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北方冬小麦/夏玉米轮作体系土壤氨挥发的原位测定

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摘要:采用通气法测定了北方冬小麦/夏玉米轮作体系田间土壤的原位氨挥发。结果表明,与冬小麦施用基肥相比,夏玉米追肥后土壤的氨挥发速率很快升高,但挥发高峰期持续时间较短,最大氨挥发速率亦低于冬小麦。冬小麦拨节期追肥,氨挥发速率低且呈波动变化,未出现高峰值。从整个生长季节来看,冬小麦不施氮和每公顷施氮 120、240、360kg **时的累计挥发量分别为** 4.4、6.9、13.0、38.4kg N/hm²**,夏玉米为** 8.4、15.1、20.0、26.1kg N/hm²。**按我国北方冬小麦/夏玉米播种面积** 1864.4 **万** hm² **计,每年由氨挥发向大气排放的氮素达** 23.8～120.2 **万** t**,其中** 17.2～96.4 **万** t **来自氮肥,相当于氮肥投入的** 2.1%～9.5%。

关键词:冬小麦;夏玉米;土壤氨挥发;田间原位测定

In Situ Determination of Ammonia Volatilization from Wheat-Maize Rotation System Field in North China

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Abstract: Ammonia volatilization from soil is an important pathway for fertilizer N loss from field, and also a major source for air and environment pollution. Majority of soils in north China are calcareous ones with higher pH that has created a condition favorable for such loss, and intensive cropping with over application of N fertilizer and unreasonable fertilization practices has made the situation more serious. Winter wheat (*Triticusp aestvum* L.) and summer maize (*Zea Mays* L.) are major crops in this area and a rotation of wheat followed by maize constitutes the common cropping system. For understanding the seriousness of ammonia volatilization in this area, experiments were carried out on a field with the rotation system at China Agriculture University in Beijing from October 1998 to October 1999. N fertilizer was applied at the rates of 120, 240 and 360 kg N/hm² respectively with no N fertilizer as control, and 26 kg P/hm² was applied for all the N levels, using urea as N fertilizer and calcium superphosphate (containing 5.2% of P) as P fertilizer. The P fertilizer was uniformly mixed with topsoil as base just before wheat being sown, and the N fertilizer was applied twice: one-half being supplied with P fertilizer together, and the other half being dressed on April 9, 1999 at wheat elongation stage. Winter wheat was sown on October 8, 1998. After wheat being harvested, summer maize was sown immediately at June 21, 1999 with the same N rates as winter wheat. However, for summer maize, the phosphate fertilizer was not applied

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and one-half of the N fertilizer was dressed on July 5 at 3-leaf stage of maize, and the other half on August 5 at 10-leaf stage. Ammonia volatilization from soil of this rotation system was determined by venting method immediately after N fertilizer was applied at different stage.

The obtained results showed that the rates and the amounts of volatilized ammonia differed in different growing seasons and with different N rates. For winter wheat, ammonia volatilization occurred immediately after N fertilizer was added to soil followed by wheat sowing. It was gradually increased to the maximum value at the 3rd to 5th day with the corresponding volatilized rates of 0.27, 0.57, 1.96 and 5.53 kg N/(hm^2 · d) respectively for the plots received 0, 60, 120, 180kg N/hm^2. Since then it was decreased slowly and no significant difference could be observed among the volatilization rates of different plots at the 17th day after fertilization. The cumulative amounts of the volatilized ammonia from each plot were 2.9, 4.8, 10.5 and 35.7 kg N/hm^2 during the determined period from October 8 to November 18, 1998. However, after dressing of N fertilizer at the elongation stage of wheat, the ammonia volatilization from the soil kept low, stable rates, which fluctuated from 0.01 to 0.17 kg N/(hm^2 · d). The cumulative amounts of ammonia emitted from different plots were 1.5, 2.1, 2.4 and 2.7 kg N/hm^2 during the determining period from April 10 to May 15, 1999. For the entire growing stages of wheat, the total amounts of ammonia released from the field were 4.4, 6.9, 13.0 and 38.4 kg N/hm^2, correspondingly to the N rates of 0, 120, 240 and 360 kg/hm^2.

