Strategies to mitigate greenhouse gas emissions in intensively managed vegetable cropping systems in subtropical Australia

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Abstract

The greenhouse gas fluxes and effective mitigation strategies in subtropical vegetable cropping systems remain unclear. In this field experiment, nitrous oxide (N$_2$O) and methane (CH$_4$) fluxes from an irrigated lettuce cropping system in subtropical Queensland, Australia were measured using manual sampling chambers. Four treatments were included: Control (no fertiliser), U100 (100 kg N ha$^{-1}$ as urea), U200 (200 kg N ha$^{-1}$ as urea) and N100 (100 kg N ha$^{-1}$ as nitrate-based fertilisers). The N fertilisers were applied in three splits and irrigation was delivered sparingly and frequently to keep soil moisture around the field capacity. The cumulative N$_2$O emissions from the control, U100, U200 and N100 treatments over the 68-day cropping season were 30, 151, 206 and 68 g N$_2$O-N ha$^{-1}$, respectively. Methane emission and uptake were negligible. Using N$_2$O emission from the Control treatment as the background emission, direct emission factors for U100, U200 and N100 treatments were 0.12%, 0.09% and 0.04% of applied fertiliser N, respectively. Soil ammonium (NH$_4^+$) concentration, instead of nitrate (NO$_3^-$) concentration, displayed a significant correlation with N$_2$O emissions at the site where the soil moisture was controlled within 50-64% water-filled pore space (WFPS). Furthermore, soil temperature rather than water content was the main regulating factor of N$_2$O fluxes in the fertilised treatments. The fertiliser type and application rates had no significant effect on yield parameters. Partial N balance analysis indicated that approximately 80% and 52% of fertiliser N was recovered in plants and soil in the treatments receiving 100 kg N ha$^{-1}$ and 200 kg N ha$^{-1}$, respectively. Therefore, in combination with frequent and low intensity irrigation and split application of fertiliser N, substitution of NO$_3^-$-based fertilisers for urea and reduction in fertiliser N application rates were considered promising mitigation strategies to maintain yield and minimise N$_2$O emissions during the low rainfall season.

Keywords: Nitrous oxide, Methane, Vegetable, Subtropical climate, Greenhouse gas mitigation
Introduction

Agricultural manipulation of the soil nitrogen (N) cycle during past decades has caused a significant increase in N\textsubscript{2}O emissions (Yan et al. 2003; Dong et al. 2007). Agricultural soils are the primary source of anthropogenic N\textsubscript{2}O emissions, and global N\textsubscript{2}O emissions from this source are approximately 3.9 Tg N yr\textsuperscript{-1} (FAOSTAT, 2014). Nitrous oxide production in soil is mainly through the microbial processes of nitrification (oxidation of NH\textsubscript{4}\textsuperscript{+} to NO\textsubscript{3}\textsuperscript{-}) and denitrification (anaerobic reduction of NO\textsubscript{3}\textsuperscript{-} to gaseous NO, N\textsubscript{2}O or N\textsubscript{2}). The most important factors controlling these processes are soil available carbon (C) and N, temperature, moisture and pH (Dalal et al. 2003).

Due to continuous decline in soil fertility in agricultural production systems (Dalal and Mayer 1986) and in order to increase productivity to meet the needs of a rapidly increasing human population (Vallejo et al. 2005), N fertiliser applications have become essential for sustaining crop production systems. However, the tendency to apply N fertilisers in excess of crop requirements often results in high mineral N concentrations in the surface soil (Wagner-Riddle et al. 2007; He et al. 2007, 2009), which intensifies N\textsubscript{2}O emissions from cultivated soils (Mosier and Kroeze 2000).

Vegetable cropping systems are associated with high N fertiliser application rates and intensive cultivation. However, the N recovery from intensively cultivated vegetable fields is only 20 to 50% of the applied N fertiliser (Huang et al. 2006), suggesting that large amounts of N surplus to crop requirements can be lost by nitrate leaching, runoff and/or emissions of gases including N\textsubscript{2}O. Synchronizing the soil N supply with crop requirements during the growing season and improving fertiliser and irrigation management practices would increase N use efficiency in the soil-plant systems and consequently reduce N losses (Vanlauwe et al. 2001; Dalal et al. 2003).

The atmospheric concentration of CH\textsubscript{4} has increased rapidly in recent years with a concentration of around 1803 ppbv in 2011 (IPCC 2013). Agriculture, especially animal production, is responsible for about 52% of total anthropogenic CH\textsubscript{4} emissions (Smith et al. 2008). The production and consumption of CH\textsubscript{4} in soil is mainly driven by the biological decomposition of organic materials in
anoxic conditions and biological oxidization in aerobic environments (Mosier et al. 1998). It has been reported that well-irrigated vegetable fields could emit CH$_4$ during wet periods and consume CH$_4$ during dry periods of the growing season (Jia et al. 2012). Striegl (1993) demonstrated that diffusion of atmospheric CH$_4$ into well-drained agricultural soils is the main factor limiting its biological oxidation rate.

Field measurements of N$_2$O and CH$_4$ emissions conducted in vegetable production systems are limited. Although subtropical farms of Queensland contribute more than 30% of the Australian gross vegetable value, there is a lack of knowledge about greenhouse gas production and mitigation options in these intensive cropping systems. The main objectives of this study were therefore to: (1) compare different fertiliser management practices (nitrate vs. urea application at different rates) in relation to greenhouse gas emissions, crop yield and fertiliser N use efficiency; and (2) identify the factors regulating N$_2$O emissions during the cropping season. The underlying hypothesis was that avoiding excessive N application and changing the fertiliser type from urea to nitrate-based products in combination with controlled irrigation would reduce N$_2$O emissions during the dry cropping season.

