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# 双季稻田添加脲酶抑制剂 NBPT 氮肥的最高减量潜力研究

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**摘要:【目的】**添加脲酶抑制剂(Urease inhibitor, UI)是提高肥料利用率的有效途径,在尿素(Urea,U)中添加 1% 的脲酶抑制剂 NBPT(N-丁基硫代磷酰三胺)是目前研究使用证明效果最可靠的添加比例。针对当前稻田氮肥施用水平过高的问题,本文采用田间小区试验研究了目前脲酶抑制剂添加比例下稻田氮肥的减施潜力以及脲酶抑制剂的节肥增效机理。**【方法】**本试验在我国长江中下游的双季稻田进行,脲酶抑制剂用量 NBPT 为尿素用量的 1%。尿素用量设五个水平为 N 90、112.5、135、157.5 和 180 kg/hm$^2$,分别依次记为 U1、U2、U3、U4 和 U5, 7 个处理为 CK(不施氮肥)、U1+UI、U2+UI、U3+UI、U4+UI、U5+UI、U5(U5 为传统施氮量, N 180 kg/hm$^2$ 为农民习惯施氮量),三次重复。U1 ~ U5 处理施氮量分别是在农民习惯施氮量的基础上降低 50%、37.5%、25%、12.5%、0%。通过取样分析水稻分蘖期和孕穗期各处理对土壤脲酶活性、硝酸还原酶活性、土壤铵态氮含量、硝态氮含量以及微生物量碳、氮的含量,研究 NBPT 对水稻两个主要生育期土壤氮素供应的影响,比较各处理的产量以及氮肥利用率来得出氮肥的减施潜力,在此基础上通过逐步回归分析研究以上各指标对产量的影响,探明脲酶抑制剂(NBPT)在双季稻田的增效机理。**【结果】**1) 在双季稻田,添加 NBPT 后,施氮量为 N 135 kg/hm$^2$ 的籽粒产量达到最高。与传统施氮(单施尿素 N 180 kg/hm$^2$)处理相比,早、晚稻可分别增产 8.54% 和 12.87%,氮肥当季利用率分别提高 6.78% 和 9.46%,可节约氮肥 25%; 2)与传统施氮相比,添加 NBPT 显著降低了水稻分蘖期的土壤脲酶活性和铵态氮含量,显著提高了孕穗期的铵态氮含量,而对此时期的脲酶活性无显著影响,NBPT 对两个时期的硝酸还原酶活性、硝态氮含量及微生物量碳、氮含量均无明显影响,可见基施的 NBPT 主要是降低尿素水解速率方面效果显著,并且 NBPT 具有时效性,其主要是在水稻孕穗期之前起作用,在生态上较为安全; 3)从各项土壤指标与水稻产量相关性的逐步回归分析结果来看,水稻分蘖期与孕穗期稻田土壤中铵态氮含量对水稻产量影响显著,而且孕穗期的影响大于分蘖期,其余指标则对产量无明显影响。**【结论】**由于脲酶抑制剂 NBPT 减缓了分蘖期尿素的水解作用,提高了孕穗期土壤中的铵态氮含量,为水稻后期生长提供充足的氮肥,在双季稻减肥方面具有显著的效果。在本试验土壤条件下,尿素中添加 1% 的 NBPT,可在提高产量的同时,将传统施氮肥量减少 25%,是适于稻田应用的脲酶抑制剂。

**关键词:** 稻田; 脲酶抑制剂; NBPT; 脲酶活性
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# Highest potential of subtracting nitrogen fertilizer through addition of urease inhibitor NBPT in double-cropping paddy fields

