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Nitrogen deposition and its contribution to nutrient inputs to intensively managed agricultural ecosystems

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Abstract. Interest in nitrogen inputs via atmospheric deposition to agricultural ecosystems has increased recently, especially on the North China Plain because of extremely intensive agricultural systems and rapid urbanization in this region. Nitrogen deposition may make a significant contribution to crop N requirements but may also impose a considerable nutrient burden on the environment in general. We quantified total N deposition at two locations, Dongbeiwang near Beijing and Quzhou in Hebei province, over a two-year period from 2005 to 2007 using an ^{15}N tracer method, the integrated total N input (ITNI) system. Total airborne N inputs to a maize–wheat rotation system at both locations ranged from 99 to 117 kg N·ha^{-1}·yr^{-1}, with higher N deposition during the maize season (57–66 kg N/ha) than the wheat season (42–51 kg N/ha). Plant available N from deposition for maize and wheat was about 52 kg N·ha^{-1}·yr^{-1}, accounting for 50% of the total N deposition or 31% of total N uptake by the two crop species. In addition, a correction factor was derived for the maize season to adjust values obtained from small pots (0.057 m^2) compared with field trays (0.98 m^2) because of higher plant density in the pots. The results indicate that atmospheric N deposition is a very important N input and must be taken into account when calculating nutrient budgets in very intensively managed agricultural ecosystems.

Key words: atmospheric N deposition; ^{15}N dilution method; plant-available N from deposition; North China Plain.

INTRODUCTION

Atmospheric nitrogen (N) deposition refers to the process whereby airborne nitrogenous compounds (inorganic N including NH_3, particulate NH_4^+, NO_x, HNO_3, and particulate NO_3^-, and organic N including urea, amines, proteins, and nucleic acids) are deposited on the Earth's surface by wet deposition and/or dry deposition. Dry deposition occurs by diffusion (e.g., NH_3) and Brownian motion (e.g., fine particle NH_4^+) and to a much lesser extent by sedimentation or impaction (coarse particles, size >2.5 μm). In contrast, wet deposition occurs by rainout (in-cloud processes) and below-cloud scavenging (washout). In addition, plants can absorb N directly through stomatal uptake (Lockyer et al. 1986, Wollenweber and Raven 1993). Atmospheric N deposition has become an important component in the global N cycle with increasing anthropogenic atmospheric reactive N emissions (Vitousek et al. 1997, Galloway et al. 2004). Elevated N deposition will reduce the biodiversity and ecological functions of various ecosystems via acidification and eutrophication (Stevens et al. 2004, Phoenix et al. 2006, Clark and Tilman 2008). However, most studies on N deposition have focused on the impact of N deposition on natural ecosystems (e.g., Nadelhoffer 2001, Stevens et al. 2004, Duce et al. 2008). There have been few studies evaluating the contribution of N deposition to intensive agricultural ecosystems (Fahey et al. 1999).

The development of intensive agriculture has been characterized by over fertilization, high stocking rates of livestock, rapid growth in energy consumption, and increasing emissions of reactive N in both reduced and oxidized forms to the atmosphere with subsequent redeposition onto the surfaces of terrestrial and marine ecosystems. It has been estimated that more than 55 Tg NH_3-N are emitted annually from terrestrial ecosystems into the atmosphere, of which 50–75% are derived from farm animals and fertilizers (Mosier 2001). In China, NH_3 and NO_x emissions were estimated to be up to 10.4 Tg NH_3-N and 3.4 Tg NO_2-N in 2000, derived mainly from agricultural activities and industrial emissions (including transportation and power plants), respec-

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tively (data *available online*).[6] All these losses represent a considerable burden on the environment. Nitrogen fertilizer recommendations must be modified to reduce the N surplus (defined as fertilizer N input minus crop N removal) in Chinese agriculture, which was about 120 Tg N in total during the 45 years from 1949 to 1993 (Zhu 1998).

The North China Plain (NCP), an area that includes Beijing, can be seen as China's granary because it is the region of highest agricultural productivity in the country. It is particularly noteworthy for overuse of fertilizer- and manure-N, resulting in large reactive N emissions due to the rapid development of intensive agriculture as well as the transportation industry. Winter-wheat–summer-maize double cropping is the main rotation system in this region, with high fertilizer N application rates of >500 kg $\mathrm{N \cdot ha^{-1} \cdot yr^{-1}}$ in conventional farming practice (Ju et al. 2006). Most of the soils are calcareous, with pH values ranging from 7.5 to 8.0, leading to conditions with high potential for NH_3 volatilization. Intensive animal production (mostly pigs and poultry) has also increased in the region since the late 1980s. Inappropriate disposal of animal wastes is a serious environmental problem because most livestock farms lack waste storage or treatment systems such as manure lagoons or storage tanks. According to the China Agricultural Yearbook (Anonymous 1990–2006), livestock densities in Beijing city are even higher than in The Netherlands (Eurostat Newsletter 1998) or in New York State in the United States (Fahey et al. 1999). In addition, the number of motor vehicles in Beijing city has increased from fewer than 30 000 in 1966 to more than 3 million in 2007 (Yi 2007). All these changes will contribute to relatively high NH_y and NO_x emissions (Olivier et al. 1998). This is extremely consistent with the tropospheric NO_2 concentration over central and east China observed from space (Richter et al. 2005). In turn, N emissions are likely to affect atmospheric N deposition to land surfaces, crop canopies, and water bodies.

