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土壤硝态氮时空变异与土壤氮素表观盈亏 Ⅱ. 夏玉米

周顺利，张福锁，王兴仁

（中国农业大学植物营养系，北京 100094）

摘要：在不同氮肥用量下研究了夏玉米生育期间土壤硝态氮的时空变化特征，同时对不同生育阶段土壤氮素的盈余与亏缺进行了表观估算，结果表明：0～100cm 土体内，夏玉米一生中土壤硝态氮均表现为在中间土层含量低，上层和下层含量高，一般以表层最高，但受降雨的影响在高氮肥处理会出现下层高于表层的现象。施氮肥提高了土壤硝态氮含量，而且提高程度与用量成正相关。降雨时土壤硝态氮可随水下移，在干旱条件下也可随水上移。土壤硝态氮的运移不仅受土壤水分状况的影响，还取决于硝态氮含量，含量越高，向下移动的越深，淋失的可能性越大；在本试验条件下，土壤氮素盈余主要出现在夏玉米播种～9 叶展和 9 叶展～吐丝两个生育阶段，吐丝～收获则出现土壤氮素的亏缺。随着氮肥用量的增加，玉米一生中土壤氮素的表观盈余量明显增大，最高平均可达 274.1 kgN/hm²。研究结果表明，土壤氮损失是盈余氮素的一个主要去向，而硝态氮淋洗是夏玉米生育期间土壤氮素损失的一个重要途径。

关键词：夏玉米；施氮量；土壤硝态氮；土壤氮素的表观盈亏

The Spatio-temporal Variations of Soil NO_3^--N and Apparent Budget of Soil Nitrogen Ⅱ. Summer Maize

ZHOU Shun-Li, ZHANG Fu-Suo, WANG Xing-Ren (*Department of Plant Nutrition, China Agricultural University, Beijing 100094, China*). ***Acta Ecologica Sinica*, 2002, 22(1): 48～53**

Abstract: To minimize the loss and residual rate of soil NO_3^--N, the rate, time and method of nitrogen fertilization must be fitted to the crop needs and uptake capacity. Therefore, the spatio-temporal variations of soil NO_3^--N and apparent budget of soil N in summer maize were studied under different nitrogen fertilizer (Nf) level.

A field trail was conducted at Wuqiao Research Station, Wuqiao county, Hebei province in 1998. The experiment was laid out in a split-plot design, 5 doses of nitrogen were in the main plot and 6 genotypes were represented in the subplot with three replications. The 5 doses of nitrogen were 0, 112.5, 250, 337.5 and 450 kg/hm², and the 6 genotypes were Tangkang5, Yedan22, Luyuandan14, Danyu13, Nongda108 and Nongda 3315 (the former three are the type of erectophile, plant density is 72 000 plants/hm²; the later three are the type of planophile, plant density is 57 000 plants/hm²). The soil texture is a salted light loam soil but which turns clammy at deeper layer (about 130～170cm) and is a fine sandy loam soil at the layer of 170～200cm depth. Nf was divided as 2 split applications (40% at sowing + 60% at 9-leaf expanded, by side-dressing). 103.5kg P_2O_5/hm², 162.7kg K_2O/hm² and 30kg $ZnSO_4$/hm² were applied at sowing. At pre-sowing the field was irrigated, but there no irrigations during summer maize growth period because of the 2 rainfalls in July (516mm, was mainly composed of 2 heavy rainfalls) and August (118mm).

Soil samples were obtained from all plots at 4 growth stages [sowing, 9-leaf expanded (before fertilization), silking and harvest] in 20cm increments to a depth of 100cm. Mixing samples of multi-boring per plot were taken with a soil auger and the sample was frozen immediately. The determination steps of soil mineral N (i.e. N_{min}, including NO_3^--N and NH_4^+-N) as follows: defrosted→mixed the sample fully and then sifted it with a 2mm-sieve→10g of each sample were extracted with 0.1L of 0.01mol/L $CaCl_2$ on a

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作者简介：周顺利（1970～），男，河南开封人，博士，讲师。目前在中国农业大学农学系工作，主要从事作物高产栽培生态生理及作物营养方面的工作。

horizontal shaker for 0.5 hour→filtered→N_{min} were determined using an auto analyzer (TRAACS2000). At the same time soil water content of each sample was determined, too.