Materials and methods

Study site and experimental design

The experimental site was located at Gatton Horticultural Research Station (27° 32' 39" S, 152° 19' 38" E) in the Lockyer Valley, one of the key horticultural regions in north-east Australia. The soil at this site is a black Vertosol (Isbell, 2002) and the clay mineralogy of the soil is dominated by smectite (~60%; Dalal and Mayer, 1986). The experimental area has a mean annual air temperature of 20°C and a mean annual precipitation of 772 mm. Soil properties in the 0-90 cm profile summarised in Table 1.
Table 1: Initial physico-chemical characteristics of the experimental soil

<table>
<thead>
<tr>
<th>Soil Depth (cm)</th>
<th>Bulk Density (g cm$^{-3}$)</th>
<th>pH (1:5 water)</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Sand (%)</th>
<th>CEC (cmol kg$^{-1}$)</th>
<th>Exchangeable K (mg kg$^{-1}$)</th>
<th>Colwellb P (mg kg$^{-1}$)</th>
<th>Total OCc (%)</th>
<th>Total N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10</td>
<td>1.17</td>
<td>7.69</td>
<td>41</td>
<td>24</td>
<td>35</td>
<td>37.9</td>
<td>312</td>
<td>136</td>
<td>1.54</td>
<td>0.11</td>
</tr>
<tr>
<td>10-30</td>
<td>1.32</td>
<td>7.79</td>
<td>43</td>
<td>23</td>
<td>34</td>
<td>37.2</td>
<td>207</td>
<td>115</td>
<td>1.53</td>
<td>0.11</td>
</tr>
<tr>
<td>30-60</td>
<td>1.41</td>
<td>7.77</td>
<td>55</td>
<td>15</td>
<td>30</td>
<td>41.2</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>60-90</td>
<td>1.51</td>
<td>7.84</td>
<td>47</td>
<td>15</td>
<td>38</td>
<td>40.1</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
</tbody>
</table>

a Exchangeable K extracted with 1M NH$_4$Cl at pH = 7; b Colwell P with 0.5M NaHCO$_3$; c Total organic carbon was determined by pre-treatment of soil samples with sulphurous acid (H$_2$SO$_3$) and then dry combustion using a LECO CN analyser (TruMac NO. 830-300-400).

The field experiment was conducted in an intensively managed vegetable cropping system typical of the subtropical climatic zone and consisted of four treatments: (1) no fertiliser application (Control); (2) urea applied at 100 kg N ha$^{-1}$ (U100); (3) urea applied at 200 kg N ha$^{-1}$ (U200); and (4) predominantly NO$_3^-$-based fertilisers applied at 100 kg N ha$^{-1}$ (N100, Table 2). The U200 treatment represents approximately the highest N application rate in the region. The fertilised treatments received three splits of N applications during the growing season to better match N supply with plant demand during the growing season (Table 2). The fertilisers were applied by broadcasting on the surface immediately before irrigation. The experiment was arranged using a randomized block design with four replicates (7.0m × 1.5m plots). Iceberg lettuce (Lactuca sativa, var. capitata cv. Kong) was transplanted on 9th May 2012 and harvested on 16th July 2012.
Table 2: Date, type and application rates (kg N ha\(^{-1}\)) of N fertilisers

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Application Date</th>
<th>Total N Rate (kg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>9/05/2012</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4/06/2012</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>18/06/2012</td>
<td>0</td>
</tr>
<tr>
<td>U100</td>
<td>50 kg N as urea</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>25 kg N as urea</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25 kg N as urea</td>
<td></td>
</tr>
<tr>
<td>U200</td>
<td>50 kg N as urea</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>50 kg N as urea</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 kg N as urea</td>
<td></td>
</tr>
<tr>
<td>N100</td>
<td>27 kg NH(_4)-N + 23 kg NO(_3)-N as Nitrophoska(^a)</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>25 kg N as Ca(NO(_3))(_2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25 kg N as KNO(_3)</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Nitrophoska Blue Special: Incitec Pivot, Australia; containing 6.5% NH\(_4^{+}\)-N and 5.5% NO\(_3^{-}\)-N

The irrigation regime aimed to keep the soil moisture content close to field capacity using a sprinkler irrigation system, as this was considered to be optimal for growth and less inductive to N losses. Therefore, several light irrigations were applied throughout the lettuce growing season according to soil moisture content, except for the 4th June when heavy rainfall was received just after the irrigation (Fig. 1a).

**Soil sampling and analysis**

Prior to fertiliser application, soil samples were collected to a depth of 90 cm in four increments of 0-10 cm, 10-30 cm, 30-60 cm and 60-90 cm to determine the physicochemical properties of the experimental site (Table 1). This sampling was also repeated after crop harvest to provide information about N leaching and the N budget for different treatments. During the growing season, soil samples were taken once per fortnight at two depths (0-10 cm and 10-30 cm) from all plots (4 treatment × 4 replications). The sampling location was marked to avoid resampling the same spots.

Field-moist samples were transported to the laboratory and kept at 4°C until mineral N extraction (within 48 h). The soil samples were extracted with 2 M KCl at a soil to solution ratio of 1:5. The NO\(_3^{-}\)-N and NH\(_4^{+}\)-N concentrations in the extractant were determined using colorimetric techniques
Total extractable mineral N was calculated as the sum of NO$_3^-$-N and NH$_4^+$-N concentrations. All results were expressed on an oven-dry basis. Soil pH was measured in a 1:5 volumetric suspension of soil in distilled water (Rayment and Lyons 2011).

Before planting, and one week prior to the harvest, three replicate undisturbed soil cores were collected using stainless steel cylinders (10 cm in diameter and 10 cm in length) to measure surface soil bulk density. The cores were dried for 48 h at 105°C and weighed. Bulk density was calculated from the oven dry soil weight divided by the core volume. Field capacity (FC%) was determined using the method described by Cassel and Nielsen (1986).

**Measurement of N$_2$O and CH$_4$ fluxes**

In order to investigate the effect of the crop on gas fluxes, two different types of manual gas sampling chamber were used: a) cylindrical polyethylene chambers (23.5 cm diameter and 12 cm height) installed between plants and b) cubic chambers (50×50×50 cm) with stainless steel frames, opaque PVC panels and a circulating fan (Wang et al. 2011) installed over a growing lettuce plant. Each treatment was instrumented with eight cylindrical and four cubic chambers. The chambers were relocated every 3 weeks to minimise spatial variability in fluxes and to minimise the impact of crop roots exclusion in the cylindrical chambers during the growing season.

