华北平原大气氮素沉降的时空变异

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摘要: 利用量雨器和湿沉降自动收集仪在华北平原 9 个监测点通过 2a 的试验, 研究了农田生态系统中大气氮素沉降的时空变异。结果表明: 华北平原大气氮素混合沉降的平均值为 28.0 kg/(hm^2·a), 降水中铵态氮和硝态氮量平均分别为 3.76 mg/L 和 1.85 mg/L。不同地区比较, 北京大气氮素沉降为 32.5 kg/(hm^2·a), 明显高于山东和河北两省的 23.6 kg/(hm^2·a)。北京各监测点的大气氮素沉降也存在明显空间变异, 东北旺、房山的氮素沉降水平较高, 延庆、顺义的氮素沉降水平较低。大气氮素沉降的年内分布不均, 60% 的沉降集中在降水较丰沛的 6~9 月份。氮素的输入与降雨量呈乘幂型正相关(r^2 = 0.67), 在农田生态系统中以铵态氮的沉降为主, 铵态氮的沉降量是硝态氮的 2.0 倍; 城市生态系统中以硝态氮的沉降为主, 铵态氮的沉降量是硝态氮的 0.79 倍。在东北旺试验点近两年的监测结果表明, 在等量降雨量条件下湿沉降输入的氮素(18~20.6 kg/hm^2) 明显低于混合沉降(26.3 kg/hm^2), 湿沉降的氮素输入仅占后者的 73%, 而混合沉降中的超量部分主要来自铵态氮, 表明干沉降尤其是降尘带入的铵态氮也是华北平原大气氮素沉降的重要来源。

关键词: 大气氮素沉降; 湿沉降; 华北平原; 北京地区; 农田生态系统

文章编号: 1000-0933(2006)06-1633-07 中图分类号: Q142.2, Q143, X517 文献标识码: A

Spatial and temporal variation of atmospheric nitrogen deposition in North China Plain

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Abstract: Attention to atmospheric N deposition, as a nutrient resource and as a part of acid deposition, is increasing with the acceleration of global N cycling. However, the information on atmospheric N deposition, especially the spatial and temporal variation of N deposition in the intensive agroecosystems within the North China Plain, is still scarce. Therefore, it is essential to determine the budgets and spatial and temporal variation of atmospheric N deposition in North China Plain in terms of the requirement of integrated N management and the assessment of N deposition effect on surrounding ecosystems.

A monitoring network was established to determine the spatial and temporal variation of atmospheric N deposition in the North China Plain over a 2-year period. The network included 9 monitoring sites: seven in Beijing city, one in Shandong province and one in Hebei province. Except one urban monitoring site in Beijing Academy of Agro-Forestry Sciences (BAAFS), all the other 8 sites were located at typical field areas. Rain gauges (diameter 20 cm, height 80 cm) were installed in all the nine sites for the

基金项目: 国家自然科学基金资助项目(30370287, 30390080); 教育部博士点基金资助项目(20030019038); 国家农业部 948 重大引进资助项目(202003-Z53); 中德教育科研资助项目

收稿日期: 2005-02-23; 修订日期: 2005-07-20

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Foundation item: The project was supported by National Natural Science Foundation of China (No. 30370287, 30390080); Foundation of MOE for Ph. D. Work (No. 20030019038); The Key Import Project of MOA (No. 202003-Z53); and the Sino-German Cooperative Project

Received date: 2005-02-23; **Accepted date**: 2005-07-20

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collection of bulk deposition, and an Automatic Wet-only Sampler (APS-Ⅲ, Wuhan Tianhong Inc.) was installed at Dongbeiwang site, Beijing, for the collection of wet deposition (the sampler opens only when rainfall happens). Rainwater was collected, thoroughly mixed and stored in plastic bottles immediately after each rain event, then was frozen in a refrigerator until analysis by a Continuous Flow Analyzer (TRACC2000, Germany) within three months. Rain gauges and the wet-only sampler were cleaned by deionized water just after collection.

Annual bulk deposition of inorganic N in the North China Plain ranged from 19.2 to 38.5 kg/hm^2 and averaged 28.0 kg/hm^2. Concentration of NH_4^+-N and NO_3^--N in rainwater averaged 3.76 and 1.85 mg/L, which were significantly higher than the values in background sites of China. Annual bulk deposition of inorganic N in the Beijing area was as high as 32.5 kg/hm^2, while lower annual N deposition of 23.6 kg/hm^2 was found in Shandong and Hebei provinces. Bulk deposition of inorganic N showed distinguished monthly variation due to monthly change of precipitation, and 60% of bulk deposition occurred from June to September. Bulk deposition of NH_4^+-N was 2.0 times of NO_3^--N deposition in rural monitoring sites. However, the situation was reversed in an urban monitoring site (BAAFS). The results suggest that reduced N in precipitation is dominant in rural region but oxidized N is the major form in urban region. Furthermore, the positive relationship between inorganic N deposition and precipitation can be fitted well by a power equation (r^2 = 0.67), showing the increase of NH_4^+-N and NO_3^--N inputs with increased precipitation. Wet deposition of N accounted for 73% of the corresponding bulk deposition, implying that dry deposition of N particular NH_4^+-N input from dust is important in the North China Plain.