Plant samples were taken three times (at 9-leaf expanded, silking and harvest stage). All the samples were killed at 105℃ for 0.5 hour and dried at 70℃. Total plant N was analyzed by the Kjeldahl digestion method.

The estimating method of apparent budget of soil N (ABSN): after reviewed relevant studies, Zhu Zhao-Liang showed that the increment of mineralized soil N after fertilization is approximately equal to the biological fixed rate of fertilizer N. So based on the assumption, the calculating formula of ABSN as follows:

ABSN =(Total amount of original N_{min}+Rate of applied N+Rate of mineralized N)−(Total amount of residual N_{min}+Rate of uptake N by crop+Rate of fixed N)
=(Total amount of original N_{min}+Rate of applied N)−(Total amount of residual N_{min}+Rate of uptake N by crop)

The results of soil N_{min} indicated, during the growth period of summer maize the difference of soil NH_4^+-N content among soil layers was smaller under different Nf level, while the change of soil NO_3^--N content(SNC) was very distinct, so only the spatio-temporal variations of soil NO_3^--N was discussed here.

At sowing SNC was maximum at the top layer, then decreased following soil depth deepened, and was minimum at the layer of 40～60cm depth, afterward, the SNC increased again following soil depth deepened further.

The further results indicated, in 0～100cm depth soil SNC was lower in the middle layer and in the upper or lower layer was higher during summer maize growth period. Generally, in the top layer SNC was the highest, but rain strongly influenced soil NO_3^--N movement, i.e. SNC. It was about at elongation stage there were two violent rainfalls, as a results, at 9-leaf expanded in the highest Nf treatment the SNC in the layer of 80～100cm depth increased significantly compared with at sowing and was higher than the top layer. Meanwhile, in 337.5kg N/hm^2 treatment the increase of SNC in the layer of 80～100cm depth also was observed and in the top layer there no difference among Nf treatments (including no Nf treatment). Fertilization at 9-leaf expanded had significantly improved SNC in the top layer at silking stage, but the SNC in lower layers were different among Nf treatments (because there no irrigation and rainfall after fertilization): the bigger Nf rate was, the bigger the increments of SNC in a lower soil layer, and the deeper the depth of soil NO_3^--N leaching downward. So it is obvious that the movement of soil NO_3^--N not only had been influenced by soil water content, but also SNC. At harvest stage there was a light increase of SNC in the layer of 80～100cm depth, at lower Nf level it may be caused by the move upward of soil NO_3^--N from the lower layer.

The estimated results of ABSN indicated, under the experimental condition, soil N surplus mainly appeared before silking (in no Nf treatment it appeared before the 9-leaf expanded), after silking soil N appeared deficit (in no Nf treatment soil N deficit appeared after the 9-leaf expanded). Following Nf rate increased, the apparent surplus amount of soil N also increased significantly and the mean maximum value of 6 genotypes was 274.1kg N/hm^2.

According to the results, N loss was the main outlet for surplus soil N, and the leaching loss(NO_3^--N) was the main form of soil N loss during summer maize growth period.

Key words: summer maize; N-fertilizer rate; soil NO_3^--N; apparent budget of soil N

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对地下水硝酸盐污染调查研究结果表明,过量施氮导致的土壤硝态氮残留和淋洗对污染负有重要责任。Owems 等[1]**在美国俄亥俄州的草地上进行了长达 15a 的试验,前 5a 每年施氮 224kg/hm^2,地下水中硝态氮逐渐上升到 10mg/L 左右,停止施肥后改种绿肥,则地下水中的硝态氮迅速下降,两年即下降 50%,然后逐渐恢复到施肥前水平。这个实验有力地说明了施肥对环境的影响。在夏玉米生长季节,由于降雨量比较大,而玉米对肥料氮的利用率比较低**[2,3]**,硝酸盐淋失带来的地下水污染倍受关注,近年来关于这方面的报道越来越多。北京地区由于氮肥施用过量和施用不合理,在蔬菜、玉米等作物生育期有明显的氮素淋溶损失**[4,5]**;夏玉米生长季节硝酸盐淋洗量可高达 450～615kg/hm^2**[6]**;Roth and Fox**[7]**发现,种植玉米后即使**

采用经济施氮量，在夏季仍有41～138kg N/hm^2被淋洗到1.2m土层。

要减少土壤硝态氮残留量，施氮量、施肥时间和方法都必须适合作物的需要和吸收潜力。因此，本文重点研究了不同氮肥用量下夏玉米不同生育阶段土壤NO_3^--N的变化特征及土壤氮素的盈余与亏缺，这对于在夏玉米生长季节实现对环境友好的氮肥合理施用具有重要的理论与实际意义。