During the growing season of summer maize, the ammonia volatilization rate was high and increased more quickly after dressing of N fertilizer. At 3-leaf stage, it reached the highest rates at the 1st day after fertilization, which were 0.33, 1.82, 3.33 and 5.41 kg N/(hm^2 · d) for the plots added 0, 60, 120 and 180 kg N/hm^2 respectively, and at 10-leaf stage, the highest rates were found at the 2nd day with the corresponding values of 0.70, 2.50, 3.11 and 3.25 kg N/(hm^2 · d). However, the high speed of volatilization continued only for a shorter period. Seven days after fertilization, the volatilization rates for the plots received fertilizer had decreased to the lowest values, being of no significant difference among plots with and without N fertilization. The cumulative amounts of ammonia volatilized from different plots were 8.4, 15.1, 20.0 and 26.1 kg N/hm^2 during the period from July 6 to September 20, 1999.

Ammonia volatilized from the fertilized plots derived from two sources: one from the N fertilizer added to soil and the other from the residual organic and inorganic N existing in soil. Assuming that the amount of ammonia emitted from the residual N were equal to that from the plot without N fertilization, the amount of ammonia emitted from the N fertilizer could be estimated from the difference of the amount determined between plots with and without N addition. In this way of calculation, the total emitted ammonia from N fertilizer was 2.5, 8.6 and 34.0 kg N/hm^2 for winter wheat, and 6.7, 11.6 and 17.7 kg N/hm^2 for summer maize during their entire growing seasons, corresponding to the rate of 120, 240 and 360 kg N /hm^2. Based on these data obtained from the experiments, it can be estimated that the total amount of ammonia emitted to the air from soil would be as high as 238 000 to 1 202 000 tons of N during the entire growing season of the 18.64 million ha of wheat-maize in north China. Of these, about 172 000 to 964 000 tons of N were from N fertilizer, which accounted for 2.1% to 9.5% of the total amount of the fertilizer being applied.

Clearly, large amount of N from fertilizer was lost by ammonia volatilization during the winter wheat growing seasons, and most of the ammonia loss occurred when N were applied as basal fertilizer. This is related with the unreasonable fertilization measures. Before wheat being sown, farmers always apply fertilizer a few days after irrigation, when the soil moisture is suitable for tillage, this subsequently keeps most of the fertilizer existing in topsoil. When the fertilizer, such as urea is hydrolyzed to ammonium, it

is prone to volatilize to air from soil surface. During the growing season of summer maize, N fertilizers are usually dressed before irrigation, and the fertilizer N can be leached to a deeper soil layer by water, thereby the ammonia volatilization reduced to a great extend. However, this can enhance the risks of N leaching out of the soil layer where the plant roots reside for taking up the available nutrient. Fertilization and irrigation are the important measures in agriculture production, and also the major factors affecting soil N transformation and ammonia volatilization. Therefore optimization of field water and fertilizer management is of great importance for increasing N use efficiency and eliminating environmental pollution caused by unreasonable application of N fertilizer.

Key words: winter wheat; summer maize; ammonia volatilization from soil; *in situ* determination of ammonia volatilization

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氮肥的应用有力地促进了农业生产，但随用量增加和施用方法不当，也带来了许多环境和生态问题。施入土壤的氮肥，除被作物吸收外，还可随降水和灌溉水淋入土壤深层[1,2]，或经氨挥发、反硝化作用，以氨(NH_3)[3]、氮氧化物(NO_x)[4]的形式进入大气。其中氨挥发是氮肥气态损失的重要途径[3]。进入大气的氨虽然可随降水或干湿沉降重新进入农田和自然生态系统，但耕地仅占地球表面的一小部分，存在于大气中的氨大部分要进入森林、草原、江河、湖泊等，引起自然土壤和水体的氮素含量升高，发生富营养化[5,6]，导致植物种类更替和部分品种灭绝[7]。朱兆良等采用微气象学方法研究了我国水田生态系统的土壤氨挥发，发现在石灰性水稻土上尿素和碳酸氢氨的氨挥发损失分别高达 30%和 39%；而在酸性水稻土上仅为 9%和 18%[3]。说明除肥料品种外，土壤酸碱特性是决定氨挥发数量高低的重要因素，pH 值高于 7.0 的石灰性土壤更有利于氨挥发。我国北方耕地占全国农田总面积的 60%以上，多为石灰性土壤；同时，随着对粮食需求的增加，氮肥施用量越来越高。1997 年全国投入氮肥 2171.3 万 t(以纯氮计)，比 1987 年增加 63.7%，其中北方旱地的用量占 1/3 以上[9]。过量施氮加上不合理的施用方法、干旱的气候和土壤 pH 较高，使北方旱地的氨挥发更为严重。由于测定技术限制，这一地区土壤氨挥发的研究长期以盆栽试验和室内模拟为主，所得结果难以反映田间实际[9,10]。

