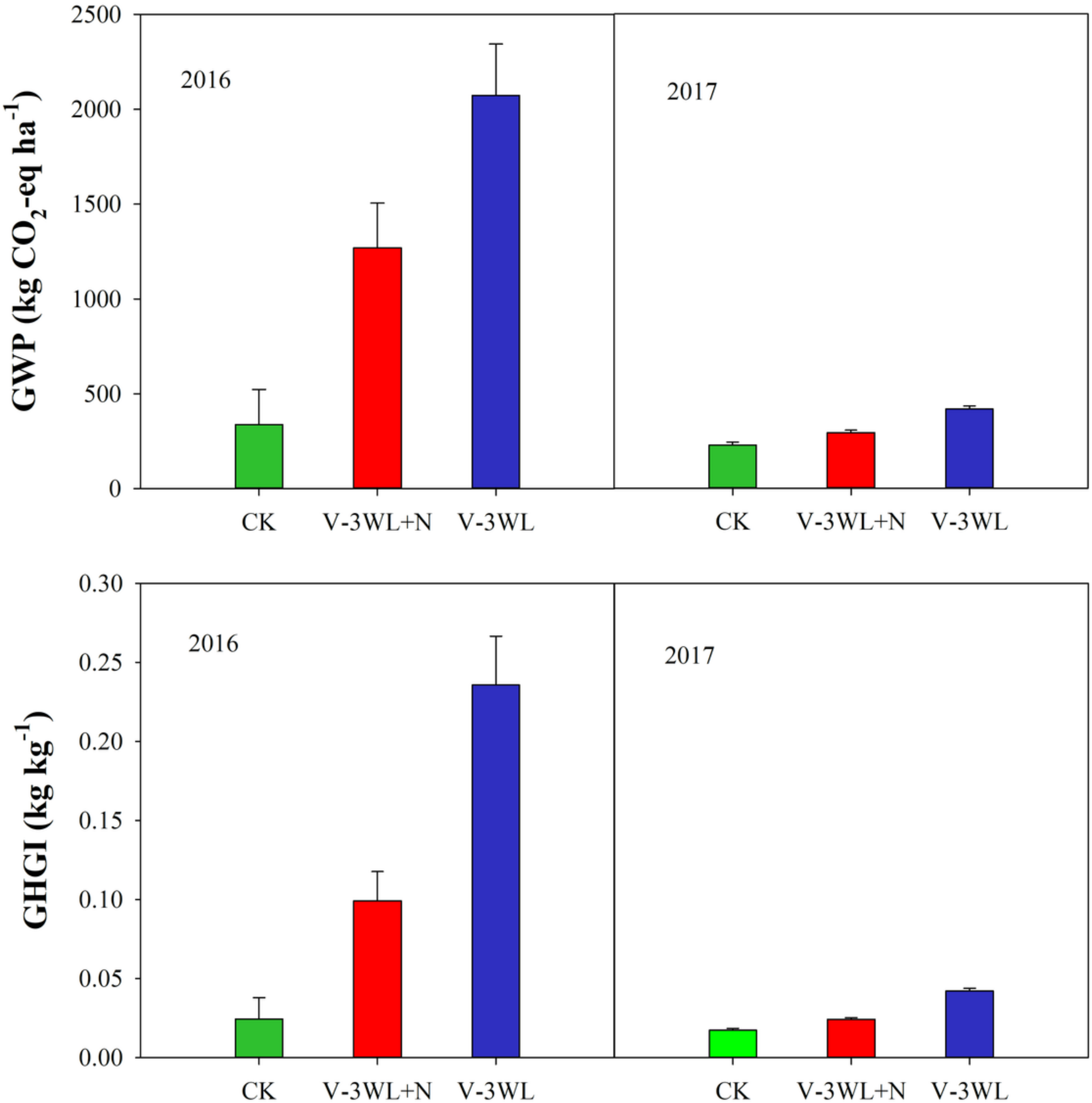

Figure 2

Effects of applying nitrapyrin on warming potential under waterlogged field

V-3WL, waterlogging treatment with urea application only; V-3WL+N, waterlogging treatment with urea and nitrapyrin application; CK, not waterlogged but applied only urea