1 材料与方法

1.1 气候条件 试验于1998年在河北省吴桥县吴桥实验站进行。根据实验站气象站的观测记录，夏玉米生长期间降雨量及多年平均资料见图1。

1.2 试验设计与田间管理 以唐抗5、掖单22和鲁原单14三个紧凑型，丹玉13、农大108和农大3315三个平展型玉米为试验作物，设置5个氮肥处理，每公顷分别施纯氮0、112.5、225、337.5和450kg。采用2因素裂区试验设计，主区处理为氮肥，副区处理为品种，重复3次。

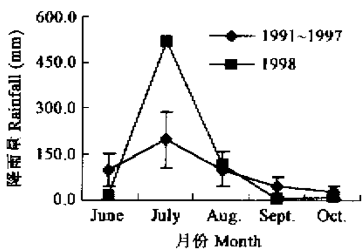

图1 吴桥实验站夏玉米生长期间降雨量变化

Fig.1 Rainfall during the growing season for summer maize at Wuqiao Research Station

试验地土壤为轻壤质低粘盐化潮土，前茬为小麦。玉米于10月14日铁茬播种，等行距种植。紧凑型行距60cm，密度72 000株/hm^2；平展型行距80cm，密度57 000株/hm^2。氮肥分基肥和追肥(在9叶展期施用)两次施入，比例为4∶6。基肥中每处理施等量三料钙镁磷肥225kg/hm^2(含$P_2O_5$46%)；氯化钾225kg/hm^2；硫酸锌30kg/hm^2。基肥和追肥均条施(5～10cm深)。玉米播前浇底墒水，追肥时由于土壤墒情较好，未灌水，生育后期也未灌水。

1.3 调查测定项目与分析方法

1.3.1 土壤N_{min}(铵态氮和硝态氮)测定 夏玉米播种、9叶展(追肥前)、吐丝期和收获期在小区内按对角线布点，分层取1m土体土样，每20cm一层。每个小区取多点混合样，样品取后立即冰冻保存。样品处理和测定步骤如下：样品解冻后，充分混匀过2mm筛，称取10g土，加入100ml0.01mol/L的$CaCl_2$，振荡30min后过滤，浸提液立刻冰冻保存(或测定)。测定前将浸提液解冻，利用流动分析仪(TRAACS2000)测定土壤N_{min}。土壤处理的同时，测定土壤含水量。

1.3.2 植株氮吸收量的测定 在取土壤样品的同时，取植物样品，每小区取3～5株。样品取回后在105℃杀青0.5h后，温度降至70℃烘干，称重。粉碎后采用凯氏定氮法测定植株全氮含量。

1.4 土壤氮素表观盈亏量的计算方法 朱兆良[8]综述有关研究结果后认为，从数量上讲，因加入化肥氮所增加的土壤氮素的矿化量($N_{矿化}$)与被土壤中生物固定的化肥氮($N_{固定}$)基本相当。基于此，以土壤N_{min}测定为基础，采用以下公式计算土壤氮素的表观盈亏量：

$$表观盈亏量=(土壤N_{min}起始总量+施氮量+N_{矿化})-(土壤N_{min}残留总量+作物吸氮量+N_{固定})$$
$$=(土壤N_{min}起始总量+施氮量)-(土壤N_{min}残留总量+作物吸氮量)$$

2 结果与分析

2.1 土壤硝态氮的时空变化特征

虽然夏玉米不同基因型的土壤硝态氮时空变化在数量上有差异，但其趋势却基本相同，限于篇幅，本文仅给出了掖单22和农大108两个基因型的测定结果(见图2)。

夏玉米播种前土壤硝态氮的测定结果表明，表层土壤硝态氮含量最高，随土壤深度增加，硝态氮含量略有降低，以40～60cm土层最低，以后又随土壤深度的增加而增加。

夏玉米9叶展时，不同氮肥处理硝态氮分布特征同播种前一样，都表现为中间土层低，上层和下层高的趋势，但氮肥用量不同，上下层硝态氮含量高低有差异。不施氮肥处理，表层土壤硝态氮含量明显高于下层，虽然从40～60cm土层往下(个别基因型从20～40cm开始)土壤越深硝态氮含量越高，但在20～40cm