本研究采用通气法[11]，对我国北方冬小麦/夏玉米轮作系统的土壤氨挥发进行了原位测定。

1　材料和方法

1.1　土壤挥发氨的捕获装置及使用方法

1.1.1　捕获装置　试验采用的通气法装置由聚氯乙烯硬质塑料管制成(图 1)，内径 15cm，高 10cm。测定过程中分别将两块厚度均为 2cm、直径为 16cm 的海绵均匀浸以 15ml 的磷酸甘油溶液(50ml 磷酸＋40ml 丙三醇，定容至 1000ml)后，如图置于硬质塑料管中，下层的海绵距管底 5cm，上层的海绵与管顶部相平。

1.1.2　田间试验　(1)冬小麦田间试验　1998 年 10 月至 1999 年 6 月，在中国农业大学科学园试验地进行，前作为玉米。田间小区面积 21×6m²，区间埂宽为 0.5m。在每公顷施磷(P)26kg 的基础上，设施氮(N)0、120、240、360kg 4 个水平。1998 年 10 月 8 日播种，小麦品种为农大 518，播量为 120kg/hm². 磷肥用过磷酸钙，播前与耕层土壤混匀施入；氮肥用尿素，1/2 和磷肥一起施入；1/2 于小麦拔节期(1999 年 4 月 9 日)灌水前均匀施入，然后采用喷灌灌水。施用基肥和追肥后，分别采用通气法测定田间土壤的氨挥发。

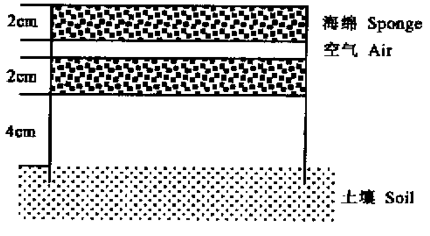

图 1　测定田间土壤氨挥发的通气法装置

Fig. 1 The equipment of venting method for determination of ammonia volatilization from soil in field

(2)夏玉米田间试验　于 1999 年 6 月至 1999 年 10 月进行，在前作冬小麦收获后，于 6 月 21 日在原小区上点播夏玉米，品种为农大 80。播种时顺小区长边

成行，行株距 50cm×30cm。氮肥用量同小麦，亦设施氮 0、120、240、360kg 4 个水平，不施磷肥。氮肥用尿素，其中 1/2 在 3 叶期（7 月 5 日），1/2 在 10 叶期（8 月 5 日）灌水前均匀撒施，然后喷灌灌水。从 3 叶期追施氮肥开始采用通气法测定土壤氨挥发。

1.2 田间取样及测定

土壤挥发氨的捕获于施肥后的当天开始，在各小区的不同位置，分别放置 5 个通气法氨捕获装置，次日早晨 8:00 取样。取样时，将通气装置下层的海绵取出，迅速按小区号分别装入塑料袋中，密封；同时换上另一块刚浸过磷酸甘油的海绵。上层的海绵视其干湿情况 3～7d 更换 1 次。变动摆放位置后，将装置重新放好，开始下一次田间吸收。把取下的海绵带回试验室后，分别装入 500ml 的塑料瓶中，加 300ml 1.0mol/L 的 KCl 溶液，使海绵完全浸于其中，振荡 1h 后，浸取液中的铵态氮用蒸溜定氮法或连续流动分析仪（TRACCS2000）测定。