Gas fluxes were measured 3 times per week between 9:00 and 11:00am local time to minimize the effect of diurnal variation on flux patterns. This schedule is reported to be the optimum timing for intermittent manual flux measurements in the field with lowest deviation in the seasonal cumulative emissions (Liu et al. 2010; Wang et al. 2011; Deng et al. 2012). Gas samples were collected from the chamber headspace approximately one hour after chamber closure using a 25 mL gas-tight syringe and immediately transferred to pre-evacuated 12 mL glass vials (Exetainer, Labco Ltd, High Wycombe, UK).
Gas samples were analysed for N$_2$O and CH$_4$ concentrations within 5 days of sampling using a gas chromatograph (Varian CP-3800, Varian Inc., Middleburgh, the Netherlands) as described by Wang et al. (2011). Standards were injected after every ten samples to monitor instrument precision. Gas fluxes were calculated from the increases in the N$_2$O and CH$_4$ concentrations during the sampling time. Linearity tests on gas concentration increases were performed on a subset of sampling occasions during the growing season for all treatments by taking samples after chamber closure every 30 min for 1.5 hours. In general, N$_2$O and CH$_4$ fluxes showed a linear trend over the measurement period. The emissions for the days without gas sampling were estimated using the arithmetic mean of the two closest measurements. The cumulative seasonal emissions were calculated by summing up the daily flux measurements.

Measurements of environmental factors

Climate parameters including daily rainfall and hourly air temperature during the entire monitoring period were obtained from an on-site automatic weather station. Immediately after planting, soil moisture and temperature were logged hourly using moisture probes (Theta Probe, Delta-T Devices Ltd., Cambridge, UK) installed at 7-13 cm depth and temperature probes (Measurement Engineering Australia Ltd., SA, Australia) installed at 5-7 cm depth inside and outside a cylindrical and a cubic chamber. Moisture probe readings were calibrated against simultaneous measurements of soil water contents using the oven drying method. The calibrated volumetric moisture content was then converted to water-filled pore space (WFPS) using the following equations:

$$WFPS\,\% = \frac{\text{Volumetric soil water content},\%}{1 - \frac{\text{Soil bulk density},\,\text{g cm}^{-3}}{2.65}} \times 100\%$$ (1)

Volumetric soil water content = Gravimetric soil water content,\% × Soil bulk density,\,\text{g cm}^{-3} (2)

where 2.65 g cm$^{-3}$ was assumed to be soil particle density.
Nitrogen balance

To aid understanding of the N use efficiency of applied fertilisers, the N balance for each treatment was calculated using equation (3), as described by Patil et al. (2001).

\[ N_{\text{balance}} = (N_{\text{crop}} + N_{\text{min harvest}}) - (N_{\text{min planting}} + N_{\text{fer}} + N_{\text{irri}}) \]  

(3)

where \( N_{\text{crop}} \) = total N uptake in the lettuce biomass (kg N ha\(^{-1}\)), \( N_{\text{min harvest}} \) = soil mineral N in the 0–90 cm depth immediately after harvest (kg N ha\(^{-1}\)), \( N_{\text{min planting}} \) = soil mineral N at 0–90 cm depth before planting (kg N ha\(^{-1}\)), \( N_{\text{fer}} \) = total N from applied fertiliser (kg N ha\(^{-1}\)), and \( N_{\text{irri}} \) = total N from irrigation water (kg N ha\(^{-1}\)).

Lettuce yield was determined by manually harvesting and weighing 12 lettuce heads per replicate and multiplying by the plant population (60,000 plants ha\(^{-1}\)). The lettuce sub-samples for each of the four replicate plots were dried at 65°C for 72 hours to measure dry matter content and then ground (<1 mm) before analysing for total N content using an Isotope Ratio Mass Spectrometer (Sercon Hydra 20-22, Sercon Europa EA-GSL). Lettuce heads and wrappers were measured separately.

Statistical analysis

Statistical analysis was performed using the SPSS 19 software package. Differences at \( P \leq 0.05 \) were considered statistically significant and variables were tested for normality of distribution. Soil ammonium concentration data had a square root transformation to meet the normal distribution requirement for statistical analysis. Stepwise multiple linear regression analysis was used to identify relationships between soil/environmental factors and N\(_2\)O emission fluxes.

Results

Seasonal pattern of environmental conditions and mineral N dynamics

Total rainfall and irrigation were 127mm and 137mm respectively during the 68-day cropping season. The WFPS of the soil at field capacity was 57% (Fig. 1a). The mean daily WFPS ranged
from 50% to 64%, with a seasonal mean of 57% (equal to field capacity) in the 7-13 cm depth. The mean daily soil temperature at 5-7 cm depth ranged from 11.3°C to 18.1°C and air temperature from 11.1°C to 19.6°C during the growing season, with an average of 14.6°C for soil and 14.9°C for air temperature. The results showed a similar temporal pattern for air and soil temperatures during the investigation period (Fig. 1b).

Fig. 1. Rainfall, irrigation and soil moisture (WFPS) at 7-13 cm depth (a) and daily mean air and soil temperatures at 5-7 cm depth (b) during the lettuce growing season.

The concentrations of NO$_3^-$-N and NH$_4^+$-N in the top 0-10 cm and the 10-30 cm layers indicated moderate mineral N leaching from the surface soil (Fig. 2). There were distinctive differences in
mineral N distribution patterns following the application of nitrate-based and urea-based fertilisers, especially in the top 0-10 cm soil. Soil NH$_4^+$-N concentrations increased sharply after fertilisation with urea (Figs 2a and b) and then decreased rapidly. The concentrations of NH$_4^+$-N in the N100 treatment (including 27 kg NH$_4^+$-N/ha in the first application) were consistently lower compared to those in the urea treatments. Mineral N concentrations in all fertilised treatments at the end of the experiment declined to low levels similar to those in the control treatment, regardless of the amount of fertiliser applied.

Fig.2. Soil NH$_4^+$-N and NO$_3^-$-N concentrations in the 0-10 cm (a and c) and 10-30 cm (b and d) depth intervals in all treatments. The black arrows indicate the timing of fertiliser application. Control = no fertiliser; U100 = 100 kg N ha$^{-1}$ as urea; U200 = 200 kg N ha$^{-1}$ as urea; N100 = 100 kg N ha$^{-1}$ mainly as nitrate-based fertilisers.

$N_2O$ and $CH_4$ fluxes

The daily and cumulative $N_2O$ emissions during the lettuce growing period are summarised in Figure 3. Several emission peaks occurred following irrigation or rainfall events in the fertilised treatments. After the first N fertiliser application, the $N_2O$ fluxes from the fertilised plots initially increased, and
then gradually decreased to the pre-fertilisation level. The magnitude of these fluxes was higher in
the U100 treatment than in the N100 treatment although the concentrations of NO$_3^-$-N were higher in
the latter. The results showed no significant differences between the chambers placed between
lettuce plants and the chambers that contained a lettuce plant inside for the whole period of
experiment. Thus, the lettuce plants did not have any significant effect on N$_2$O emissions.