It was found that annual bulk (i.e., mostly wet) inorganic N deposition was up to 30.6 kg N/ha in the Beijing area (Liu et al. 2006) and averaged 27 kg $\mathrm{N \cdot ha^{-1} \cdot yr^{-1}}$ across the NCP (Zhang et al. 2008*a*). On the other hand, N wet plus dry deposition (excluding NH_3 and organic N) averaged 7–9 kg $\mathrm{N \cdot ha^{-1} \cdot yr^{-1}}$ in the eastern United States (U.S. EPA 2007) and 14–21 kg $\mathrm{N \cdot ha^{-1} \cdot yr^{-1}}$ in Western Europe (Holland et al. 2004), the two regions typically considered to have the highest N deposition in the world. The daily concentration of inhalable particulate matter in Beijing was found to average 161 $\mu g/m^3$ in 2006 (Beijing Municipal Environment Protection Bureau 2007), far exceeding the European threshold level (i.e., the concentrations of pollutants in the atmosphere above which direct adverse effects on receptors, such as plants, ecosystems, or materials may occur according to present knowledge) of 50 $\mu g/m^3$ as a 24-hour mean and the Chinese threshold level of 150 $\mu g/m^3$. Total airborne N inputs will, of course, be much larger than bulk deposition, especially if both inorganic and organic N deposition and the direct uptake of atmospheric N species by aerial parts of plants are included (Russow et al. 2001). Nitrogen balances from a long-term field experiment (LTE) in Changping, Beijing have confirmed such high N inputs, i.e., about 83 kg N/ha annually (He et al. 2007). Accurate determination of the total N deposition to this agricultural area is therefore urgently needed so that the scale of the pollution problem can be more accurately assessed and farmers can be provided with more accurate predictions of crop N fertilizer requirements.

Unfortunately, the standard methods currently used for direct monitoring of N deposition, such as wet-only and bulk collectors, underestimate N inputs from the atmosphere because they fail to take into account dry deposition of N, the direct uptake of atmospheric N by aerial parts of plants (Russow et al. 2001), and organic N (Cape et al. 2001). Methods to measure and calculate dry N deposition, particularly gases and aerosols (e.g., NH_3, NO_x, and/or HNO_3) require complicated equipment and real-time weather data (Sievering 1987, Wyers et al. 1992). Furthermore, there are large variations or uncertainties for the concentrations and deposition velocities of reactive N gases and aerosols. To simplify the measurements, a new scheme, the ITNI (integrated total nitrogen input) system, was developed based on a ^{15}N isotope dilution technique (Mehlert et al. 1995) and tested in the field (Weigel et al. 2000). It was found to be the only technique that determined total atmospheric N inputs, including organic N and inorganic N from wet, dry (gas and particulate matter) deposition and direct N uptake by aboveground plant parts. However, pot experiments are used in the ITNI system and correct extrapolation of the results from pots to the field scale is very important. Most extrapolations of the airborne N inputs from a vessel up to an area of 1 ha have been performed based on a vessel surface area of 0.038 m^2 by Russow's group (Russow et al. 2001, Böhme et al. 2002, 2003). However, this can still lead to an overestimation of the airborne N inputs if the plant densities in the pots are different from those in actual field conditions (e.g., maize). It is therefore crucial to find a proper extrapolation method when using the ITNI system.

This paper describes a study that was carried out to determine the best method of extrapolating pot experiment data using the ITNI system to simulate field conditions and then to obtain an accurate measure of total airborne N inputs to a typical intensively managed maize–wheat rotation on the NCP for the development of a fertilizer recommendation system. We have also re-evaluated some of the initial data published previously by He et al. (2007).

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[6] ⟨http://www.jamstec.go.jp/frsgc/research/d4/emission.htm⟩

MATERIALS AND METHODS

Study sites

The experimental work was conducted at two locations, both of which are important areas for wheat and maize production. One was at Dongbeiwang (DBW) on the outskirts of Beijing where intensive agriculture and high traffic density exist together (see Plate 1). The other was at Quzhou (QZ) in Hebei province, about 500 km south of Beijing, where intensive agriculture is the most important source of N pollution. The two locations are shown in Fig. 1.

Trial installation

The ITNI system is based on ^{15}N isotope dilution and allows the inclusion of direct N uptake by the plant as well as the absorption of gaseous N compounds by the soil-plant system (Russow et al. 2001). The receiving pool (i.e., the sand–plant system, see Fig. 2) is labeled with ^{15}N solution and N deposition in the sand/plant system leads to the dilution of the ^{15}N tracer with the natural abundance N. A manual ITNI system (Fig. 2) was used consisting of four components: a vegetation pot (inner diameter 27 cm and height 30 cm) containing 18 kg quartz sand, the indicator plant (maize or wheat), a buffer vessel, and the ^{15}N-labeled solution. At the start of the experiment the sand–plant system was labeled with ^{15}N in the form of $Ca(^{15}NO_3)_2$ at a ^{15}N abundance of 5 atom%. During the growth of the plants the tracer was diluted by inputs of atmospheric N and the amount of N deposited from the atmosphere was calculated from the dilution. The N-free quartz sand was supplied with ^{15}N-labeled nutrient solution added manually and regularly from a buffer vessel. Surplus nutrient solution and rainwater were returned to the buffer vessel. Nutrients were thus recycled and the system was exposed to the atmosphere only at the surface of the pot and the aerial parts of the plants. The composition of the nutrient solution was (mmol/L): 0.75 K_2SO_4, 0.65 $MgSO_4$, 0.1 KCl, 2.0 $Ca(NO_3)_2$, 0.25 KH_2PO_4, 1×10^{-3} H_3BO_3, 1×10^{-3} $MnSO_4$, 1×10^{-4} $CuSO_4$, 1×10^{-3} $ZnSO_4 \cdot 7H_2O$, 5×10^{-6} $NaMoO_4$, and 0.1 Fe-EDTA.