最初 1 周，每天取样 1 次；第 2～3 周，视测到的挥发氨数量多少，每 1～3d 取样 1 次，以后取样间隔可延长到 7d，直至监测不到氨挥发时为止。由下式计算田间土壤的氨挥发速率：

$$NH_3\text{-}N(\mathrm{kg/(hm^2 \cdot d)}) = (M/(A \times D)) \times 10^{-2}$$

其中，M 为通气法单个装置平均每次测得的氨量（NH_3-N，mg）；A 为捕获装置的横截面积（m^2）；D 为每次连续捕获的时间（d）。

2 结果与分析

2.1 冬小麦生长季节田间土壤的氨挥发

华北平原是我国冬小麦生产基地，也是氮肥投入最高的地区之一，不少地方施氮量高达 300kg/hm^2 以上。大量研究证明，冬小麦的氮肥利用效率仅为 28%～41%[12]，氨挥发是土壤氮素损失的主要原因。采用通气法测定（图 2）表明，在施用基肥和播种冬小麦（1998 年 10 月 8 日）后，田间土壤的氨挥发逐渐增强，达到最高点，然后又缓慢下降。施肥水平虽不影响这一趋势，但不同施肥处理的氨挥发速率和累计挥发量却存在明显差异。施肥后第 3～5 天，不施肥和每公顷施氮 60、120、180kg 小区的氨挥发速率达到最高，分别为 0.27、0.57、1.96、5.53kg N/(hm^2·d)。此后缓慢降低；17d（10 月 25 日）后，施肥与不施肥小区的氨挥发速率已无明显差异，介于 0.02～0.08kg N/(hm^2·d)。从 10 月 8 日到 11 月 18 日，41d 的连续测定期间，不施肥和每公顷施氮 60、120、180kg 小区的累计氨挥发量分别达到 2.9、4.8、10.5、35.7kg N/hm^2。1999 年 1 月 19 日的监测表明，各小区的挥发速率仍介于 0.02～0.06kg N/(hm^2·d)，说明寒冷的冬季，田间土壤一直保持较弱的氨挥发。

施肥小区中挥发氨的来源有二：一是土壤原来残留的氮素，一是施入的氮素。假定施肥小区来自土壤残留氮素的氨挥发等于不施氮小区的挥发量，那么施氮小区来自肥料的挥发氨可由其与不施肥小区的差值来估算。因此，每公顷施氮 60，120，180kg 的小区来自肥料的氨挥发损失依次为 1.9、7.6、32.8kg N/hm^2，占施氮量的 3.2%、6.3% 和 18.2%。

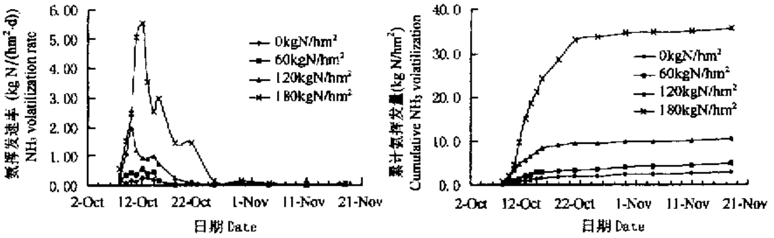

图 2　施用基肥和播种冬小麦后田间土壤的氨挥发

Fig. 2　Ammonia volatilization from soil in field after basal fertilization and sowing of winter wheat

与基肥的情况不同，冬小麦拔节期追肥（1999 年 4 月 10 日），田间土壤的氨挥发波动变化，挥发强度一

直较低（图 3）。在 35d 的连续测定期间，不施肥和每公顷施氮 60、120、180kg 的小区氨挥发速率未出现最高峰值，一直在 0.01～0.17kg N/(hm^2·d)之间上下起伏，平均速率分别为 0.04、0.06、0.07、0.08kg N/(hm^2·d)；累计氨挥发量为 1.5、2.1、2.4、2.7kg N/hm^2。施氮小区氮肥的氨挥发量分别为 0.6、1.0、1.3kg N/hm^2，占施氮量 1.0%、0.8% 和 0.7%。冬小麦春季追肥后土壤的氨挥发速率和累计挥发量低的主要原因是测定期间北京地区多雨，追肥、灌水后的连续降雨使施入土壤的尿素态氮直接淋入土壤深层[13]；过高的土壤水分含量也限制了氨的挥发[14]。