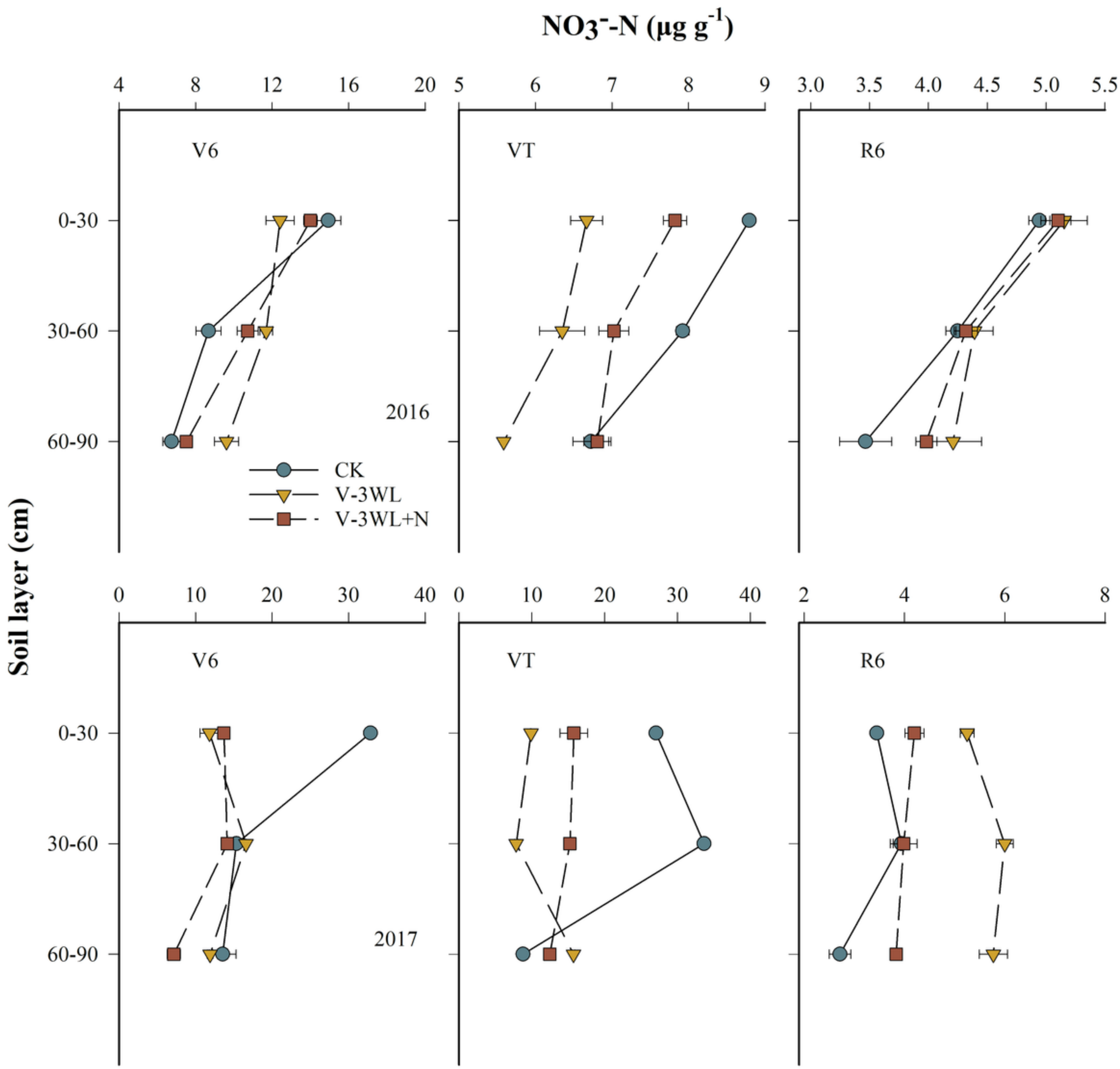

Figure 3

Effects of applying nitrapyrin on soil NO_3^--N content in waterlogged maize field