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**Abstract**:【**Objectives**】The addition of urease inhibitor is proved to be an effective measure to improve the efficiency of mineral fertilizer. Addition of urease inhibitor N-(n-butyl) thiophosphoric triamide [NBPT] at a rate of 10 g/kg of urea has been widely used in researches. From the point of the high urea input in present rice production, the highest potential of saving nitrogen fertilizer through adding 1% of NBPT in urea was studied using a field experiment in paddy soils, and the mechanism of saving fertilizer and synergism from urease inhibitor were investigated.【**Methods**】A field experiment was conducted in a double-cropping paddy field in middle and lower reaches of the Yangtze River area, Southern China. Urea was mixed with urease inhibitor NBPT at a rate of 10 g/kg urea, five urea levels: N 90, 112.5, 135, 157.5 and 180 kg/ha were designed and recorded as U1, U2, U3, U4 and U5 in turn, plus a no N control and a normal urea of N 180 kg/ha in the experiment. A completely randomized design with seven treatments and three replicates was as follows, 1) CK (no N control); 2) U1 + UI; 3) U2 + UI; 4) U3 + UI; 5) U4 + UI; 6) U5 + UI; 7) U5. The subtracting ratio of N fertilizer for U1, U2, U3, U4 and U5 is 50%, 37.5%, 25%, 12.5% and 0% respectively. The activities of urease and nitrate reductase, the contents of $NH_4^+$-N, $NO_3^-$-N and microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) in soil were analyzed in tillering and booting stages. The rice yield and N efficiency were investigated.【**Results**】1) With the addition of UI, the highest yield was obtained at N rate of 135 kg/ha. Compared with the normal urea N rate of 180 kg/ha, the grain yields were increased by 8.54% and 12.87% in early and late rice, the recovery of applied N improved by 6.78% and 9.46%, respectively, and 25% of N fertilizer could be saved as a result. 2) The addition of NBPT in urea notably reduced urease activity, and soil $NH_4^+$-N content at the tillering stage and increased soil $NH_4^+$-N content at the booting stage, while there were no obvious effects on nitrate reductase activity (NRA), soil $NO_3^-$-N content and MBC and MBN. There was no significant difference in urease activity between with and without NBPT at the booting stage. Therefore, the urease inhibitor NBPT was effective before the booting stage and had less long term negative influence on soil environment. 3) The stepwise regression analysis reveals that the grain yield of rice is significantly associated with $NH_4^+$-N content in soil at the tillering and booting stages, especially, the latter. However, other properties in soil have no obvious effects on the grain yield.【**Conclusions**】The potential of saving N fertilizer from NBPT is outstanding in double-cropping paddy fields. Compared with the normal urea, N fertilizer is saved by 25% when NBPT is used. NBPT slows down the hydrolytic action of urea and dramatically improves soil $NH_4^+$-N content in the booting stage, which appears to be the dominant factor of saving N fertilizer. The above results suggest that NBPT could remain adequate N resources at late growth stage for rice and serve as a urease inhibitor for developing slow release fertilizer in paddy soils.

**Key words:** paddy field; urease inhibitor; NBPT; urease activity

水稻是我国三大粮食作物之一,其种植面积与产量分别占粮食作物总量的27%和38%左右,其中双季稻的播种面积约占水稻总面积的40.1%(2012年)[1],主要分布在我国华南与长江中下游稻区。近年来,稻田的氮肥利用率与氮素损失备受关注,据报道,稻田的氮素损失位于三大作物之首[2],损失率高达30%~70%[3]。以尿素施入稻田为例,根据土壤及气候因素的不同,尿素施入稻田后2~10天内完全水解[4],释放大量的铵态氮,导致田面水的pH值迅速上升,造成严重的氨挥发损失。另外,氮肥施入稻田的当季,硝化-反硝化损失也是重要的氮素损失途径[3],大量的氮素损失造成环境、经济、社会问题,因此,有效减少双季稻田氮素损失、提高氮肥利用率对社会及生态效益意义重大。

添加脲酶抑制剂可以减缓尿素的氮损失,提高氮肥利用率[4]。有研究报道,脲酶抑制剂与尿素一起施用可以延缓酰胺态氮向铵态氮的转化进程7~14天,从而减少氮素损失,提高氮肥利用率[4,5-7]。在世界农业领域应用最广泛而且唯一商业化的脲酶抑制剂NBPT[(N-(n-butyl) thiophosphoric triamide, N-丁基硫代磷酰三胺][4,7-8],是一种高效无毒、环境友好型抑制剂[9]。NBPT的分子式为$C_4H_{13}N_3PS$,其化学结构与尿素相似,属于竞争性抑制剂,当二者混合施用时,NBPT可以与尿素竞争脲酶的活性位点,从而减少了脲酶与尿素的结合几率,延缓了尿素的水解反应[10]。

经过大量的田间试验验证[4],包括在热带的淹水稻田[6,11],NBPT 可以有效地提高作物产量[12-14]以及氮肥利用率[13,15],但关于脲酶抑制剂对我国稻田氮素转化影响的研究较少,本文研究尿素添加脲酶抑制剂(NBPT)对我国双季稻田的无机氮含量、酶活性、微生物量碳、氮含量以及氮素回收率等的影响,确定早稻与晚稻添加脲酶抑制剂时的适宜施氮量,为稻田减少氮素损失、提高氮肥利用率提供科学依据,为稻田施肥提供技术指导。