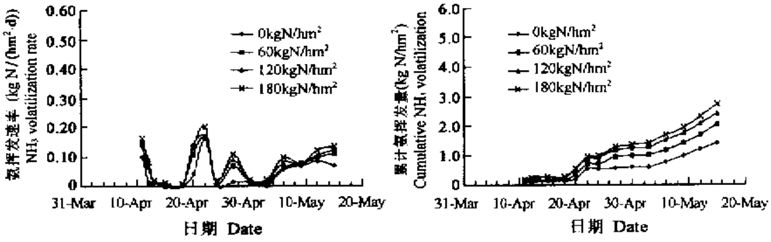

图 3　施用追肥后冬小麦田间土壤的氨挥发

Fig. 3　Ammonia volatilization from soil in winter wheat field after dressing fertilization

2.2　夏玉米生长季节田间土壤的氨挥发

夏玉米生长季节正值夏季，农民一般采用先撒施肥料后灌水的方式追肥。表施氮肥加上高温的气候条件，常导致肥料中的铵态氮素大量挥发损失。田间测定结果（图 4）表明，3 叶期（1999 年 7 月 5 日）追肥后，土壤氨挥发迅速增高，施肥后第 1 天（7 月 6 日），不施和每公顷施氮 60、120、180kg 小区的氨挥发速率已达最高，分别为 0.33、1.82、3.33、5.41kg N/(hm^2·d)；此后迅速降低。7d（7 月 12 日）后，不同处理小区的氨挥发速率已无明显差异，介于 0.01～0.18 kg N/(hm^2·d)。连续 30d 的测定表明，不施肥与每公顷施氮 60、120、180kg 小区的累计氨挥发量分别为 3.0、5.1、7.9、11.5kg N/hm^2；施肥小区来自氮肥的氨挥发依次为 2.1、4.9、8.5kg N/hm^2，相当于施氮量的 3.6%、4.1%和 4.7%。

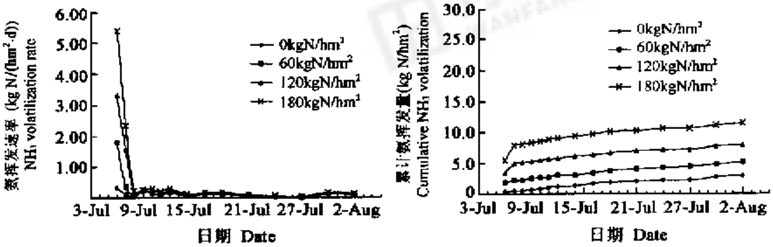

图 4　夏玉米 3 叶期追肥后田间土壤的氨挥发

Fig. 4　Ammonia volatilization from soil in summer maize field after dressing fertilization at 3-leave stage

10 叶期（1999 年 8 月 5 日）追肥后，土壤氨挥发的动态变化和 3 叶期的情况基本一致（图 5），不施肥和每公顷施氮 60、120、180kg 小区的氨挥发速率在施肥后第 2d（8 月 7 日）分别达到最高值，依次为 0.70、2.50、3.11、3.25kg N/(hm^2·d)；此后迅速降低。7d 后（8 月 14 日），不同施肥小区的氨挥发速率差异亦不再明显，介于 0.04～0.15kg N/(hm^2·d)。连续 46d 的测定表明，不施肥和每公顷施氮 60、120、180kg 小区的累计氨挥发量分别达到 5.4、10.0、12.1、14.6kg N/hm^2；施肥小区内来自氮肥的挥发氨依次为 4.6、6.7、9.2kg N/hm^2，相当于施氮量的 7.6%，5.6%和 5.1%。

3　讨论

研究表明，和冬小麦施用基肥相比，夏玉米追肥后氨挥发速率升高较快，但挥发高峰期持续时间较

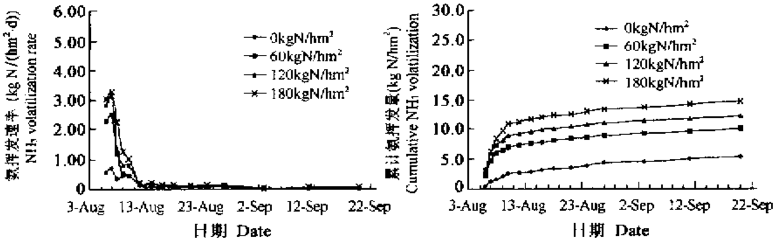

图 5 夏玉米 10 叶期追肥后田间土壤的氨挥发

Fig. 5 Ammonia volatilization from soil in summer maize field after dressing fertilization at 10-leave stage