Key words: atmospheric deposition; nitrogen; precipitation; North China Plain; agro-ecosystem

大气氮素沉降是氮素生物地球化学循环中的重要环节之一。由于化学肥料使用,矿物质燃烧以及畜牧业发展,人类活动导致了大气活性氮浓度的持续升高[1~3],这也使得大气氮素沉降已经从发达地区迅速扩展到全球范围[4]。据保守估计,目前大气氮素沉降的全球平均值为5 kg/(hm^2·a)[2],其中欧洲为10 kg/(hm^2·a)[5],亚洲为7 kg/(hm^2·a)[6]。Twonsend等[7]通过氮沉降模型模拟结果表明,中北美、西欧和亚洲的中国、印度已经成为全球氮沉降的三大集中分布区。显然,这些来自大气环境中的氮素沉降已经或即将对陆地及水生生态系统产生深远的影响[8]。我国虽然从20世纪70年代末80年代初以来陆续开展了氮素沉降(雨水氮)的收集与定量工作[9~11],但整体而言这方面的研究还较零散,尤其缺少对某一地区多点网络式综合研究。

华北平原是我国重要的商品粮基地,也是我国氮肥高投入地区。据赵久然等[12]调查,在北京地区小麦-玉米轮作体系中,肥料氮的年施用量高达565 kg/hm^2。过量施肥造成深层土壤硝态氮累积[13]、地下水硝酸盐污染[14]以及氨挥发[15]和N_2O排放[16]等问题,已经严重影响到农业经济和生态环境的可持续发展。另一方面,氮肥的大量损失尤其是氨挥发也会显著增加大气氮素沉降的数量,从而加重农田生态系统的氮素盈余。本文旨在研究华北平原农田生态系统中大气氮沉降的时空分布规律,为农田生态系统中氮素资源的综合管理提供科学依据。

1 材料与方法

1.1 监测点概况

沉降收集在华北平原9个监测点进行(表1)。各监测点均位于平坦开阔的空间,地面有植被覆盖,周围无障碍物影响样品采集。该区域气候类型属于暖温带半湿润季风型气候,年平均温度8~14℃,年有效积温3200~4500℃,多年平均降水量400~800 mm,主要集中在6~9月份,雨热同期。

1.2 取样及分析

试验自2003年1月起陆续在各监测点安装雨量器,收集降雨(参见表1)。同时在北京东北旺安装APS-Ⅲ型降水降尘自动收集仪(武汉天虹仪器有限公司生产),并于2003年6月开始收集湿沉降样品。

每次降雨后,用雨量杯收集并计量降雨量,充分混匀后取部分水样冷冻储藏。雨量器,雨量杯事先用去离子水冲洗干净。湿沉降用降水降尘自动收集仪收集,该仪器灵敏度为0.1 mm,有降水事件发生时自动打开,

降雨停止 10 min 后自动关闭, 样品收集不受降尘和飘尘的影响。湿沉降取样和储藏与降雨样品相同。所有样品均在 3 个月内用连续流动分析仪(TRACC2000) 测定 NH_4^+-N 和 NO_3^--N 含量。沉降总量根据每次降雨中无机氮浓度与降雨量乘积而累加得出。

表1 华北平原大气氮素沉降监测点概况

Table 1 Introduction of the atmospheric nitrogen deposition monitoring sites in the North China Plain

省份 Provinces	监测点 Monitoring site	定位 Location	监测时段 Period of monitoring	监测点类型 Monitoring type
北京 Beijing	东北旺 Dongbeiwang	40°03′N, 116°17′E	2003-01~2004-12	远郊 Suburb site
	农大科学园 (CEF)	39°50′N, 116°25′E	2003-01~2004-12	远郊 Suburb site
	房山 Fangshan	39°41′N, 116°08′E	2004-04~2004-09	乡村 Rural site
	北京市农林科学院 (BAAFS)	39°56′N, 116°17′E	2004-04~2004-08	城市 Urban site
	顺义 Shunyi	40°03′N, 116°41′E	2004-04~2004-09	乡村 Rural site
	大兴 Daxing	39°35′N, 116°20′E	2004-04~2004-09	乡村 Rural site
	延庆 Yanqing	40°26′N, 115°55′E	2004-04~2004-09	乡村 Rural site
山东 Shandong	惠民 Huimin	37°29′N, 117°32′E	2003_01~2004_12	乡村 Rural site
河北 Hebei	曲周 Quzhou	36°52′N, 115°01′E	2003_01~2004_12	乡村 Rural site