以下各土层间差异不大(农大 108 由于前期生长势弱,对深层硝态氮的利用能力较小,表现为 80～100cm 土层硝态氮含量较高)。随着氮肥用量的增加,20～40cm 以下各土层在氮肥处理间和不同土层间差异均增大,表现为氮肥用量越大,土层越深,硝态氮含量越高。值得一提的是,在 0～20cm 土层各氮肥处理硝态氮含量差异不大,这是由于在夏玉米拔节前后两次强降雨(总降雨量高达 516mm)导致上层土壤硝态氮淋入土壤深层,使下层土壤硝态氮含量升高,而且施氮量越大淋洗量越大,其中以 450kg N/hm^2 处理 80～100cm 土层的硝态氮含量升高最为明显。

到了夏玉米吐丝期,施氮处理由于 9 叶展时氮肥的补充,表层土壤硝态氮含量都明显增加,且氮肥用量越高,增幅越大。但由于追肥时没有灌水,表层土壤硝态氮向下层的移动受到限制,下层土壤硝态氮的增加在低氮肥处理远没有表层明显,但不同处理间仍有差异,112.5kg N/hm^2 处理的部分基因型在 20～40cm 土层硝态氮含量提高;225kg N/hm^2 处理 6 个基因型 20～40cm 土层硝态氮含量都明显提高;337.5kg N/hm^2 处理在 20～80cm 土层硝态氮含量有提高,但在这 3 个层次随深度的增加硝态氮的增加量减少;450kg N/hm^2 处理在 20cm 以下土层均有大幅度提高,以 40～60cm 土层的硝态氮含量最低(可能与根系的吸收有关)。可见,土壤硝态氮的运移还与硝态氮含量有关,硝态氮含量越高,向下淋洗的深度越深,淋洗量越高,淋失的可能性越大。相反在施氮量小于 225kg/hm^2 处理,由于根系的吸收,下层土壤中硝态氮的差异变小(与上一次测定结果相比)。在不施氮肥处理,各层次土壤硝态氮含量都有所降低,其中表层和下层降低更甚,使得下面 4 层的差异变小。

到了收获期,随着玉米对硝态氮的进一步吸收,80cm 以上土体内各个氮肥处理土壤硝态氮含量均有所降低。但在 0～337.5kg/hm^2 施氮量范围内,80～100cm 土层硝态氮含量反而略有增高,这可能与 1m 以下土层硝态氮随水向上层移动有关(追肥时,由于土壤墒情较好没有灌水,后期没有降雨,也没有灌水,玉米收获时 1m 土体土壤含水量较低),在高氮肥处理也可能与上层土壤硝酸盐向下层移动有关。在不同土壤层次,以表层土壤硝态氮含量最高,中间土层(不施氮肥处理在中间 3 层)硝态氮含量最低,以后又随深度的增加而升高。随氮肥用量的增加,土壤硝态氮含量增大。

2.2　土壤氮素盈亏量的表观估算

对夏玉米生育期间土壤氮素的表观盈亏的计算结果表明(表 1),本试验条件下,根据播种和收获两次测定值计算时,施氮量低于 112.5kg/hm^2 的土壤氮素(矿质态氮＋肥料氮)不足以满足夏玉米一生对氮素的需要量,即出现土壤氮素亏缺(表中数值为负值);在高氮肥处理则多于夏玉米需要量,即出现了土壤氮素盈余。但实际上,夏玉米一生中土壤氮素在低氮肥处理并不总是亏缺的,在高氮肥处理也并不总是盈余的。不同生育阶段的计算结果表明,在夏玉米播种～9 叶展期间即使在不施氮肥处理土壤氮素也是盈余的,9 叶展～吐丝期间 112.5kg N/hm^2 处理有一半基因型表现为盈余;但在吐丝～收获期间即使在最高氮肥处理土壤氮素也表现为亏缺。不同基因型的计算结果表现出相同的趋势。因此,研究玉米不同生育期土壤氮素盈亏变化及其与氮肥管理和土壤残留硝态氮含量的关系对于指导施肥更有意义。

对夏玉米一生中氮素的表观盈余总量(各生育阶段盈余量之和)计算结果表明,随着氮肥用量的增加,夏玉米不同基因型土壤氮素总的表观盈余量均明显增大,最高氮肥处理平均可达 274.1kg N/hm^2。而在不施氮肥处理土壤氮素虽然也有盈余,但其表观盈余总量很小。