V-3WL, waterlogging treatment with urea application only; V-3WL+N, waterlogging treatment with urea and nitrapyrin application; CK, not waterlogged but applied only urea

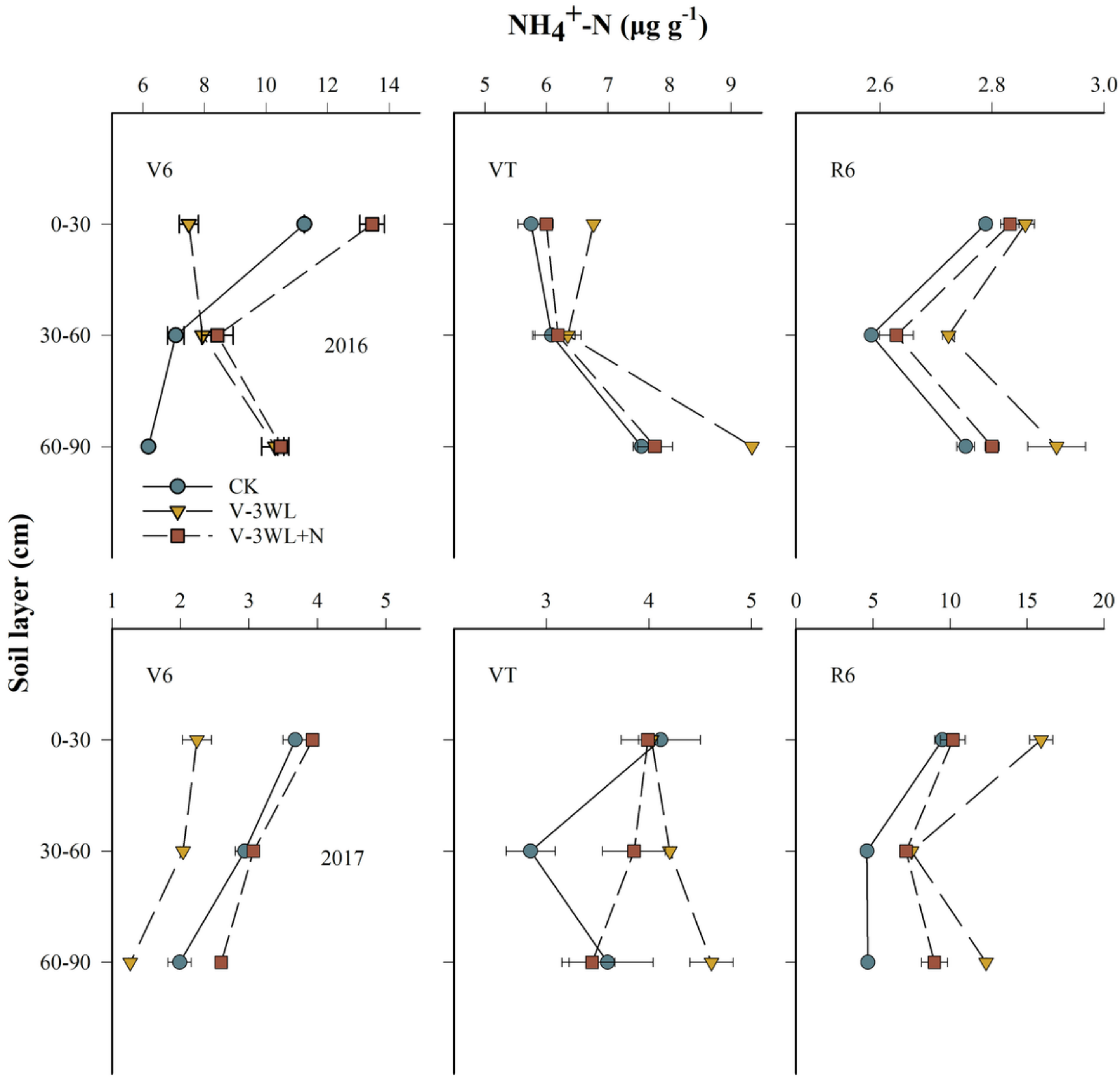

Figure 4

Effects of applying nitrapyrin on soil NH_4^+-N content under waterlogged field

V-3WL, waterlogging treatment with urea application only; V-3WL+N, waterlogging treatment with urea and nitrapyrin application; CK, not waterlogged but applied only urea