CEF Campus Experimental Farm; BAAFS Beijing Academy of Agro-Forestry Sciences

2 结果与讨论

2.1 华北平原大气氮素混合沉降的空间变异

2003~2004 年北京(东北旺、农大科学园), 山东惠民, 河北曲周四点的监测结果(表 2) 表明, 华北平原过去两年的降雨量在 384~639 mm 之间。氮素沉降量在 19.2 kg/(hm^2·a) 至 38.5 kg/(hm^2·a) 之间, 平均 28.0 kg/(hm^2·a), 是农田生态系统中一项稳定的氮素输入。氮素沉降中可溶性无机氮的浓度, 铵态氮为 3.76 mg/L, 硝态氮为 1.85 mg/L, 相当于我国降水中氮素组成平均浓度的 3~5 倍[17], 同欧洲、北美和日本等国家相比, 铵态氮和硝态氮浓度分别相当于其 5~8 倍和 3~4 倍[18-21]。氮素沉降中两种形态氮的比例, 铵态氮占总量的 67%, 硝态氮占 33%。该结果与我国大气氮素沉降中氮素组成的总体比例, 以及与北美和西欧非城市地区大气氮素沉降中氮素的组成比例基本一致[22, 23]。

表2 华北平原大气氮素沉降的时空变异

Table 2 Spatial and temporal variation of atmospheric nitrogen deposition in the North China Plain

监测点 Monitoring site	时间 Year	降雨量(mm) Precipitation	浓度 Concentration (mg/L)			输入量 Input (kg/hm^2)			NH_4^+-N/NO_3^--N
			NH_4^+-N	NO_3^--N	Σ	NH_4^+-N	NO_3^--N	Σ	
农大科学园 CEF	2003	483.0	5.19	2.44	7.63	25.07	11.79	36.86	2.13
	2004	446.2	3.25	2.18	5.43	14.50	9.73	24.23	1.49
东北旺 Dongbeiwang	2003	484.9	5.60	2.33	7.93	27.17	11.29	38.46	2.41
	2004	472.8	4.45	1.95	6.40	21.03	9.23	30.26	2.28
惠民 Huimin	2003	620.5	2.30	0.80	3.10	14.26	4.96	19.22	2.88
	2004	639.4	2.72	1.86	4.58	17.36	10.75	18.44	1.62
曲周 Quzhou	2003	624.2	2.82	1.13	3.95	17.59	7.04	24.63	2.50
	2004	384.1	3.71	2.13	5.84	14.25	8.2	22.45	1.74
2004-04~2004-09									
农大科学园 CEF		419.8	2.88	2.10	4.98	12.09	8.83	20.92	1.37
东北旺 Dongbeiwang		443.1	3.83	1.64	5.47	16.99	7.26	24.25	2.34
大兴 Daxing		435.0	2.85	1.35	4.20	12.41	5.86	18.27	2.12
顺义 Shunyi		435.0	2.09	1.61	3.70	9.08	6.99	16.07	1.30
房山 Fangshan		499.3	3.27	1.75	5.02	16.32	8.74	25.06	1.87
延庆 Yanqing		398.0	2.15	1.37	3.53	8.56	5.47	14.06	1.57
北京市农林科学院 BAAFS		361.5	2.10	2.65	4.75	7.58	9.60	17.18	0.79

北京农林科院监测点只包括 2004 年 4 月~8 月的雨样 Rainwater samples at BAAFS site only includes precipitation during April to August, 2004