# 1　材料与方法

## 1.1　试验地概况

试验于 2012 年 4 月至 10 月在江西省进贤县红壤所试验站(116°20′24″E, 28°15′30″N)实施,土壤为河流冲积物发育而成。该区属于亚热带湿润气候,海拔高度 26 m,平均气温 17.8 ℃,无霜期长达 240～307 d,年降水量 1400～1662 mm,降水季节分配不均,全年降水 50% 以上集中在 4～6 月。播种前土壤有机质含量 38.80 g/kg,全氮含量 2.53 g/kg, 铵态氮和硝态氮含量分别为 42.46 mg/kg 和 1.04 mg/kg,有效磷 16.78 mg/kg,速效钾 120.1 mg/kg,pH 5.50。

## 1.2　试验设计

水稻供试品种:早稻为德农 88,晚稻为汕优 456;脲酶抑制剂为 NBPT;供试肥料品种:氮肥为尿素(含 N 46%),磷肥为钙镁磷肥(含 $P_2O_5$ 12%),钾肥为氯化钾(含 $K_2O$ 60%)。

早稻与晚稻试验均设 7 个处理:CK、U1 + UI、U2 + UI、U3 + UI、U4 + UI、U5 + UI、U5。CK,不施氮肥;U,尿素;UI,脲酶抑制剂;U1～U5 的施氮量依次为:N 90、112.5、135、157.5 和 180 kg/hm$^2$;N 180 kg/hm$^2$ 为传统施氮量,U1～U5 的施氮量分别降低 50%、37.5%、25%、12.5%、0%,以确定添加脲酶抑制剂条件下氮肥的减施潜力;脲酶抑制剂用量为尿素的 1%,施入前将二者混合均匀。试验设 3 次重复,各小区随机区组排列,每个小区面积 30 m$^2$(5 m × 6 m),各小区以 50 cm 的分隔行隔开,小区间的田埂高 40 cm,并用塑料薄膜包裹以达到各小区单灌单排的管理目的。试验中磷($P_2O_5$)、钾($K_2O$)的用量分别为 75 kg/hm$^2$ 和 150 kg/hm$^2$。氮肥和磷肥全部用作基肥于移栽前一次性施入;钾肥分 3 次施入,40% 作基肥,30% 作分蘖肥,30% 作孕穗肥。早稻于 2012 年 3 月 16 日播种,4 月 23 日移栽,7 月 20 日收获,晚稻于 6 月 17 日播种,7 月 25 日移栽,10 月 20 日收获。田间的施肥措施以及各项管理同当地农民习惯。

在水稻分蘖期、孕穗期分别采集各小区耕层土壤样品,测定脲酶与硝酸还原酶活性、铵态氮与硝态氮含量、微生物量碳、氮含量;用于测定酶活性、无机氮的土样若不能立即测定需保存于 −20℃,用于测定微生物量碳、氮含量的土样则保存于 4℃;成熟期测定各小区产量以及植株氮含量。

## 1.3　测定方法与计算

1.3.1 土壤中脲酶与硝酸还原酶活性的测定　脲酶活性采用 $NH_4^+$ 释放量法测定[16],硝酸还原酶活性通过测定 $NO_2^-$-N 产生量的方法[17]计算。

1.3.2 土壤中铵态氮与硝态氮含量的测定　土壤中的铵态氮与硝态氮含量用 1 mol/L 的 KCl 溶液浸提,采用 Smartchem™200 discrete chemistry analyzer (West-Co Scientific Instruments, Brookfiel, CT, USA) 仪器测定。

1.3.3 微生物量碳、氮含量测定与计算　土壤微生物量碳、氮含量的测定采用氯仿熏蒸—$K_2SO_4$ 浸提法[18-21],其含量计算如下:

$$B_C = E_C/K_C$$

$$B_N = E_N/K_N$$

其中,$B_C$、$B_N$ 分别为土壤微生物量碳、氮含量;$E_C$、$E_N$ 分别为熏蒸和未熏蒸样品中有机碳、全氮含量之差;$K_C$、$K_N$ 为回收系数,$K_C = 0.45$[19-20],$K_N = 0.54$[21]。

1.3.4 植株氮素含量的测定　取植株粉碎样,用浓 $H_2SO_4 - H_2O_2$ 消化,用 Smartchem™ 200 discrete chemistry analyzer (West-Co Scientific Instruments, Brookfiel, CT, USA) 仪器测定。