Maize (*Zea mays*) was sown at the end of May and harvested in the middle of September 2005, and then wheat (*Triticum aestivum* L.) was sown at the end of September 2005 and harvested at the end of May 2006. This experimental period covered the whole year from June 2005 to May 2006. Then the experiment was repeated beginning with winter wheat sown at the beginning of October 2006 and harvested at the end of May 2007 and with maize sown at the beginning of June and harvested at the end of September 2007. The repeat experiment covered the period from October 2006 to September 2007.

The pot surface area was 0.057 m^2 and the number of plants per pot was 1 for maize and 24 for wheat, which corresponded to 17.5 plants/m^2 for maize and 421 plants/m^2 for wheat in the field. However, the conventional density in the field on the NCP is 6 plants/m^2 for maize and 450 plants/m^2 for wheat, rather less than that in the pot for maize and similar to that in the pot for wheat. Therefore, in order to simulate field conditions, six maize plants were planted in a quadrate concrete tray with a surface area of ~0.98 m^2 (1.4 m × 0.7 m) and a height of 0.4 m from the beginning of June to the middle of September of 2006 and 2007 at DBW. At the same time pot experiments were conducted as in the previous season to compare the data with those from the trays.

All treatments in these experiments (pots and trays) were replicated four times and pots were placed on the soil surface. Maize and wheat were also planted around the pots and trays to simulate commercial field conditions. In addition, all of the measurements were made within a large typical agricultural field in which maize and wheat were grown approximately simultaneously with the plants in the pot experiments. Thus, on the whole, the air chemistry over the whole agricultural field was relatively consistent to avoid the influence of uncontrolled factors on N deposition.

Sampling, measurement, and calculation

At the end of each growing period maize and wheat plants were harvested together with sand and nutrient solution. The ^{15}N abundance in the sand, nutrient solution, and the roots, grains, leaves and straw of the plants was analyzed by mass spectrometry (DELTA-PLUS XP, Thermo Finnigan, Thermo Electron Corporation, Bremen, Germany).

The ITNI system is based on the isotopic ^{15}N dilution method where the inputs of atmospheric N will lead to a dilution of the ^{15}N tracer in the sand/plant system. The amount of N deposited can be calculated as follows (Russow et al. 2001):

$$\mathrm{AdN} = \mathrm{ANnet} = \mathrm{N_S} \times (1 - a'_{\mathrm{S}}/a'_{\mathrm{T}}) - \mathrm{N_o} \qquad (1)$$

where AdN is atmospherically derived N; ANnet is net atmospheric N deposition; a' is the measured ^{15}N abundance of samples; thus a', the excess ^{15}N abundance of samples, is a – 0.366%); N is amount of N in milligrams; S is system, T is tracer, and o is seed.

AdN consists of two fractions. One is the part measured in the sand and the remaining nutrient solution, and the other is the part measured in the plant. There is an airborne N exchange between the sand and the plant, i.e. airborne N in the sand is absorbed by the plant and airborne N from the plant is released into the sand in the form of root exudates. Hence, the ITNI system cannot distinguish between airborne-N inputs into sand and plant. We therefore regarded the airborne N measured in the plant as the plant available N from deposition. This can be calculated as follows:

$$\mathrm{AdPN} = \mathrm{N_p} \times (1 - a'_{\mathrm{P}}/a'_{\mathrm{T}}) - \mathrm{N_o} \qquad (2)$$

where AdPN is plant available N from deposition.

The ITNI system is based on a pot experiment, from which the results must be extrapolated to the field.

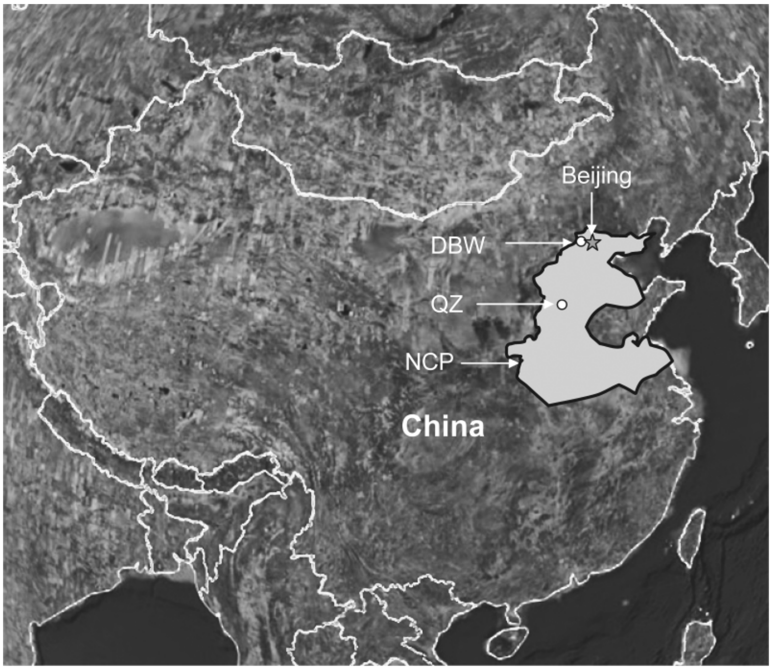

FIG. 1. Location of the two experimental sites Dongbeiwang (DBW) and Quzhou (QZ) on the North China Plain (NCP).