3　讨论

3.1　土壤硝态氮含量与水分的关系

硝酸根在土壤中易随水移动决定了土壤硝态氮含量受水分的影响很大。夏玉米生长期间,由于降雨强度和频度都很大,很容易使上层土壤硝态氮随水下移,造成硝态氮的淋洗。在本研究中,夏玉米 9 叶展时各氮肥处理表层土壤硝态氮含量差异不大,高氮肥用量处理下层土壤硝态氮含量的明显增加是由于拔节前后两次强降雨带来的硝酸盐淋洗造成的。相反,在干旱条件下,由于深层土壤水分向上的移动,土壤硝酸盐也会随水向上移动。本试验中,不施氮肥处理和低氮肥处理夏玉米收获期 80～100cm 土层硝态氮含量的增加可能与下层土壤硝酸盐的随水上移有关。

3.2　土壤硝态氮含量与硝态氮淋失量的关系

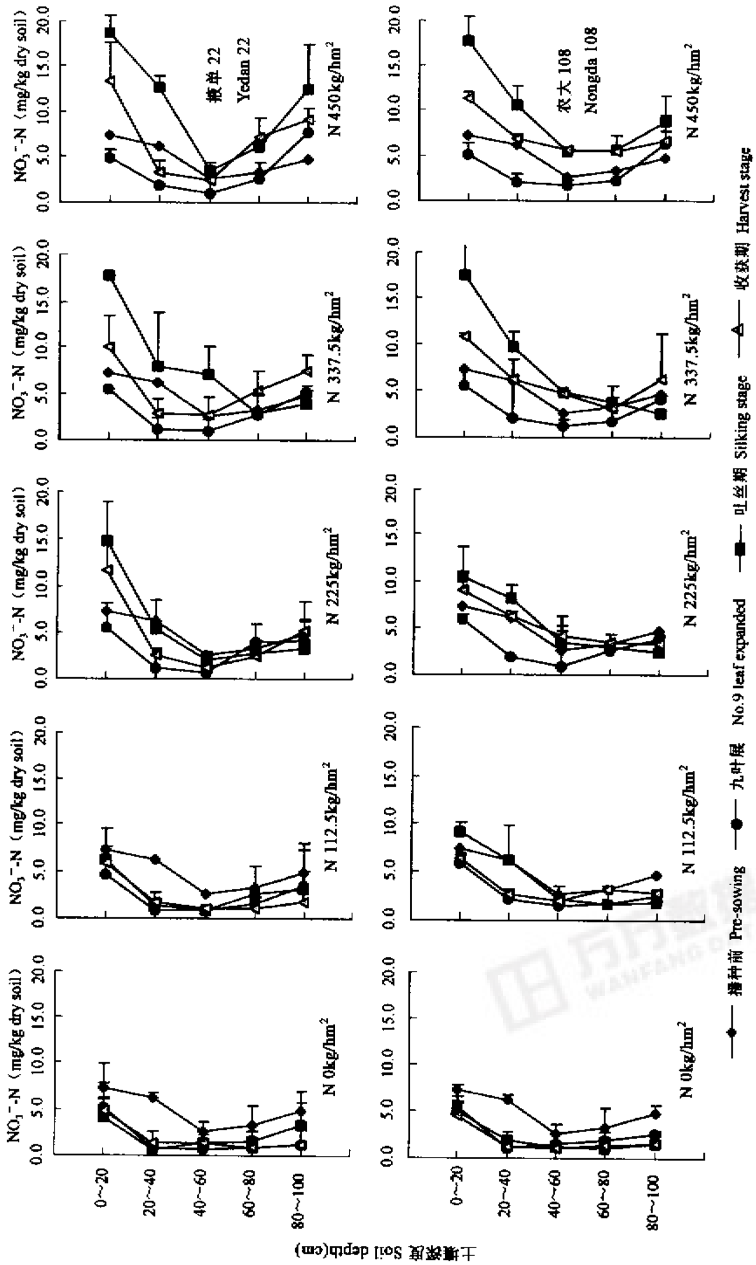

图 2 不同氮肥用量下夏玉米掖单 22 和农大 108 土壤 NO$_3^-$-N 时空变化

Fig. 2 The spatio-temporal variations of soil NO$_3^-$-N of genotype Yedan22 and Nongda108 under different N-fertilizer level