1.3.5 数据处理　所有数据采用 Excel 2007、SAS 9.1 软件进行统计分析,运用 Excel 2007 软件作图。

# 2　结果与分析

## 2.1　不同处理对水稻产量的影响

由图 1 可知,各处理对水稻产量的影响显著($P < 0.05$)。对于早、晚稻,处理 U3 + UI 的产量最高,且与处理 U5 的差异显著,说明与传统施氮(单施尿素 N 180 kg/hm$^2$)相比,施用尿素添加脲酶抑制剂 NBPT 时,施氮量为 N 135 kg/hm$^2$ 可显著提高水稻产量,早、晚稻分别提高 8.54% 和 12.87%;此处理不仅增产显著,而且减少氮肥(N)用量 45 kg/hm$^2$,

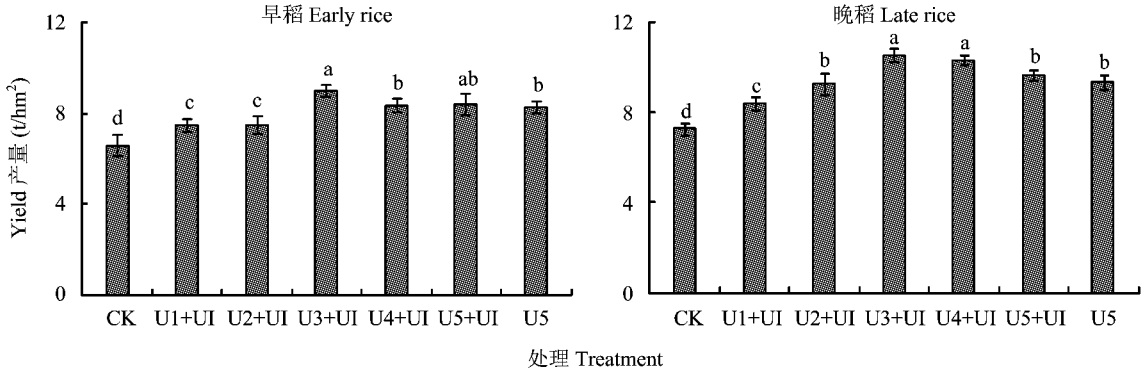


**图1 不同处理水稻产量**

**Fig. 1 Yield of rice under different treatments**

[注(Note): CK—不施氮肥 No N control; U—尿素 Urea; UI—脲酶抑制剂 Urease inhibitor; U1 ~ U5 的施氮量依次为 N 90、112.5、135、157.5、180 kg/hm² The N application rates of U1 – U5 were N 90, 112.5, 135, 157.5 and 180 kg/ha, respectively. 柱上不同小写字母代表处理间差异在5%水平显著 Different small letters above the bars mean significantly different among treatments at 5% level.]

即节约氮肥25%。在晚稻产量中,处理U3 + UI、U4 + UI显著高于处理U5 + UI的,在田间观察到U5 + UI处理的植株贪青晚熟,可能是其产量下降的主要原因。

## 2.2 不同处理对水稻氮素回收率的影响

由图2可知,不同处理对氮素回收率的影响显著($P < 0.05$),在早、晚稻,处理U1 + UI ~ U3 + UI的氮素回收率均显著高于处理U5的。与处理U5相比,处理U1 + UI的氮素回收率在早、晚稻分别高出9.48%和10.30%,处理U3 + UI则分别高出6.78%和9.46%。