Therefore, the method of extrapolation is critical. The basic methods of extrapolation outlined below have been described in greater detail by Russow and Böhme (2005). Here we just introduce them briefly.

First, the area method (ratio between the area of the field plot and the area of the pot):

$$\text{ANDa}\ [\text{g N}\cdot\text{ha}^{-1}\cdot\text{d}^{-1}] = \text{AdTN}\ [\text{mg N}\cdot\text{pot}^{-1}\cdot\text{d}^{-1}]\times 10/A_{\text{pot}}\ [\text{m}^2] \quad (3)$$

where ANDa is total atmospheric N deposition calculated with the area method; A_{pot} is pot area (0.057 m^2); and AdTN is net N input, including that in the sand and solution (AdSN) and plant (AdPN). This is regarded as the simplest method of extrapolation because only the pot area A_{pot} is required as an additional parameter. However, the influence of the dry matter (DM) production of the monitored plant is neglected and this is the main disadvantage of this method.

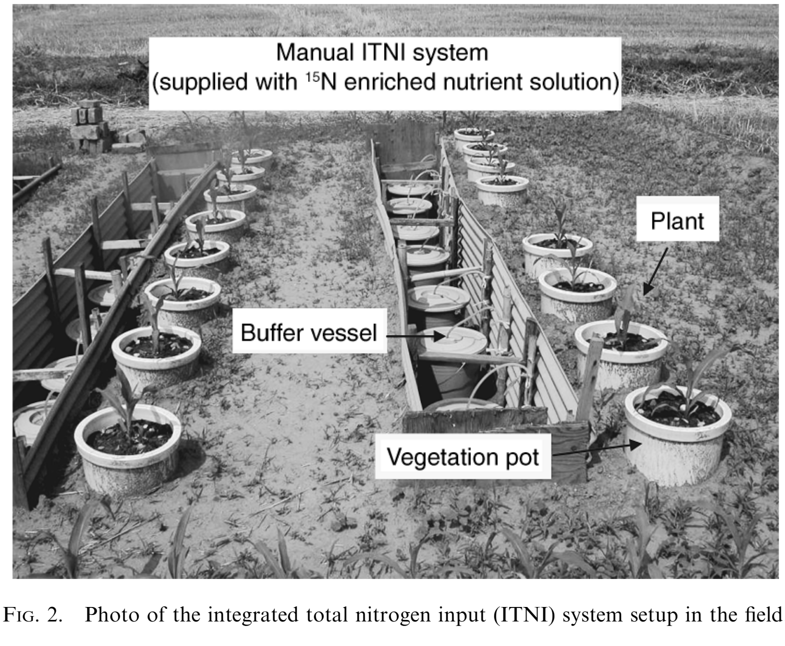

FIG. 2. Photo of the integrated total nitrogen input (ITNI) system setup in the field.

TABLE 1. Comparison of extrapolation of total N deposition from pots to the field scale using the area (ANDa) and the plant number (ANDn) approaches.

Crop, period, and site	ANDa (kg N/ha)	Number of plants/m^2		ANDn (kg N/ha)	ANDn/ANDa
		Pot	Field		
Maize					
Jun–Sep 2005†					
DBW	84.7	17	6	29.0	0.34
QZ	91.4	17	6	31.2	0.34
Jun–Sep 2006					
DBW	87.9	17	6	30.1	0.34
DBW ‡	47.6	6	6	46.6	0.98
Jun–Sep 2007					
DBW	131.0	17	6	44.8	0.34
DBW‡	67.5	6	6	66.2	0.98
QZ	157.8	17	6	54.0	0.34
Wheat					
Oct 2005–May 2006					
DBW	44.8	421	450	47.9	1.07
QZ	40.2	421	450	43.0	1.07
Oct 2006–May 2007					
DBW	39.2	421	450	41.9	1.07
QZ	61.2	413	450	65.4	1.07

Note: Abbreviations are: DBW, Donbeiwang; QZ, Quzhou.

† Data for the 2005 maize season are from He et al. (2007).

‡ Six maize plants were planted in each tray at the DBW site with a surface area of 0.98 m^2; others were planted in pots with a surface area of 0.057 m^2.

Second, the plant number method (ratio between the number of plants in the field plot and the number of plants in the pot):

$$\text{ANDa}\ [\text{g N} \cdot \text{ha}^{-1} \cdot \text{d}^{-1}] = \text{AdTN}\ [\text{mg N} \cdot \text{pot}^{-1} \cdot \text{d}^{-1}] \times Z_\text{F} \times 10/Z_\text{pot} \times A_\text{pot}\ [\text{m}^2] \qquad (4)$$

where Z_F is number of plants in the field per m^2 and Z_pot is number of plants per pot (plants per m^2); ANDn is total atmospheric N deposition calculated with the plant number method. The number of plants per pot (Z_pot, e.g., converted to 1 m^2 as in Eq. 3) and the actual plant density in the field, $Z_\text{F,}$ are required additional parameters in this method.

Statistical analysis

Statistical analysis of the data including total plant biomass, total N deposition and plant available N from deposition between monitoring sites or years was conducted using one-way analysis of variance. Least significant difference at the 5% level or another stated statistic was calculated if significant differences between sites or years were found.