The Control, U100, U200 and N100 treatments had cumulative N$_2$O emissions of 30, 151, 206 and
68 g N$_2$O-N ha$^{-1}$, respectively, during the experimental season. The cumulative N$_2$O emissions were
significantly higher for the fertilised treatments compared to the Control. During the growing season,
the N100 treatment reduced total N$_2$O emission compared to the U100 treatment by 55% ($P < 0.01$).
The U100 treatment also reduced the total N$_2$O emission by 27% in comparison to the U200
treatment ($P < 0.05$).

![Fig.3. Daily (a) and cumulative (b) N$_2$O emissions from different fertiliser treatments in the lettuce
field. The black arrows indicate the timing of fertiliser application. Control = no fertiliser; U100 =
100 kg N ha$^{-1}$ as urea; U200 = 200 kg N ha$^{-1}$ as urea; N100 = 100 kg N ha$^{-1}$ mainly as nitrate-based
fertilisers.]

The CH$_4$ fluxes were minor during the early growing stages and higher emissions were recorded
during the late stages of the growing season (Fig. 4). The Control, U100, U200 and N100 treatments
respectively emitted 20.5, 6.2, 6.8 and 16.8 g CH$_4$ ha$^{-1}$ during the experiment’s season, which were
not significantly different at $P = 0.05$. Similar to N$_2$O emissions, the results from different chamber
types did not show any significant difference in CH$_4$ fluxes during the experimental period.
Fig. 4. Daily (a) and cumulative (b) CH₄ emissions from different fertiliser treatments in the lettuce field. Control = no fertiliser; U100 = 100 kg N ha⁻¹ as urea; U200 = 200 kg N ha⁻¹ as urea; N100 = 100 kg N ha⁻¹ mainly as nitrate-based fertilisers.

Relationships of N₂O fluxes with environmental factors and soil mineral nitrogen contents

For each treatment, stepwise linear regression was used to model N₂O fluxes using soil NO₃⁻-N and NH₄⁺-N concentrations, WFPS and soil temperature as variables. The stepwise regressions indicated that the seasonal variations in N₂O emissions from the control were positively correlated with soil moisture:

\[
\text{N}_2\text{O flux for Control (g N}_2\text{O-N ha}^{-1}\text{ d}^{-1}) = -7.112 + 0.126 \text{ WFPS (¢); } \\
\text{n = 48, r = 0.30, P < 0.05.}
\]

In the urea treatments, soil NH₄⁺-N concentration and soil temperature were the most important factors controlling the magnitude of N₂O emissions:

\[
\text{N}_2\text{O flux under U100 (g N}_2\text{O-N ha}^{-1}\text{ d}^{-1}) = -5.170 + 0.444 \text{ Soil T (°C) + 0.244 (NH}_4^+\text{)}^{1/2} (\text{mg N kg}^{-1}); } \\
\text{n = 48, r = 0.61, P < 0.05}
\]

\[
\text{N}_2\text{O flux under U200 (g N}_2\text{O-N ha}^{-1}\text{ d}^{-1}) = -4.018 + 0.361 \text{ Soil T (°C) + 0.303 (NH}_4^+\text{)}^{1/2} (\text{mg N kg}^{-1}); } \\
\text{n = 48, r = 0.54, P < 0.05}
\]

In the N100 treatment, soil NH₄⁺-N concentration appeared to be the only dominant factor regulating N₂O fluxes and there was no significant effect of any environmental factor:

\[
\text{N}_2\text{O flux under N100 (g N}_2\text{O-N ha}^{-1}\text{ d}^{-1}) = 0.012 + 0.269 (\text{NH}_4^+) ^{1/2} (\text{mg N kg}^{-1}); } \\
\text{n = 48, r = 0.48, P < 0.01}
\]
Direct N$_2$O emission factors

Using the N$_2$O emission from the control treatment as the background emission, the proportions of the N$_2$O emissions attributable to N fertiliser application were calculated to be 80%, 86% and 57% for U100, U200 and N100 treatments, respectively. The direct emission factors [(N$_2$O-N from fertilised treatment - N$_2$O-N from control)/fertiliser-N*100%] for U100, U200 and N100 treatments were 0.12%, 0.09% and 0.04% respectively. These emission factors over 68 days are substantially lower than the IPCC default emission factor of 1.0%. The results indicate that the nitrate fertiliser form had the lowest direct emission factor and the higher urea application rate decreased the direct emission factor.

Lettuce yield

Total fresh yield of lettuce increased by more than two-fold with N fertiliser application (P<0.05; Table 3). There was no difference in yield between the nitrate-based fertiliser and urea. Reducing urea application from 200 kg N ha$^{-1}$ to 100 kg N ha$^{-1}$ did not have any significant negative impact on lettuce yield.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>TFY (t ha$^{-1}$)</th>
<th>TDY (t ha$^{-1}$)</th>
<th>FHY (t ha$^{-1}$)</th>
<th>HDMY (t ha$^{-1}$)</th>
<th>HDM (%)</th>
<th>FWY (t ha$^{-1}$)</th>
<th>WDMY (t ha$^{-1}$)</th>
<th>WDM (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>34.8 (a)</td>
<td>1.8 (a)</td>
<td>26.7 (a)</td>
<td>1.4 (a)</td>
<td>5.0 (a)</td>
<td>8.1 (a)</td>
<td>0.4 (a)</td>
<td>5.5 (a)</td>
</tr>
<tr>
<td>U100</td>
<td>77.0 (b)</td>
<td>3.1 (b)</td>
<td>64.7 (b)</td>
<td>2.5 (b)</td>
<td>3.9 (b)</td>
<td>12.3 (ab)</td>
<td>0.6 (a)</td>
<td>4.9 (a)</td>
</tr>
<tr>
<td>U200</td>
<td>81.5 (b)</td>
<td>3.2 (b)</td>
<td>67.7 (b)</td>
<td>2.6 (b)</td>
<td>3.8 (b)</td>
<td>13.8 (b)</td>
<td>0.6 (a)</td>
<td>4.8 (a)</td>
</tr>
<tr>
<td>N100</td>
<td>80.9 (b)</td>
<td>3.3 (b)</td>
<td>68.5 (b)</td>
<td>2.7 (b)</td>
<td>3.9 (b)</td>
<td>12.4 (ab)</td>
<td>0.6 (a)</td>
<td>5.2 (a)</td>
</tr>
</tbody>
</table>

*The different letters in parentheses within a column indicate significant differences between the treatments (P< 0.05)