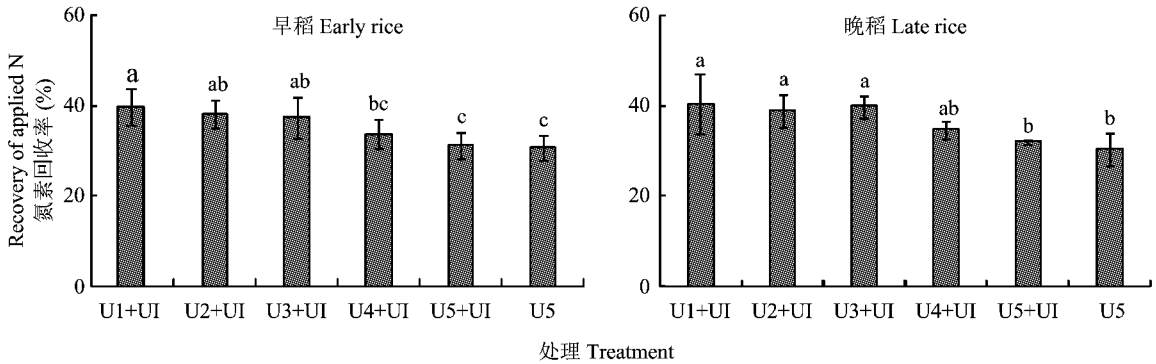


**图2 水稻地上部的氮素回收率**

**Fig. 2 Recovery of applied N in above-ground parts of rice**

[注(Note): U—尿素 Urea; UI—脲酶抑制剂 Urease inhibitor; U1 ~ U5 的施氮量依次为 N 90、112.5、135、157.5、180 kg/hm² The N application rates of U1 – U5 were N 90, 112.5, 135, 157.5 and 180 kg/ha, respectively. 柱上不同小写字母代表处理间差异在5%水平显著 Different small letters above the bars mean significantly different among treatments at 5% level.]

## 2.3 不同处理对土壤脲酶与硝酸还原酶活性的影响

由图3可知,土壤脲酶活性在处理间的差异达显著水平($P < 0.05$);施氮处理的脲酶活性显著高于对照处理的,说明施用氮肥显著提高了脲酶活性,可能由于基质的增加,促进了水稻根系以及微生物的生长,引起脲酶活性增加。在分蘖期,早、晚稻处理U5的脲酶活性均显著高于其余处理,分别高达$NH_4^+$-N 15.48 μg/(g · 2h)和$NH_4^+$-N 15.71 μg/(g·2h),分别高出U5 + UI处理22.02%和22.17%,说明添加脲酶抑制剂NBPT显著降低了脲酶活性,表明NBPT对脲酶活性有显著的抑制作用。

在孕穗期,添加NBPT的处理与传统施氮处理间无显著差异,可能由于时间的推移,NBPT逐渐降

解，失去了对脲酶的抑制作用，尿素也被完全分解，脲酶活性基本恢复等原因导致。

与土壤脲酶活性相比，硝酸还原酶活性极其微弱，早稻土壤小于 $NO_2^-$-N 0.08 μg/(g·24h)，晚稻小于 $NO_2^-$-N 0.06 μg/(g·24h)；同一生育期内，处理间无显著差异(图 3)，表明不同水平的氮肥对稻田硝酸还原酶活性没有明显影响，添加 NBPT 对硝酸还原酶活性也无明显作用。