从表 2 可知, 北京地区(农大科学园和东北旺两点) 大气氮素沉降平均为 32. 5 kg/ (hm^2 • a) , 其数量明显高于山东惠民和河北曲周的沉降量(23. 6 kg/ (hm^2 • a)) 。北京地区氮素沉降的结果与孙昭荣等[24] 在中国农科院土肥所 1986~ 1992 年连续 7a 测得的雨水年均输入氮量 30. 9 kg/ hm^2 没有明显差异。但是需要指出, 北京地区的年降雨量已从 20 世纪 80 年代的约 600 mm 减少至目前的 500 mm 以下, 说明当前雨水氮素浓度已明显高于 20a 前的水平。从表 2 中氮素混合沉降的浓度可以看出, 北京地区降水受大气氮素污染的程度显著高于河北和山东地区。同时, 北京地区 2004 年 4 月至 9 月 7 个监测点的结果(表 2) 表明, 各点氮素沉降具有明显的空间变异, 雨水中氮的浓度和输入量以东北旺、房山最高, 农大科学园和北京农林科学院(后者缺 9 月份数据) 居中, 而大兴、顺义、延庆的雨水氮浓度和输入量相对较低。除北京市农林科学院监测点铵态氮与硝态氮的沉降比值(0. 79) 小于 1 外, 其它各点铵态氮的输入均明显大于硝态氮, 其铵硝比比(1. 8: 1) 与北京、河北、山东 4 个监测点连续 2a 的平均铵硝比(2: 1) 接近。这说明在农业生态系统中大气氮素沉降以铵态氮为主, 而在城市生态系统中, 由于交通等污染源的影响, 硝态氮是大气氮素沉降的主要形态。

统计数字显示, 我国南方地区大气氮素混合沉降量在 6. 6~ 23. 1 kg/ (hm^2 • a) 之间[9,10, 25, 26] , 北方地区(华北、东北、西北地区) 降雨输入到农田系统中的氮量多数在 5. 1~ 25. 4 kg/ (hm^2 • a) 之间[11, 27~ 29] 。显然, 本文报道的华北平原农田大气氮素的沉降年通量明显高于我国其他地区。而同一地区农田生态系统中氮素沉降的通量也显著高于森林生态系统中林外雨输入的氮素通量[30, 31] 。而大气降水化学组成的背景监测表明, 在不受人为活动干扰的情况下, 大气氮素的沉降量仅为 1. 8~ 3. 2 kg/ (hm^2 • a) [32~ 34] , 这说明华北平原工农业活动向环境中排放的氮素是大气氮素沉降的一个主要来源。

2. 2 华北平原大气氮素沉降的时间变异

受降雨量的影响, 华北平原 72% 的降雨集中的 6~ 9 月份, 而同期由降雨输入的氮素占总输入量的 60% 。对 2003~ 2004 年北京东北旺、农大科学园、山东惠民、河北曲周四点降水化学特征的研究表明, 氮素沉降的输入量与降雨量呈乘幂型正相关(图 1) , 其决定系数平均达 0. 67, 说明华北平原约 2/3 的大气氮素混合沉降取决于降雨量的大小。