Abbreviations: TFY, total fresh yield; TDY, total dry yield; FHY, fresh head yield; HDMY, head dry matter yield; HDM, head dry matter; FWY, fresh wrapper yield; WDMY, wrapper dry matter yield; WDM, wrapper dry matter; Control, no fertiliser; U100, 100 kg N ha$^{-1}$ as urea; U200, 200 kg N ha$^{-1}$ as urea; N100, 100 kg N ha$^{-1}$ mainly as nitrate-based fertilisers.
Nitrogen balance

Mineral N concentrations in the soil profiles at the start and the end of the experiment are shown in Table 4. The post-harvest mineral N concentrations in the soil profiles showed no significant increase in the 100 kg N ha\(^{-1}\) treatments (U100 and N100) compared with the Control, but slight increases in NO\(_3^-\) concentrations in the U200 treatment (P< 0.05) were observed. In this latter treatment there was a movement of NO\(_3^-\)-N to the 60-90 cm layer, indicating N leaching out of the lettuce rooting depth in the presence of excessive available mineral N. The similar mineral N concentrations in the U100 and N100 treatments down to 90 cm confirmed that fertiliser type did not appear to have any significant effect on mineral N leaching in this controlled irrigation system.

Assuming N uptake in the above-ground biomass accounted for 88% of the total crop N uptake (Jackson et al. 1994; Gallardo et al. 1996), the amount of N in the below-ground biomass was estimated to be 5.3, 14.0, 15.5 and 14.1 kg N ha\(^{-1}\) for the Control, U100, U200 and N100 treatments, respectively. The value of calculated N balance for the Control treatment (Table 5) was positive, with \((N_{\text{crop}} + N_{\text{min harvest}})\) exceeding \((N_{\text{min planting}} + N_{\text{fer}} + N_{\text{irri}})\) by 18.7 kg N ha\(^{-1}\). This extra amount of N was attributed to the mineralisation of soil organic N. The crop N uptake was significantly enhanced by N fertiliser application and was higher for the U200 treatment than the U100 treatment but was not significantly different between different fertiliser types applied at 100 kg N ha\(^{-1}\). The N balances for the fertilised treatments were all negative and the highest negative N balance in the U200 treatment showed a substantially greater N loss compared to other fertilised treatments.
Table 4: Mineral nitrogen concentration (mg kg\(^{-1}\)) in different soil layers at the start and end of the lettuce growing season.

<table>
<thead>
<tr>
<th>Soil Depth (cm)</th>
<th>NH(_4^+)</th>
<th>NO(_3^-)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start</td>
<td>End</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>U100</td>
</tr>
<tr>
<td>0-10</td>
<td>0.9(a)</td>
<td>0.7(a)</td>
</tr>
<tr>
<td>10-30</td>
<td>0.6(a)</td>
<td>0.3(a)</td>
</tr>
<tr>
<td>30-60</td>
<td>1.1(a)</td>
<td>0.5(a)</td>
</tr>
<tr>
<td>60-90</td>
<td>1.2(a)</td>
<td>0.9(a)</td>
</tr>
</tbody>
</table>

\(a\) The different letters in parentheses within a row (separate for NH\(_4^+\)-N and NO\(_3^-\)-N) indicate significant differences between the treatments (P< 0.05). Control = no fertiliser; U100 = 100 kg N ha\(^{-1}\) as urea; U200 = 200 kg N ha\(^{-1}\) as urea; N100 = 100 kg N ha\(^{-1}\) mainly as nitrate-based fertilisers.

Table 5: Effect of different N treatments on N balance in the crop-soil system (kg N ha\(^{-1}\)).

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Soil 0-90 cm N(_{\text{min}}) transplanting</th>
<th>N fertiliser</th>
<th>N irrigation</th>
<th>crop N uptake</th>
<th>Soil 0-90 cm N(_{\text{min}}) harvest</th>
<th>N balance(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control(^b)</td>
<td>41.5</td>
<td>0</td>
<td>1.2</td>
<td>44.4(c)</td>
<td>17.0(a)</td>
<td>18.7(a)</td>
</tr>
<tr>
<td>U100</td>
<td>41.5</td>
<td>100</td>
<td>1.2</td>
<td>116.6(b)</td>
<td>25.0(a)</td>
<td>-1.1(b)</td>
</tr>
<tr>
<td>U200</td>
<td>41.5</td>
<td>200</td>
<td>1.2</td>
<td>129.5(c)</td>
<td>36.7(b)</td>
<td>-76.5(c)</td>
</tr>
<tr>
<td>N100</td>
<td>41.5</td>
<td>100</td>
<td>1.2</td>
<td>117.2(b)</td>
<td>23.9(a)</td>
<td>-1.6(b)</td>
</tr>
</tbody>
</table>

\(a\) N\(_{\text{balance}}\) = (N\(_{\text{crop}}\) + N\(_{\text{min harvest}}\)) - (N\(_{\text{min planting}}\) + N\(_{\text{fer}}\) + N\(_{\text{irri}}\)); \(^b\) Control = no fertiliser; U100 = 100 kg N ha\(^{-1}\) as urea; U200 = 200 kg N ha\(^{-1}\) as urea; N100 = 100 kg N ha\(^{-1}\) mainly as nitrate-based fertilisers; \(^c\) The different letters in parentheses within a column indicate significant differences between the treatments (P< 0.05).

Discussion

Methane emissions

Unlike the finding by Jia et al. (2012) that vegetable cropping soils normally show high CH\(_4\) emissions due to more frequent irrigation compared to other crops, the results of the current experiment in winter lettuce production on a Vertosol showed minor net CH\(_4\) emission in a low-intensity, high-frequency irrigation system. Low CH\(_4\) emissions are generally observed under high soil temperature and relatively low soil moisture conditions (Ambus and Christensen 1995; Dobbie and Smith 1996; Ruser et al. 1998). Previous studies on aerated soils also indicated that CH\(_4\)...
diffusion into the soil profile is one of the main limiting factors controlling CH$_4$ emission rates (Striegl 1993; Ball et al. 1997).

The N fertiliser type and application rate did not significantly increase CH$_4$ emission compared to the control treatment. These results are in agreement with findings of Ruser et al. (1998) and Wang et al. (2011) who reported that application of N fertilisers did not change CH$_4$ emission rates in soils under long-term experiments.