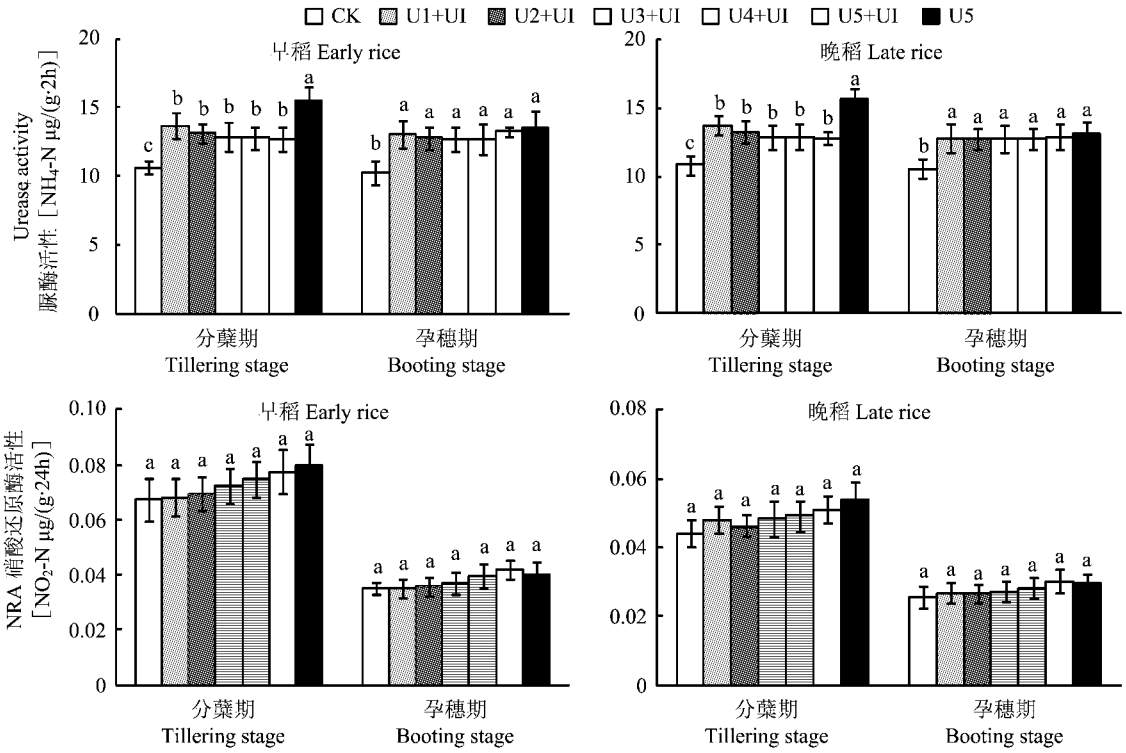


**图 3　水稻分蘖期和孕穗期土壤脲酶与硝酸还原酶活性**

**Fig. 3　Activities of urease and nitrate reductase in soil at tillering and booting stages of rice**

[注(Note)：CK—不施氮肥 No N control；U—尿素 Urea；UI—脲酶抑制剂 Urease inhibitor；U1 ～ U5 的施氮量依次为 N 90、112.5、135、157.5、180 kg/hm² The N application rates of U1 – U5 were N 90, 112.5, 135, 157.5 and 180 kg/ha, respectively. 柱上不同小写字母代表同一时期内处理间差异在 5% 水平显著 Different small letters above the bars mean significantly different among treatments in the same growth stage at 5% level.]

## 2.4　不同处理对土壤铵态氮和硝态氮含量的影响

图 4 结果表明，稻田土壤中的铵态氮含量明显高于硝态氮含量。在水稻分蘖期，处理 U5 的铵态氮含量显著高于其余处理的，早、晚稻分别高达 79.65 mg/kg 和 99.55 mg/kg；与 U5 处理相比，施氮量相同的 U5 + UI 处理在早、晚稻分别降低铵态氮含量 12.04% 和 10.41%。在孕穗期，土壤铵态氮含量急剧下降，且处理间差异显著($P < 0.05$)，可能由于此时水稻对氮肥的大量吸收所致[22]；添加 NBPT 处理的铵态氮含量随着施氮量的增加而呈递增趋势，处理 U5 + UI 的最高；与处理 U5 相比，处理 U5 + UI 的铵态氮含量在早、晚稻分别高出 21.11% 和 32.25%。以上结果说明，添加 NBPT 显著减少了分蘖期土壤的铵态氮含量，而显著增加了孕穗期的铵态氮含量。

与土壤的铵态氮含量相比，硝态氮含量极低，不足铵态氮含量的 2%，且处理间的差异始终不显著($P > 0.05$)，反映了稻田长期淹水，土壤持续厌氧环境下硝化作用极其微弱，而且不同的施氮量以及添加 NBPT 对硝态氮含量均无明显影响。

## 2.5　不同处理对微生物量碳、氮含量的影响

图 5 显示，水稻分蘖期与孕穗期的土壤微生物量碳含量、微生物量氮含量、微生物量碳/氮比值在各时期内处理间的差异不显著($P > 0.05$)，说明不同施肥处理对微生物量碳、氮含量没有显著影响，添加脲酶抑制剂对土壤生物特性没有明显影响。对同一时期的微生物量碳、氮含量进行相关性分析发现，二者存在极显著正相关关系($P < 0.01$)。分