RESULTS

Extrapolation of total N deposition from the pot to the field scale

The results of extrapolation using the area method (ANDa) and the plant number method (ANDn) from pot experiments carried out from 2005 to 2007 are shown in Table 1. There are large differences in estimated N deposition between ANDa and ANDn for maize planted in pots with a surface area of 0.057 m^2 and the ratio of ANDn/ANDa was only 0.34. However, similar results were obtained using both extrapolation techniques if the maize was planted in trays and wheat was planted in pots, resulting in ratios of ANDn/ANDa of about 0.98 and 1.07, respectively. Using the area extrapolation approach, the ratio of the ANDa value of maize planted in trays to that planted in pots was only 0.54 in 2006 and 0.52 in 2007 (calculated from Table 1), with a mean ratio 0.53. However, using the plant number approach the ANDn value of maize planted in trays was 1.55 times that of pot-grown maize in 2006 and the value in 2007 was 1.48 (calculated from Table 1), resulting in a mean value of 1.51.

TABLE 2. Dry matter yield (g) per pot of maize and wheat at the two locations in north China.

Monitoring crop and period	Donbeiwang	Quzhou
Maize		
Jun 2005–Sep 2005	164.5^{bc} ± 38.1	149.2^{c} ± 5.3
Jun 2007–Sep 2007	311.9^{a} ± 26.0	170.1^{b} ± 6.7
Wheat		
Oct 2005–May 2006	54.3^{a} ± 4.7	33.2^{b} ± 3.4
Oct 2006–May 2007	35.0^{b} ± 2.8	28.7^{b} ± 5.2

Note: Values with different letters in the same column or line within the same crop denote a significant difference at the 5% level by least significant difference.

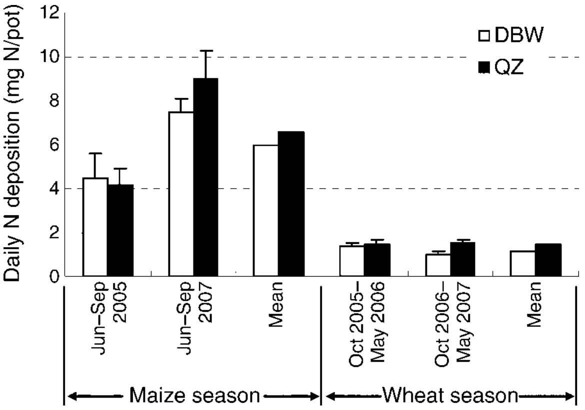

FIG. 3. Daily mean N deposition rates per pot at two locations in maize and wheat growing seasons. Error bars represent standard errors.

Total N deposition and plant available N deposition in the maize–wheat system

Table 2 shows the dry matter (DM) of maize and wheat per pot during the two full summer maize–winter wheat rotation cycles. For the year 2007 the DM yield of maize was significantly higher than in 2005 at both locations. The DM yield of wheat during the period October 2005 to May 2006 was significantly higher than that during the period October 2006 to May 2007 at DBW. There was no obvious difference in DM yield of wheat at QZ over the two years. However, the DM yield of 2007 maize and 2005–2006 wheat was significantly higher at DBW than at QZ. To a large extent, the DM yield of monitoring plants in this study showed some relationship with N deposition flux, which will be illustrated in the Discussion.

The N deposition per day and per pot (Fig. 3) of maize during the period June–September 2005 amounted to 4.47 mg N·d^{-1}·pot^{-1} at DBW and 4.17 mg N·d^{-1}·pot^{-1} at QZ, which was significantly lower than the 7.47 mg N·d^{-1}·pot^{-1} at DBW and 8.99 mg N·d^{-1}·pot^{-1} at QZ during the period June–September 2007. However, there was no significant difference for the N deposition per day or per pot of wheat between the two years. The mean values over the two years for wheat were 1.15 mg N·d^{-1}·pot^{-1} at DBW and 1.47 mg N·d^{-1}·pot^{-1} at QZ.

Fig. 4 shows the estimated total N deposition by extrapolating from pots to the field using the area method, and the extrapolation for maize, which was made using the mean correction factor of 0.53 as well. The average values of the total N inputs during the maize season over these two years were 57.2 kg N/ha at DBW and 66.0 kg N/ha at QZ, and the mean values during the wheat season were 42.0 kg N/ha at DBW and 50.7 kg N/ha at QZ. The average total airborne N inputs during the whole maize–wheat rotation period were thus 99.2 kg N/ha at DBW and 117 kg N/ha at QZ. Statistical analysis of the results of these two years revealed that the total N deposition in the maize season was significantly higher in 2007 than in 2005 at both locations, while total N deposition in the 2006–2007 wheat season was significantly higher than in the 2005–2006 wheat season only at QZ. Bulk (primarily wet) deposition of ammonium, nitrate, and organic N was measured simultaneously using a rain gauge equipped with a bottle-funnel combination at both locations over the two years. The mean value of bulk N deposition during these two rotation cycles was only 36 kg N/ha at DBW