Factors regulating N$_2$O emissions

It is essential to identify and understand the factors regulating agricultural soil N$_2$O emissions so that improved mitigation techniques can be developed. Vegetable production systems are especially important for agricultural N$_2$O mitigation as they are usually under multiple planting-harvest cycles during the year and receive high N application rates. Any factor that affects the soil N cycle is likely to alter N$_2$O emission (Xiong et al. 2006).

The present study showed that almost two thirds of the recorded N$_2$O emission peaks occurred after an increase in daily soil temperature (Fig. 1b and 3a). The only exceptions were two peaks (8/06/2012 and 22/06/2012) just after fertiliser topdressings where high emissions were observed without a significant increase in soil temperature. Soil temperature is one of the main controlling parameters of N$_2$O emission from fertilised agricultural soils when N$_2$O production in the soil is not limited by other factors such as WFPS and soil available N (Dobbie et al. 1999). Soil temperature influences N$_2$O emissions by regulating soil microbial activity, such as nitrification and denitrification. Ding et al. (2007b) reported a positive correlation between N$_2$O emission and soil temperatures up to 25°C in laboratory incubation at a certain WFPS condition favourable for nitrification and denitrification processes. Diao et al. (2013) indicated that N$_2$O emission from
vegetable fields was associated with both N fertilisation and soil temperature under appropriate soil moisture regimes (50-70% WFPS).

Soil moisture affects N\textsubscript{2}O emissions mainly by controlling the dominance of aerobic and anaerobic conditions during the growing season. Many investigations report that high N\textsubscript{2}O fluxes are mainly related to the denitrification process (Davidson 1991; Thornton et al. 1998), which is generally limited when soil moisture is below field capacity (De Klein and Van Logtestijn 1996). The frequent and low intensity irrigation scheme used in this study should have minimised anaerobic soil conditions (WFPS = 57%) and therefore probably avoided high N\textsubscript{2}O spikes from denitrification. These results are similar to the observations of Davidson (1991) and Russow et al. (2000) who reported nitrification as the main process of N\textsubscript{2}O production at soil moistures below 60% WFPS.

Ludwig et al. (2001) reported that at favourable soil temperatures and moistures for microbial activity, soil mineral N concentration is a regulatory factor of nitrification and denitrification rates. Dobbie and Smith (2003) and Vilain et al. (2010) also demonstrated the intensity of nitrification and denitrification processes as a function of soil NH\textsubscript{4}\textsuperscript{+}-N and NO\textsubscript{3}\textsuperscript{-}-N concentrations. In the current study under predominantly aerobic soil conditions, NH\textsubscript{4}\textsuperscript{+}-N rather than NO\textsubscript{3}\textsuperscript{-}-N concentrations regulated N\textsubscript{2}O emissions through the nitrification process (Eq 5, 6 and 7). In addition, the application of N fertilisers was split so that supply of mineral N more closely matched the crop demand at different stages of the growing season. This avoided accumulation of large amounts of mineral N, and thus would have restricted N\textsubscript{2}O emissions (Sehy et al. 2003; Tan et al. 2009).

Nitrous oxide emission factors and fertiliser nitrogen use efficiency under different management practices

Nitrous oxide emissions from cropping land can be derived from fertiliser N and other sources (mainly background soil N). The N\textsubscript{2}O emission factors of urea N (0.12% for U100 and 0.09% for
U200) derived from this study were substantially lower than the default 1.0% emission factor used by the IPCC (IPCC 2006). The reason could be related to the low temperature during the late autumn/winter seasons and the N/irrigation management practices as discussed below. As both cumulative N$_2$O emission and fertiliser N would increase in a multi-season vegetable crop system, we considered that the length of measurement period should not be a major factor leading to the low emission factors.

The U100 treatment resulted in lower total N$_2$O emissions than the U200 treatment, but slightly increased the direct emission factor of the fertiliser N. Meta-analyses by Kim et al. (2013) and Shcherbak et al. (2014) suggested a general trend of increasing N$_2$O emissions in response to increasing N inputs, while the emission factors may remain constant, increase or decrease with changing N input for most crop types. Ding et al. (2007a) reported that an increase in the N$_2$O emission factor with increasing N fertiliser application only occurs when soil conditions are favourable for N$_2$O production.

The N balances for the fertilised treatments in this experiment were all negative; thus N losses occurred. When the 18.7 kg N ha$^{-1}$ recovered from soil N mineralisation in the Control treatment was accounted for in the N supply, the U100, U200 and N100 treatments showed a net N loss of 20, 95 and 20 kg N ha$^{-1}$, respectively. The fertiliser N recovery for the U100, U200 and N100 treatments was 80%, 52% and 80%, respectively. Although not quantified in this study, the unrecovered N might have been lost through NH$_3$ volatilisation, NO$_3^-$ leaching to deeper soil layers (> 90 cm) as well as denitrification. The higher N loss in U200 (48% of applied N) along with no positive effect of this treatment on lettuce yield (compared to U100) suggested that application of 200 kg urea-N ha$^{-1}$ was inefficient in terms of both lettuce yield and N use, whilst significantly increasing N$_2$O emissions. This result supports previous findings that optimising N fertiliser application rates provide an efficient way of reducing N$_2$O emissions (Del Grosso et al. 2009).
One of the findings in this study was the significant relationship between \( \text{N}_2\text{O} \) emissions and soil \( \text{NH}_4^+ \) concentrations as discussed above. These results indicate that, if excessive wet conditions can be avoided by using moderate irrigation, one of the strategies for reducing \( \text{N}_2\text{O} \) emissions from intensively cropped vegetable fields in this region is to replace \( \text{NH}_4^+ \)-based fertilisers with \( \text{NO}_3^- \)-based N fertilisers during the low rainfall seasons. However, this strategy may not apply in wet seasons when \( \text{N}_2\text{O} \) emissions might be mainly produced through denitrification (Wang et al. 2011). When \( \text{NO}_3^- \)-based N fertilisers are used, it is important to use low-intensity irrigation techniques to minimise risks of denitrification under wet conditions.

Nitrophoska Blue Special (12.0% N, 5.2% P and 14.1% K; trade name Incitec Pivot Ltd.) was used for the first fertiliser application for the N100 treatment; it is considered to be a multi-nutrient fertiliser suitable for pre-planting application (to avoid direct contact with establishing seedlings) in intensive crop production systems such as vegetable fields. However, its application in the N100 treatment did not result in significant improvement in lettuce yield compared to U100. Thus, the phosphorus and potassium contained in this fertiliser provided little benefit to crop growth because of the high Colwell-P and exchangeable K contents in this soil (Table 1). The presence of 6.5% \( \text{NH}_4^+ \)-N in this fertiliser might have contributed to the higher \( \text{N}_2\text{O} \) emissions than those from the control, which were observed following the application of Nitrophoska but not \( \text{Ca(NO}_3\text{)}_2 \) and \( \text{KNO}_3 \).