短，最大速率亦低于冬小麦施用基肥的挥发速率。冬小麦施用基肥和播种后，氨挥发速率于第 3～5 天达到最高值，介于 0.27～5.53kg N/(hm^2·d)，此后逐渐下降。拔节期追肥后，氨挥发速率未出现明显的高峰值，而是波动变化。夏玉米不论在 3 叶期，还是在 10 叶期追肥，氨挥发均迅速增高，追肥第 1～2 天后即达最高速率，分别为 0.33～5.41kg N/(hm^2·d)和 0.70～3.25kg N/(hm^2·d)。产生这种现象的原因有 3 方面：①施肥措施，冬小麦播种时施用基肥是先灌水后施肥，施肥前数天灌水，水分充分下渗、土壤适合耕作时，才撒施肥料，并与耕层土壤混匀，然后播种。这样，施入的尿素大部分停留在表层土壤，水解后形成的可挥发氨数量多。夏玉米追肥则是先施肥后灌水，施入的尿素会淋入土壤深层[13]，停留在表层土壤的尿素减少，水解后形成的氨和因此而产生的氨挥发也随之减少。②土壤水分，不同的施肥和灌溉措施不仅造成表层土壤的氮素残留情况不同，也使土壤的水分数量出现差异。冬小麦施用基肥后一周内耕层土壤的水分为 16.0%～13.0%，而夏玉米追肥后土壤水分为 21.0%～16.0%。较高的土壤水分会降低液相中铵态氮浓度，从而降低氨分压和氨挥发速率[14]。冬小麦追肥后氨挥发呈不规则的波动变化，速率较低且没有出现高峰值(图 3)，进一步证明了追肥后灌水和不定期的降水所引起的土壤水分的高低波动对氨挥发的影响。③土壤温度，温度升高不仅会使尿酶活性提高，同时也减少土壤胶体对铵(NH_4^+)的吸附，加速铵向氨(NH_3)的转化，增加土壤溶液中的氨分压，促进氨由土壤表面向大气的挥发[15]。冬小麦施用基肥时，正值秋季，表层土壤温度为 17～22℃；夏玉米追肥在炎热的夏季，温度在 23～27℃左右。因此，夏玉米追肥后的氨挥发能较快地达到最高速率，而冬小麦施用基肥后则要经过较长的时间。

从整个生长季节来看，冬小麦不施氮和每公顷施氮 120、240、360kg 小区的累计挥发量分别为 4.4、6.9、13.0、38.4kg N/hm^2，夏玉米为 8.4、15.1、20.0、26.1 kg N/hm^2。冬小麦生长季节来自氮肥的氨挥发为 2.5、8.6、34.0 kg N/hm^2，分别占累计挥发量的 36.3%、66.2%、88.6%，占施氮总量的 2.1%、3.6%、9.5%；夏玉米生长季节来自氮肥的氨挥发为 6.7、11.6、17.7kg N/hm^2，分别占累计挥发量的 44.5%、58.0%、67.8%，占施氮总量的 5.6%、4.8%、4.9%。施入土壤的氮肥是小麦、玉米旱作农田生态系统氨挥发的重要来源，氨挥发又是旱地土壤肥料氮损失的重要途径。根据以上结果，按我国北方冬小麦/夏玉米播种面积 1864.4 万 hm^2 计[8]，两种作物生长季节内，经氨挥发向大气排放的氮素达 23.8～120.2 万 t，其中 17.2～96.4 万 t 来自氮肥，相当于这些地区年氮肥投入的 2.1%～9.5%。可见，降低土壤的氨挥发损失，对提高旱地作物的氮肥利用效率、防止氮素对环境的污染有重要意义。灌水与施肥是农业生产中主要的管理措施，又是影响土壤氨挥发的重要因子。在目前的农业生产中，北方农民在播种冬小麦时，一般采用先灌水后施肥的方式，使大部分氮肥停留在土壤表层，造成大量氨挥发损失；小麦和玉米追肥时则多采用先施肥后灌水的方式，虽可使氮素渗入较深的土壤，降低氨挥发，但又存在氮素从土壤淋失的危险[2]。因此，如何调节灌水和施肥，优化水肥投入的数量、时间、方式，做到既能防止氮素的氨挥发，又能减少淋失、反硝化等造成的氮素损失，是农业生产中亟待解决的问题，急需进一步研究。

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