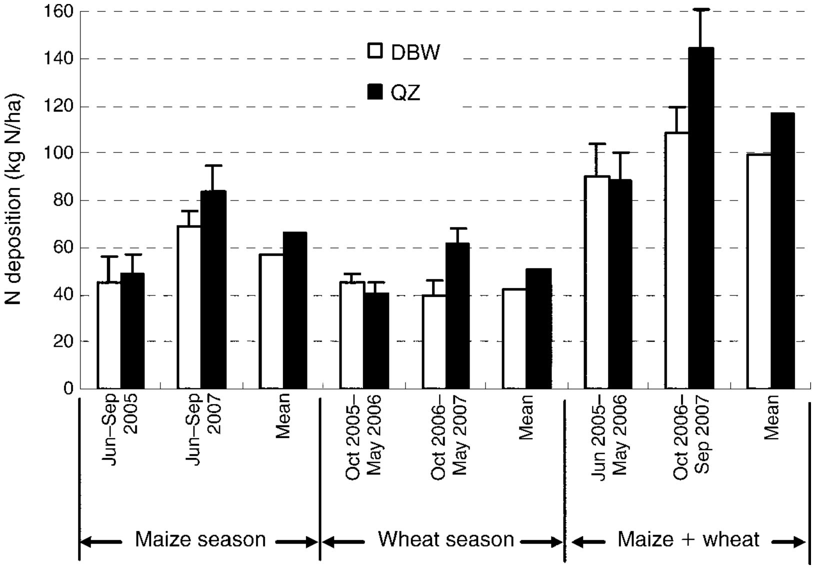

FIG. 4. Total system N deposition during the two maize–wheat rotation cycles from June 2005 to September 2007. Error bars represent standard errors.

TABLE 3. Comparison of different N deposition measurements on the North China Plain from June 2005 to September 2007.

	Donbeiwang			Quzhou		
Type of deposition	Jun 2005–May 2006	Oct 2006–Sep 2007	Mean	Jun 2005–May 2006	Oct 2006–Sep 2007	Mean
Bulk† (kg N·ha^{-1}·yr^{-1})	38.7	32.3	35.5	22.6	21.0	21.8
ITNI‡ (kg N·ha^{-1}·yr^{-1})	89.7	109	99.2	88.6	145	117
Bulk/ITNI	0.43	0.30	0.36	0.25	0.15	0.20
Precipitation (mm)	508	464	486	340	345	343

† Bulk deposition here mainly means wet deposition, including inorganic and organic N. Data are adapted from Zhang et al. (2008*a*, *b*) and Song (2008).

‡ Integrated total nitrogen input.

and 22 kg N/ha at QZ, accounting for 36% of the N deposition measured with the ITNI-system at DBW and 20% of that at QZ (Table 3). Ammonium, nitrate and organic N in precipitation averaged 57%, 29%, and 14% of the total bulk deposition across the two locations over the two years (Zhang et al. 2008*b*, Song 2008).

The amount of plant available N from deposition for maize and wheat was estimated in addition to total N deposition (Fig. 5). The mean values of the plant available N from deposition over these two years for maize were 34.5 kg N/ha at DBW and 23.0 kg N/ha at QZ, and those for wheat were 16.6 kg N/ha at DBW and 30.3 kg N/ha at QZ. For the year 2007, the plant available N from N deposition of maize was significantly higher than that of 2005 at both locations. Plant available N from N deposition of wheat during the period October 2005 to May 2006 was significantly higher than that during the period October 2006 to May 2007 at QZ and the opposite trend occurred at DBW. The average total plant available N from deposition during the whole maize–wheat rotation period was 51 kg N/ha at DBW and 53 kg N/ha at QZ, accounting for 52% of the total N deposition at the former site and 45% at the latter (Figs. 4 and 5).

Furthermore, the contribution of atmospheric N deposition to the total N content of the sand–plant system per pot over these two years was 28.9% at DBW and 28.1% at QZ for maize, with corresponding values for wheat at DBW and QZ of 22.5 and 44.4% (Fig. 6). In the case of maize the value in 2005 was markedly higher than in 2007 at both locations and the opposite trend was shown by wheat after statistical analysis.

DISCUSSION

Besides the area (ANDa) and plant number extrapolation methods (ANDn) from pot data to field, there is another method named the combined area/DM method (Russow and Böhme 2005). In this method, three additional parameters, the DM production in the pot (DM$_{pot}$), the actual DM production in the field (DM$_F$), and the ratio between DM$_{pot}$ and DM$_F$, are required for extrapolation. And the combined area/DM method was tested and regarded as the best compared to the other two if the DM$_{pot}$ and DM$_F$ are similar (Russow and Böhme 2005). However, there are usually large differ-

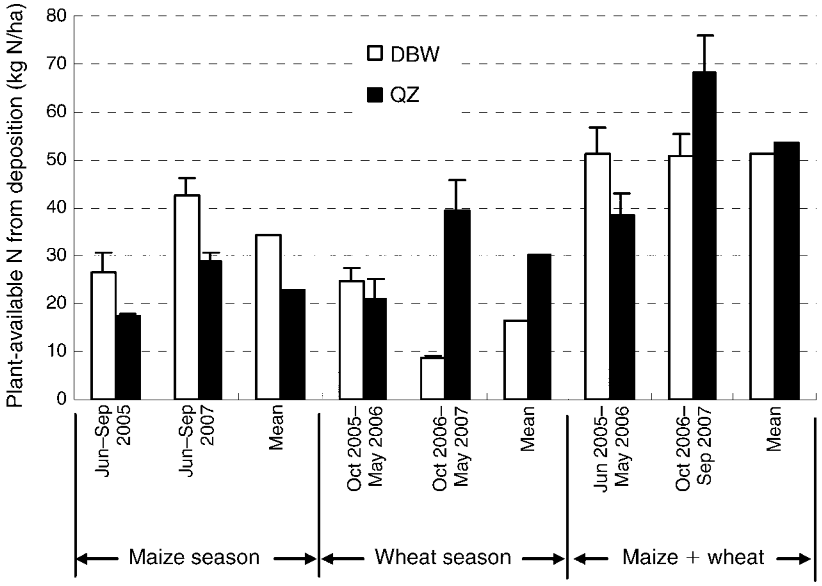

FIG. 5. Plant available N from deposition during the two maize–wheat rotation cycles from June 2005 to September 2007. Error bars represent standard errors.