The results suggested that substitution of purely \( \text{NO}_3^- \)-based fertilisers for Nitrophoska may further reduce \( \text{N}_2\text{O} \) emissions whilst maintaining the yield and thus warrant more studies.

When choosing the best fertiliser management practices for \( \text{N}_2\text{O} \) emission mitigation in a specific region, both \( \text{N}_2\text{O} \) emissions and economic returns should be considered. In this study, the use of \( \text{NO}_3^- \)-based N fertiliser combined with low intensity irrigation resulted in a considerable reduction in \( \text{N}_2\text{O} \) emission compared to the urea treatments. However, the higher cost of \( \text{NO}_3^- \)-based fertiliser than urea (nearly three times more expensive per kg N) and similar crop yields and crop N uptakes under N100 and U100 treatments may impede implementation of this management option.
Conclusions

Nitrous oxide emissions were low in these fertilised and sparingly irrigated subtropical vegetable cropping regimes in north east Australia during the autumn/winter seasons, while CH$_4$ emissions were negligible. Regression analysis indicated that the magnitude of N$_2$O emissions was mainly regulated by soil temperature and NH$_4^+$ concentration when soil moisture was maintained around field capacity. Reducing irrigation intensity to keep soil WFPS at levels near to field capacity successfully controlled N$_2$O production in soil by decreasing anaerobic conditions favourable for denitrification. Substitution of NO$_3^-$-based fertilisers for urea combined with low intensity irrigation led to significant reductions in N$_2$O emissions during the low rainfall season.

Split application of N fertilisers should have improved synchrony between soil mineral N availability in fertilised treatments and crop demand, to avoid large mineral N accumulation and thus reduce the risk of N losses and high N$_2$O emissions during the growing season. Reducing N fertiliser application from 200 kg N ha$^{-1}$ to 100 kg N ha$^{-1}$ significantly reduced the total N$_2$O emission and did not decrease crop yield. Overall, using NO$_3^-$-based fertiliser in combination with split application and efficient irrigation provides an effective N$_2$O mitigation strategy without losing yield for vegetable production during the low rainfall season.

Acknowledgements

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References


Fig. 1. Rainfall, irrigation and soil moisture (WFPS) at 7-13 cm depth (a) and daily mean air and soil temperature at 5-7 cm depth (b) during the lettuce growing season.
Fig. 2. Soil NH$_4^+$-N and NO$_3^-$-N concentrations in the 0-10 cm (a and c) and 10-30 cm (b and d) depth intervals in all treatments. The black arrows indicate the timing of fertiliser application. Control = no fertiliser; U100 = 100 kg N ha$^{-1}$ as urea; U200 = 200 kg N ha$^{-1}$ as urea; N100 = 100 kg N ha$^{-1}$ mainly as nitrate-based fertilisers.
Fig. 3. Daily (a) and cumulative (b) $\text{N}_2\text{O}$ emissions from different fertiliser treatments in the lettuce field. The black arrows indicate the timing of fertiliser application. Control = no fertiliser; U100 = 100 kg N ha$^{-1}$ as urea; U200 = 200 kg N ha$^{-1}$ as urea; N100 = 100 kg N ha$^{-1}$ mainly as nitrate-based fertilisers.
Fig. 4. Daily (a) and cumulative (b) CH$_4$ emissions from different fertiliser treatments in the lettuce field. Control = no fertiliser; U100 = 100 kg N ha$^{-1}$ as urea; U200 = 200 kg N ha$^{-1}$ as urea; N100 = 100 kg N ha$^{-1}$ mainly as nitrate-based fertilisers.
Table 1: Initial physico-chemical characteristics of the experimental soil

<table>
<thead>
<tr>
<th>Soil Depth (cm)</th>
<th>Bulk Density (g cm(^{-3}))</th>
<th>pH (1:5 water)</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Sand (%)</th>
<th>CEC (eq cmol kg(^{-1}))</th>
<th>Exchangeable(a) K (mg kg(^{-1}))</th>
<th>Colwell(b) P (mg kg(^{-1}))</th>
<th>Total OC (%)</th>
<th>Total N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10</td>
<td>1.17</td>
<td>7.69</td>
<td>41</td>
<td>24</td>
<td>35</td>
<td>37.9</td>
<td>312</td>
<td>136</td>
<td>1.54</td>
<td>0.11</td>
</tr>
<tr>
<td>10-30</td>
<td>1.32</td>
<td>7.79</td>
<td>43</td>
<td>23</td>
<td>34</td>
<td>37.2</td>
<td>207</td>
<td>115</td>
<td>1.53</td>
<td>0.11</td>
</tr>
<tr>
<td>30-60</td>
<td>1.41</td>
<td>7.77</td>
<td>55</td>
<td>15</td>
<td>30</td>
<td>41.2</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>60-90</td>
<td>1.51</td>
<td>7.84</td>
<td>47</td>
<td>15</td>
<td>38</td>
<td>40.1</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
</tbody>
</table>

\(a\) Exchangeable K extracted with 1M NH\(_4\)Cl at pH = 7; \(b\) Colwell P with 0.5M NaHCO\(_3\); \(c\) Total organic carbon was determined by pre-treatment of soil samples with sulphurous acid (H\(_2\)SO\(_3\)) and then dry combustion using a LECO CN analyser (TruMac NO. 830-300-400).
Table 2: Date, type and application rates (kg N ha\(^{-1}\)) of N fertilisers

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Application Rate</th>
<th>Total N Rate (kg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9/05/2012</td>
<td>4/06/2012</td>
</tr>
<tr>
<td>Control</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>U100</td>
<td>50 kg N as urea</td>
<td>25 kg N as urea</td>
</tr>
<tr>
<td>U200</td>
<td>50 kg N as urea</td>
<td>50 kg N as urea</td>
</tr>
<tr>
<td>N100</td>
<td>27 kg NH(_4)-N + 23 kg NO(_3)-N as Nitrophoska(^a)</td>
<td>25 kg N as Ca(NO(_3))(_2)</td>
</tr>
</tbody>
</table>