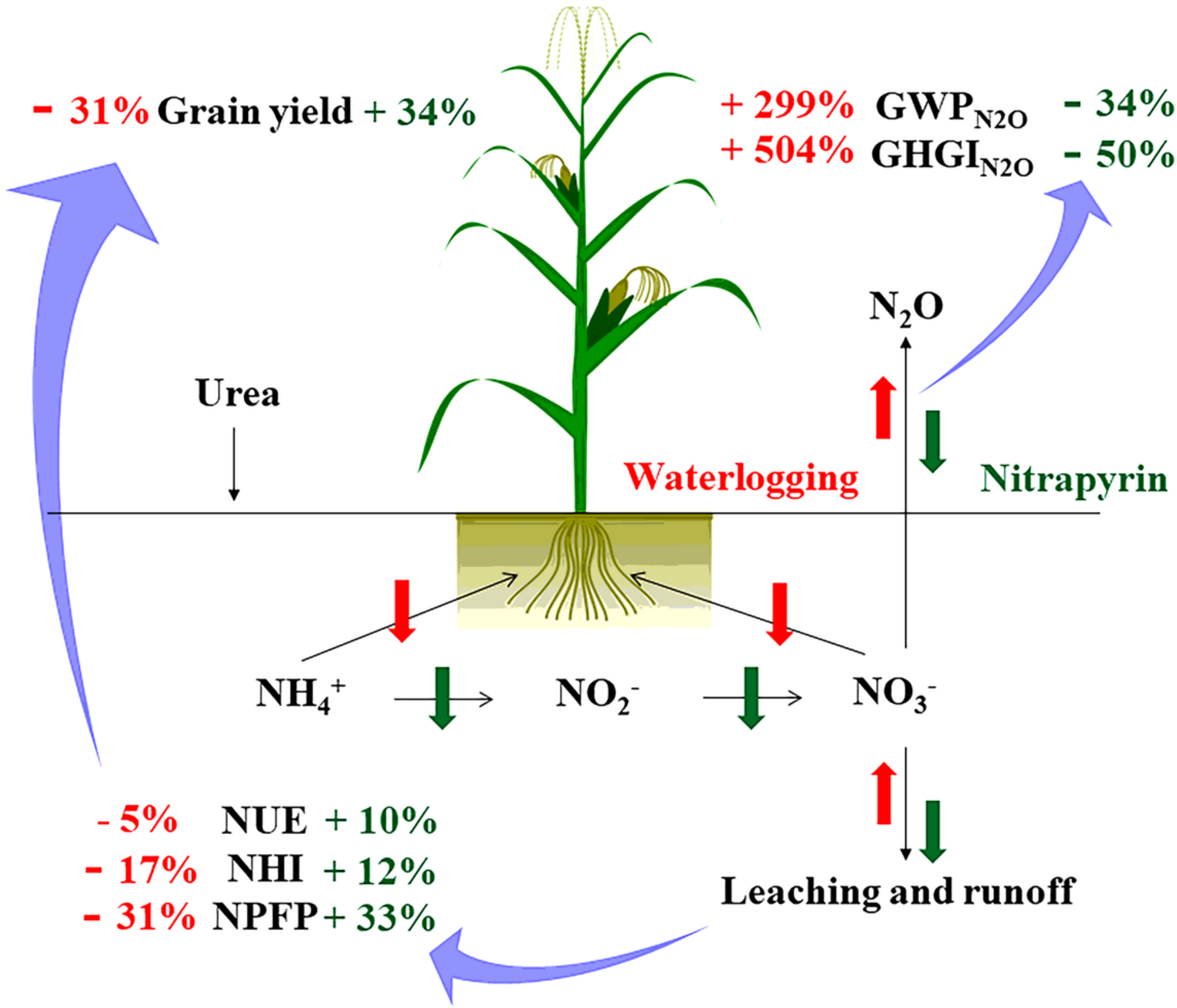

Figure 5

The influence process of applying nitrapyrin on soil N translocation under waterlogged field