ences between DM_{pot} and DM_F. In addition, DM_F figures are usually unavailable if the monitoring crops in the pots are harvested earlier to avoid gaseous NH_3 losses. The combined area/DM method of extrapolation was therefore not tested in the present study. Comparing the area method (ANDa) with the plant number method (ANDn), similar results were found when the plant density in the pots approximated that used in the field, e.g., for wheat planted in pots with a surface area about 0.057 m^2 and maize in trays with a surface area of about 0.98 m^2 (Table 1). An ANDn/ANDa ratio of 0.34 was found when there was a large difference in plant density between the pots and the field, as for maize. Due to the average ratio of the ANDa and ANDn values of maize planted in trays to the values in pots (0.53 and 1.51), both of the extrapolation methods failed for plants with high space requirements such as maize. The area extrapolation method would lead to an overestimation and the plant number extrapolation method would lead to an underestimation. Therefore, no matter which method was used for extrapolation from pots to the field, if monitoring crops have high space requirements (such as maize), a correction factor was needed and could only be obtained by simulating commercial field conditions, especially for plant density. The correction factor will depend largely upon pot area or the difference in plant density between pots and trays (reflecting field conditions) because the atmospheric environment and nutrient solution management are the same for both pot and tray systems. Similar results (0.54 vs. 0.52) were obtained from years 2006 and 2007 for the ratio of the ANDa value of maize planted in trays to that of maize in pots, indicating that 0.53 was a reliable value for the correction factor in this study. The area extrapolation method was regarded as the simplest method because only the pot area A_{pot} was required as an additional parameter and it was easier to plant maize in pots than in trays. Considering the convenience of extrapolation, the average factor of 0.53 would need to be taken into account to correct all the values of maize in pots with area of 0.057 m^2 if the area extrapolation method was used under similar conditions.

For maize, the DM yield per pot, the N deposition per day and per pot, and the total airborne N deposition per hectare at both locations were markedly lower in 2005 than in 2007 (Table 2), indicating that the total airborne N deposition was related to the DM yield. This agrees well with our previous measurements (He et al. 2007) and with the findings of Böhme et al. (2003). Thus, higher biomass production together with larger effective leaf area and higher coverage of the soil surface by the plant leaves seems to stimulate plants to take up more N from the atmosphere.

Our two-year results show that the average total airborne N inputs during the maize season at both locations were approximately 62 kg N/ha, accounting for 57% of that during the whole maize–wheat system, only slightly higher than that during the wheat season (46 kg N/ha and 43% of the annual total deposition). However, considering the much greater length of the wheat season (about twice that of maize), we can conclude that the daily N deposition is largely higher in the maize season than in the wheat season (Fig. 3). The reasons could be related to differences in climatic conditions, emission rates, vegetative characteristics (e.g., Sievering 1987, Geßler et al. 2000, Russow and Böhme 2005) and so on that differ between the two crops and seasons. For example, NH_3 volatilization rates are much higher in summer than in winter or spring. In addition, the real growing period for winter wheat is only about 4 months in the NCP condition, which may also lead to the lower daily N deposition in the wheat season.

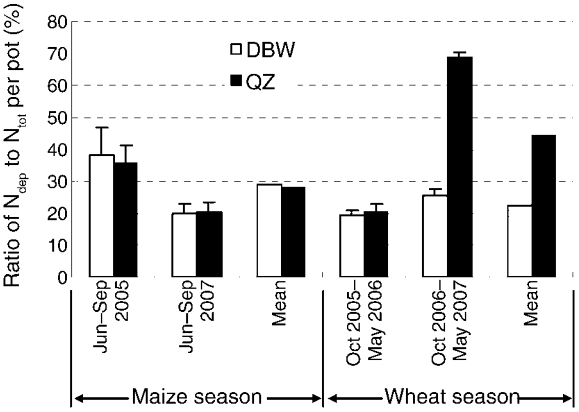

FIG. 6. Ratio of N from deposition (N_{dep}) to total N (N_{tot}) content per pot.

The average total airborne N inputs to the whole maize–wheat rotation system from ITNI measurements were 99 kg $N \cdot ha^{-1} \cdot yr^{-1}$ at DBW and 117 kg $N \cdot ha^{-1} \cdot yr^{-1}$ at QZ, which was several times higher than the bulk N deposition at DBW (36 kg $N \cdot ha^{-1} \cdot yr^{-1}$) and QZ (22 kg $N \cdot ha^{-1} \cdot yr^{-1}$) (Table 3). Such large differences between ITNI-based deposition and bulk/wet deposition suggest that dry deposition of N (including direct N uptake by the aerial plant parts) may make a major contribution (57–85%) to the total N deposition on the NCP. Our ITNI measurement results indicate very heavy atmospheric reactive N pollution and deposition (especially dry deposition) occurring on the NCP compared with central Germany (Weigel et al. 2000). Studies (Ham and Tamiya 2006, Zhang et al. 2008*b*) have shown that ammonium N (including NH_3 and particulate NH_4^+) is the major form of N deposited while nitrate N and soluble organic N make smaller contributions to the total N deposition in intensive agricultural regions. However, the contributions of wet, dry deposition and direct N uptake by the aerial plant parts to the total N deposition are still unclear because the ITNI-system cannot distinguish N forms between direct deposition and uptake by the plant. Further research is therefore required to quantify their proportional contributions to

PLATE 1. Corn before harvest at Dongbeiwang, Beijing. Photo credits: L. Xuejun.

total deposition by carrying out the ITNI method, bulk/wet-only collectors, and gases as well as aerosols deposition measurements simultaneously.