\(^a\) Nitrophoska Blue Special: Incitec Pivot, Australia; containing 6.5% NH\(_4\)-N and 5.5% NO\(_3\)-N
Table 3: Yield components of lettuce in response to the different N treatments

<table>
<thead>
<tr>
<th>Treatments</th>
<th>TFY (t ha(^{-1}))</th>
<th>TDY (t ha(^{-1}))</th>
<th>FHY (t ha(^{-1}))</th>
<th>HDMY (t ha(^{-1}))</th>
<th>HDM (%)</th>
<th>FWY (t ha(^{-1}))</th>
<th>WDMY (t ha(^{-1}))</th>
<th>WDM (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>34.8 (a)</td>
<td>1.8 (a)</td>
<td>26.7 (a)</td>
<td>1.4 (a)</td>
<td>5.0 (a)</td>
<td>8.1 (a)</td>
<td>0.4 (a)</td>
<td>5.5 (a)</td>
</tr>
<tr>
<td>U100</td>
<td>77.0 (b)</td>
<td>3.1 (b)</td>
<td>64.7 (b)</td>
<td>2.5 (b)</td>
<td>3.9 (b)</td>
<td>12.3 (ab)</td>
<td>0.6 (a)</td>
<td>4.9 (a)</td>
</tr>
<tr>
<td>U200</td>
<td>81.5 (b)</td>
<td>3.2 (b)</td>
<td>67.7 (b)</td>
<td>2.6 (b)</td>
<td>3.8 (b)</td>
<td>13.8 (b)</td>
<td>0.6 (a)</td>
<td>4.8 (a)</td>
</tr>
<tr>
<td>N100</td>
<td>80.9 (b)</td>
<td>3.3 (b)</td>
<td>68.5 (b)</td>
<td>2.7 (b)</td>
<td>3.9 (b)</td>
<td>12.4 (ab)</td>
<td>0.6 (a)</td>
<td>5.2 (a)</td>
</tr>
</tbody>
</table>

\(^{a}\) The different letters in parentheses within a column indicate significant differences between the treatments (P< 0.05)

Abbreviations: TFY, total fresh yield; TDY, total dry yield; FHY, fresh head yield; HDMY, head dry matter yield; HDM, head dry matter; FWY, fresh wrapper yield; WDMY, wrapper dry matter yield; WDM, wrapper dry matter; Control, no fertiliser; U100, 100 kg N ha\(^{-1}\) as urea; U200, 200 kg N ha\(^{-1}\) as urea; N100, 100 kg N ha\(^{-1}\) mainly as nitrate-based fertilisers.
Table 4: Mineral nitrogen concentration (mg kg\(^{-1}\)) in different soil layers at the start and end of the lettuce growing season.

<table>
<thead>
<tr>
<th>Soil Depth (cm)</th>
<th>NH(_4^+)</th>
<th></th>
<th></th>
<th></th>
<th>NO(_3^-)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start</td>
<td>Control</td>
<td>U100</td>
<td>U200</td>
<td>N100</td>
<td>Start</td>
<td>Control</td>
<td>U100</td>
</tr>
<tr>
<td>0-10</td>
<td>0.9(a)</td>
<td>0.7(a)</td>
<td>0.5(a)</td>
<td>1.3(a)</td>
<td>0.6(a)</td>
<td>4.9(a)</td>
<td>1.0(a)</td>
<td>2.5(a)</td>
</tr>
<tr>
<td>10-30</td>
<td>0.6(a)</td>
<td>0.3(a)</td>
<td>0.8(a)</td>
<td>0.2(a)</td>
<td>0.3(a)</td>
<td>7.5(a)</td>
<td>0.8(b)</td>
<td>1.1(bc)</td>
</tr>
<tr>
<td>30-60</td>
<td>1.1(a)</td>
<td>0.5(a)</td>
<td>0.4(a)</td>
<td>0.5(a)</td>
<td>0.5(a)</td>
<td>0.6(a)</td>
<td>0.6(a)</td>
<td>1.0(a)</td>
</tr>
<tr>
<td>60-90</td>
<td>1.2(a)</td>
<td>0.9(a)</td>
<td>0.9(a)</td>
<td>1.2(a)</td>
<td>0.9(a)</td>
<td>0.2(a)</td>
<td>0.7(a)</td>
<td>1.4(b)</td>
</tr>
</tbody>
</table>

\(^a\) The different letters in parentheses within a row (separate for NH\(_4^+\)-N and NO\(_3^-\)-N) indicate significant differences between the treatments (P< 0.05). Control = no fertiliser; U100 = 100 kg N ha\(^{-1}\) as urea; U200 = 200 kg N ha\(^{-1}\) as urea; N100 = 100 kg N ha\(^{-1}\) mainly as nitrate-based fertilisers.
Table 5: Effect of different N treatments on N balance in the crop-soil system (kg N ha$^{-1}$).

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Soil 0-90 cm $N_{\text{min transplanted}}$</th>
<th>N fertiliser</th>
<th>N irrigation</th>
<th>crop N uptake</th>
<th>Soil 0-90 cm $N_{\text{min harvest}}$</th>
<th>N balance$^{a}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control$^b$</td>
<td>41.5</td>
<td>0</td>
<td>1.2</td>
<td>44.4(a)$^c$</td>
<td>17.0(a)</td>
<td>18.7(a)</td>
</tr>
<tr>
<td>U100</td>
<td>41.5</td>
<td>100</td>
<td>1.2</td>
<td>116.6(b)</td>
<td>25.0(a)</td>
<td>-1.1(b)</td>
</tr>
<tr>
<td>U200</td>
<td>41.5</td>
<td>200</td>
<td>1.2</td>
<td>129.5(c)</td>
<td>36.7(b)</td>
<td>-76.5(c)</td>
</tr>
<tr>
<td>N100</td>
<td>41.5</td>
<td>100</td>
<td>1.2</td>
<td>117.2(b)</td>
<td>23.9(a)</td>
<td>-1.6(b)</td>
</tr>
</tbody>
</table>

$^a$ N$_{\text{balance}} = (N_{\text{crop}} + N_{\text{min harvest}}) - (N_{\text{min planting}} + N_{\text{fer}} + N_{\text{irri}})$; $^b$ Control = no fertiliser; U100 = 100 kg N ha$^{-1}$ as urea; U200 = 200 kg N ha$^{-1}$ as urea; N100 = 100 kg N ha$^{-1}$ mainly as nitrate-based fertilisers; $^c$ The different letters in parentheses within a column indicate significant differences between the treatments ($P<0.05$)