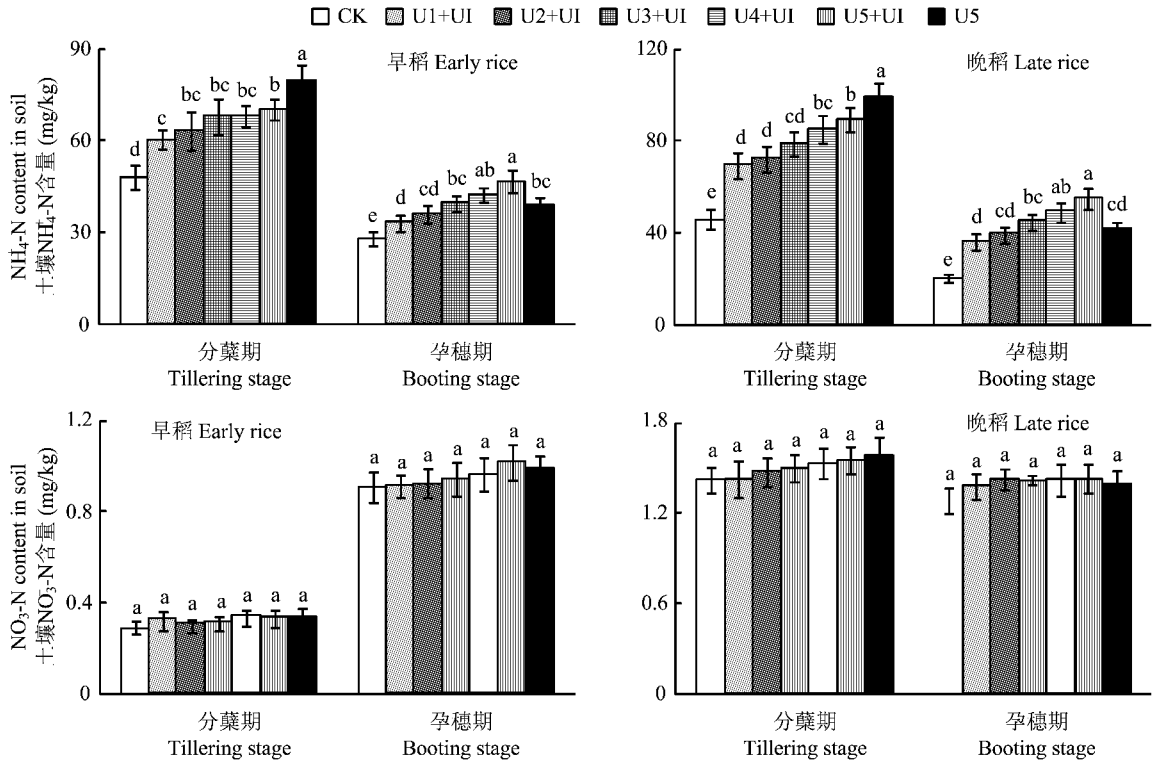


**图4 水稻分蘖期与孕穗期土壤铵态氮与硝态氮含量**

**Fig. 4 Contents of $NH_4^+$-N and $NO_3^-$-N in soil at tillering and booting stages of rice**

[注(Note): CK—不施氮肥 No N control; U—尿素 Urea; UI—脲酶抑制剂 Urease inhibitor; U1 ~ U5 的施氮量依次为 N 90、112.5、135、157.5、180 kg/hm$^2$ The N application rates of U1 - U5 were N 90, 112.5, 135, 157.5 and 180 kg/ha, respectively. 柱上不同小写字母代表同一时期内处理间差异在5%水平显著 Different small letters above the bars mean significantly different among treatments in the same growth stage at 5% level.]

别对以上三项指标在早、晚稻两个时期的变化进行分析,结果表明,微生物量碳、氮含量在晚稻两个时期之间的差异显著($P<0.05$),而在早稻的差异不显著($P>0.05$),这说明晚稻的季节变化对微生物量碳、氮含量的影响较施肥处理的影响更大。

### 2.6 土壤生物特性与水稻产量的相关性

将水稻两个生育期的土壤脲酶活性、硝酸还原酶活性、铵态氮含量、硝态氮含量、微生物量碳含量、微生物量氮含量、微生物量碳/氮比值7项指标对产量的影响进行逐步回归分析($n=21$)。结果表明,只有铵态氮含量进入回归方程,说明土壤铵态氮含量对产量的影响显著,而其余6项指标对产量的影响不显著。回归方程的相关参数见表1。由表1可知,对于早、晚稻,两个时期的铵态氮含量对产量的影响均达极显著水平($P<0.01$),而且,孕穗期的影响大于分蘖期的,说明氮肥对于水稻产量的提高作用显著,尤其是孕穗期的氮肥更为重要。

## 3 讨论与结论

土壤酶活性受到诸多因素的影响[23-24],如脲酶活性与基质浓度、温度、pH、有机质含量、微生物生物量、总氮量等因素呈正相关关系[25-31],短期内可被脲酶抑制剂抑制(脲酶抑制剂有一定的时效性,如NBPT施入土壤后2周左右可降解为N、P、S等元素[9])。本研究发现,在早稻与晚稻的分蘖期,施用氮肥显著提高了土壤脲酶活性,而添加NBPT后脲酶活性并没有随着施氮量的增加而增加,且添加NBPT下各处理的脲酶活性均显著低于传统施氮处理的,说明基质的增加会提高脲酶活性,而NBPT则对脲酶活性有较强的抑制作用;到孕穗期,可能由于脲酶抑制剂NBPT逐渐降解失去抑制效应,尿素完全水解,脲酶活性趋于平稳,施用氮肥的各处理间无显著差异。对于硝酸还原酶活性,在早稻与晚稻的两个时期,活性始终维持在极低水平,可能由于稻田长期淹水的特殊环境导致;不同处理间没有显