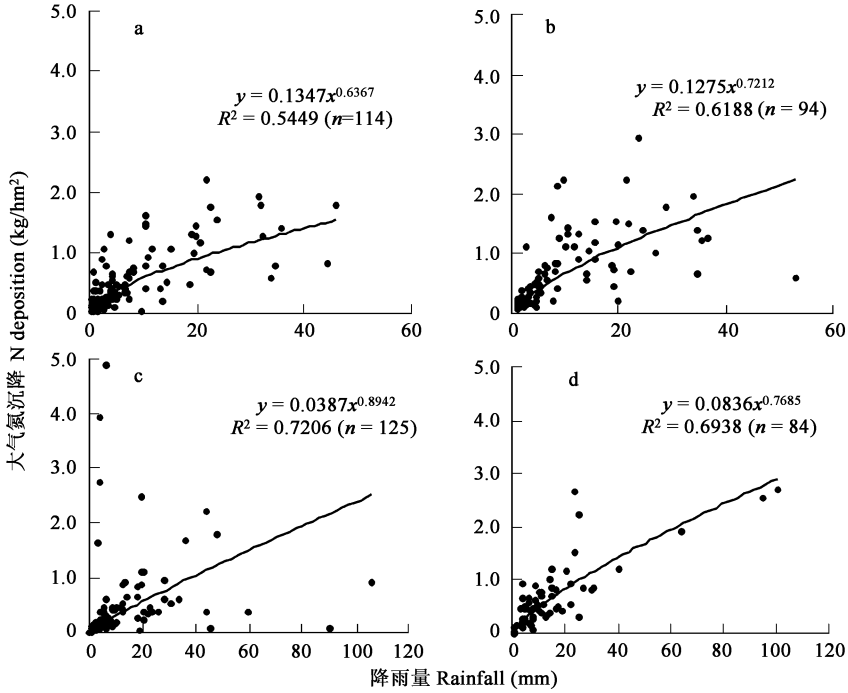

图 1 降雨量对大气氮素沉降的影响

Fig. 1 Relationship between rainfall and nitrogen deposition

a. 农大科学园 CEF; b. 东北旺 DBW; c. 惠民 Huimin; d. 曲周 Quzhou

2.3 大气湿沉降输入的氮素

受降尘的影响, 常规降水样品中混有一部分干沉降, 因此, 这部分氮素的输入是混合沉降(bulk deposition, 即传统方法收集的雨水)。因此, 由湿沉降(wet deposition, 只在降雨期间收集雨水所得的沉降) 输入的氮量带入的氮素数量、其与混合沉降氮素输入的差异是人们关注的问题。根据 2003 年(6~ 11 月份) 和 2004 年(4~ 11 月份) 在东北旺监测点用湿沉降自动收集仪所得的结果(表 3) , 湿沉降输入的氮素分别为 18.0 kg/hm^2 和 20.6 kg/hm^2, 而同一时期由混合沉降输入的氮素均为 26.3 kg/hm^2, 氮素湿沉降仅占混合沉降的 68% 和 78%, 平均为 73%。同时, 氮素湿沉降所占的比例受降雨量的影响显著, 在降水较为集中的 7~ 8 月份, 湿沉降所占的比例较高, 而在降雨量较低的月份, 湿沉降所占的比例明显下降, 尤其在春季干旱且多沙尘的月份, 干沉降占了很大比例(图 2)。这表明大气氮素干沉降对生态系统有很高的贡献率, 混合沉降中仅部分颗粒态沉降(降尘) 就占了 27%, 如考虑溶胶态氮素干沉降在内, 华北地区大气氮素沉降中干、湿沉降的比例将高于欧洲和北美地区[35~ 37], 大气氮素沉降总量应不低于欧洲高氮沉降区的水平[38,39]。

表 3　东北旺大气混合沉降与湿沉降的氮素输入比较

Table 3　Comparison of bulk N deposition and wet N deposition at Dongbeiwang site

沉降类型 Type of deposition	取样次数 No. events sampled	浓度 Content(mg/L)			沉降量 Deposition(kg/hm^2)		
		NH_4^+-N	NO_3^--N	Σ	NH_4^+-N	NO_3^--N	Σ
2003_06~ 2003_11(rainfall: 370mm)							
混合沉降 Bulk deposition	33	5.19	1.92	7.11	19.21	7.09	26.30
湿沉降 Wet deposition	33	3.51	1.34	4.85	13.00	4.96	17.96
差异 Difference		1.68	0.58	2.26	6.21	2.13	8.34
湿沉降/混合沉降 D_w/D_b							0.68
2004_04~ 2004_11(rainfall: 458mm)							
混合沉降 Bulk deposition	39	3.95	1.78	5.73	18.11	8.17	26.28
湿沉降 Wet deposition	39	3.07	1.43	4.50	14.05	6.53	20.58
差异 Difference		0.88	0.35	1.23	4.06	1.64	5.70
湿沉降/混合沉降 D_w/D_b							0.78

D_w: Wet deposition; D_b: Bulk deposition

3 结语

华北平原农田生态系统中由降水输入的大气氮素年均沉降量为 28 kg/hm^2, 是高氮沉降区。大气氮素沉降的年内分布不均, 其中 60% 集中在降水较丰沛的 6~ 9 月份, 且氮素的沉降量与降雨量呈乘幂型正相关。除市区监测点以硝态氮为主外, 铵态氮是大气无机氮沉降的主要形式, 其沉降量平均为硝态氮的 2 倍。与氮素混合沉降(含降雨和部分降尘带入的氮) 相比, 湿沉降输入的氮素只占前者的 73%, 这说明干沉降也是该地区大气氮素沉降的一个主要部分。另外, 如果考虑到干沉降中气溶胶和气态氮以及湿沉降中有机态氮的输入, 华北平原的大气氮素干湿沉降实际数量可能远高于目前报道的数据, 应该在农田氮素资源综合管理中充分考虑这部分环境氮的输入。

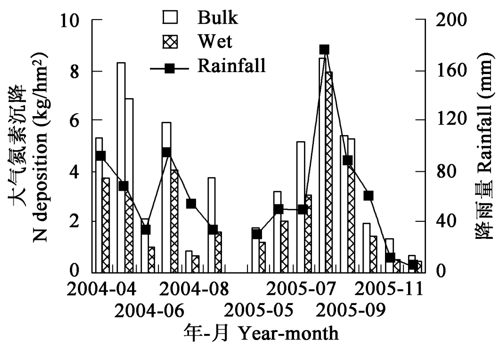

图 2　大气氮素混合、湿沉降与降雨量的关系

Fig. 2　Relationship between rainfall and nitrogen input from bulk or wet deposition

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