表 1　不同氮肥用量下夏玉米基因型土壤氮素在不同生育阶段的表观盈亏量

Table 1　Apparent budget of soil N at different stage in summer maize genotypes under different N-fertilizer level

基因型 Genotype	氮肥水平 N-fertilizer level (kgN/hm²)	表观盈亏量 Apparent budget of soil N (kgN/hm²) 播种～9 叶展 Sowing～the No. 9 leaf expanded	9 叶展～吐丝 The No. 9 leaf expanded～silking	吐丝～收获 Silking～harvest	播种～收获* Sowing～harvest
唐抗 5 Tangkang5	0	8.9	-15.4	-84.8	-91.3
	112.5	42.5	6.6	-68.5	-19.4
	225	78.9	47.4	-48.0	78.3
	337.5	113.8	98.3	-64.1	148.1
	450	155.3	121.4	-33.4	243.3
掖单 22 Yedan22	0	7.1	-48.2	-73.8	-114.9
	112.5	38.3	9.4	-74.9	-27.3
	225	80.5	29.1	-55.7	53.9
	337.5	111.4	77.8	-48.3	140.8
	450	156.8	100.2	-33.7	223.3
鲁原单 14 Luyuandan14	0	12.5	-49.9	-74.9	-112.2
	112.5	45.4	-7.7	-71.2	-33.5
	225	75.1	33.1	-60.6	47.6
	337.5	124.5	56.6	-16.3	164.8
	450	149.5	138.5	-47.4	240.6
丹玉 13 Danyu13	0	-0.1	-14.5	-58.0	-72.6
	112.5	40.8	-13.9	-25.4	1.5
	225	75.5	50.6	-51.9	74.2
	337.5	114.0	83.0	-41.3	155.7
	450	150.2	116.0	-6.8	259.4
农大 108 Nongda108	0	1.1	-35.1	-74.4	-108.4
	112.5	36.9	-13.3	-50.3	-26.7
	225	75.3	38.9	-56.8	57.5
	337.5	116.5	76.3	-56.2	136.6
	450	157.9	121.3	-48.1	231.2
农大 3315 Nongda3315	0	-0.1	-7.7	-73.4	-81.2
	112.5	37.4	14.3	-48.4	3.2
	225	78.6	56.7	-38.0	97.3
	337.5	125.2	91.5	-35.2	181.5
	450	156.9	120.8	-3.1	274.6

* 根据播种和收获两次的测定结果计算 The result was calculated according to the determined values at sowing and harvest stage

土壤硝态氮的运移受土壤水分状况和土壤硝态氮含量的影响。对不同氮肥用量下夏玉米 9 叶展和吐丝期土壤硝态氮含量的变化分析发现，土壤硝态氮含量越高，土壤硝态氮向深层移动的量越大，移动的越深。而不施氮肥处理大多数基因型土壤氮素即使在拔节前后两次高强度降雨的影响下，虽然没有出现亏缺，但其盈余量（即失踪量）却很小，个别基因型土壤氮素甚至出现了亏缺，可见，在土壤硝态氮含量低的情况下，即使土壤水分充足硝酸盐淋失的可能性也很小。

3.3　夏玉米生育期间硝态氮淋洗与施肥

对土壤中氮素的盈余与亏缺及硝态氮的时空变化特征研究结果表明，在高产条件下，夏玉米生育前期土壤氮素的供应量一般是过量的，在降雨的影响下土壤硝态氮向土壤深层的淋洗严重，淋出根层的可能性很大，造成土壤氮素的损失。在夏玉米生长季节，硝态氮的淋洗损失可能是盈余氮素损失的一个主要方式。而在夏玉米吐丝以后土壤氮素的供应量表现不足。因此，在夏玉米生育前期应酌情控制氮肥的比例，将土壤硝态氮浓度控制在一定水平内，在培育壮苗的基础上减少硝态氮向土壤深层的淋洗量，提高氮肥利用率；夏玉米生长中前期正值汛期，此期施肥应该慎重，但此期玉米生长发育的好坏对产量影响很大，如何实现合理施肥还是一个值得深入研究的问题；夏玉米吐丝期生长旺盛，土壤氮供应表现不足，应该补充氮素，实际上生产上也有施用粒肥的。但是，目前在生产中是否应该强调施用粒肥笔者认为还是值得研究的，此期施肥不仅仅操作不方便，特别是目前生产中主要种植的是绿叶成熟型品种，从资源的利用方面可能是不利的。

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