On a global scale, the North China Plain represents a "hotspot" of atmospheric N deposition. The results from our study suggest that previous estimates of global N deposition may underestimate the N deposition in China, especially in regions of extreme agricultural intensification such as the NCP (e.g., Dentener et al. 2006, Galloway et al. 2008). If we assume a mean total airborne N deposition of 90 kg $N \cdot ha^{-1} \cdot yr^{-1}$ based on our results, the total N deposition on the NCP (with a total area of about 34 million ha) could be up to 3 Tg N/yr. This airborne N deposition is comparable to that in the whole conterminous United States (3.7–4.5 Tg N/yr) but lower than that in Western Europe (8.4–10.8 Tg N/yr) (Holland et al. 2004). Nevertheless, it is a very important N input for crops such as maize and wheat. Meanwhile, the ecological impact of such heavy atmospheric N pollution and deposition in China and other regions of the world must be taken into account. As noted earlier, airborne N deposition has been an important part of the global N cycle, although much of the N is deposited close to the emission sources. However, some forms of N such as fine particles of $(NH_4)_2SO_4$ and NH_4NO_3 have low deposition velocities and prolonged atmospheric residence times and can be transported to areas far from the emission sources. Irwin and Williams (1988) reported that the transport distance of particulate ammonium and nitrate may be as far as 2500 km. Thus the high emission of reactive N from the NCP will affect not only China but also other regions such as Eastern Asia because these reactive N gases and particles can be transported globally. The major negative consequences of N deposition include acidification (Falkengren-Grerup 1986, Vitousek et al. 1997), eutrophication (Burkart and James 1999, Rabalais et al. 2002), and loss of biodiversity (Stevens et al. 2004). We speculate that such high N deposition in north China may contribute to the above environmental degradations in China and the surrounding regions, although we have not evaluated the ecological impacts of N deposition in detail. This will be the aim of future studies.

Total N deposition rates of 99 kg $N \cdot ha^{-1} \cdot yr^{-1}$ at DBW and 117 kg $N \cdot ha^{-1} \cdot yr^{-1}$ at QZ were measured for the whole maize–wheat rotation (Fig. 4), but only 52 kg $N \cdot ha^{-1} \cdot yr^{-1}$ was used directly by maize and wheat plants, accounting for approximately 50% of total N deposition (Fig. 5). The remaining 50% was found in the sand and nutrient solution and was not utilized by the current crop. The relatively low utilization efficiency of N deposition can be explained by observation that the occurrence of airborne N deposition does not match crop growth or N uptake demand. For instance, heavy precipitation (e.g., >30 mm) often occurs within a few hours in the summer (maize season) and dry N deposition (including dust storms) usually occurs in winter and early spring when wheat growth is slow. This explains why nearly half of the N deposition still remained in the sand/solution systems at crop harvest. In addition, the N released from root exudates during the crop growing season may also make a small contribution to residual deposited N in the sand/solution systems. Thus the plant available N from deposition is a "net" plant utilized N deposition. From Figs. 4 and 5 we can also conclude that there is a positive correlation between the amount of total airborne N deposition and the plant available N received from N deposition. Except for winter wheat at DBW, there was no significant difference in the ratio of plant available N from deposition to the total N deposition between the two cropping years (2005–2006 and 2006–2007). The ratio of plant available N deposition to the total N deposition therefore does not seem to be affected by the shoot DM yield of the crops. We noticed that plant available N from deposition and the ratio of N deposition to total system N per pot were much lower at DBW than at QZ in the 2006–2007 wheat season (Figs. 5 and 6). The reasons may include (1) similar growth of wheat but higher N utilization from deposition at QZ than at DBW; (2) lower total airborne N input but higher total N uptake at DBW than at QZ during the October 2006 to May 2007 period.

The contribution of atmospheric N to the total N content of the sand–plant system per pot for maize and wheat ranged from 23% to 44% (Fig. 6), falling within the range found in other studies of about 4–77% for NH_3 (Lockyer and Whitehead 1986, Wollenweber and Raven 1993) compared to 10–15% for NO_2 (Muller et al. 1996).

CONCLUSIONS

Nitrogen deposition from the atmosphere is a large component of the nitrogen cycle in regions where very intensive agriculture is practiced and must be taken into account when assessing the environmental and ecological effects of anthropogenic sources of N. When using the ITNI system and extrapolating from the pot to the field scale, the area method and the plant number method produce similar results only when the plant density in the pots approximates that in the field. In order to obtain reliable results for a crop species such as maize with a high space requirement, a correction factor is needed. This varies depending upon the atmospheric environment and experimental system, such as pot area, plant density in pots and field, and can be determined only by simulating commercial field conditions. The factor of 0.53 was required to correct the values for maize planted in pots when the area extrapolation method was used in this study.

Total airborne N inputs to the maize–wheat rotation system at both locations on the NCP averaged 99–117 kg $N \cdot ha^{-1} \cdot yr^{-1}$ and the plant available N from deposition for this rotation system was ca. 52 kg $N \cdot ha^{-1} \cdot yr^{-1}$, accounting for about 50% of the total N deposition. Therefore, at least 50 kg $N \cdot ha^{-1} \cdot yr^{-1}$ from the atmosphere should be taken into account in fertilizer N recommendations for crop production in this region. Our results reveal the importance of reevaluating total airborne N deposition and its nutritional role in intensively managed agricultural ecosystems in hotspots of N deposition around the world.

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