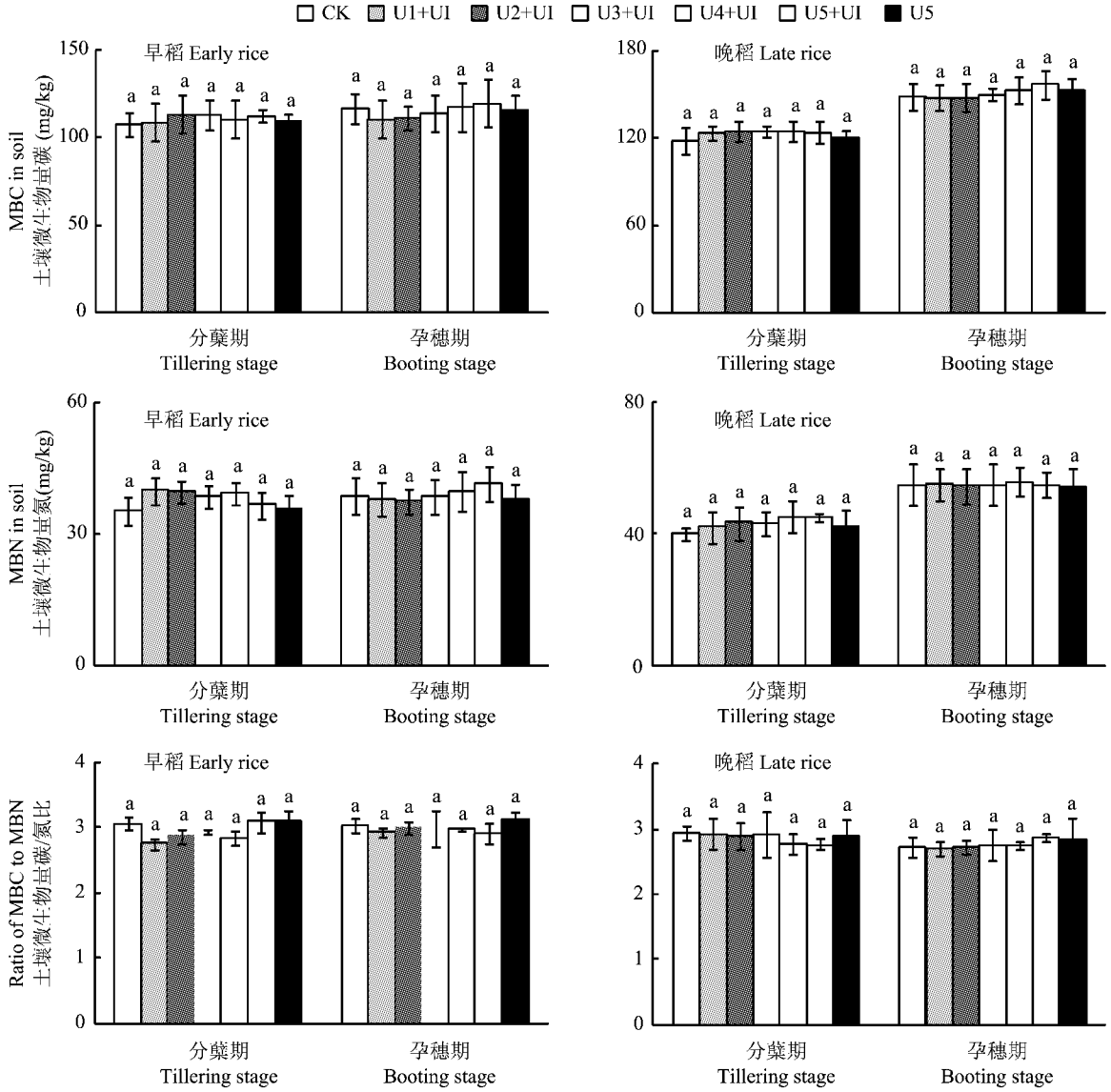


**图 5　分蘖期和孕穗期土壤微生物量碳、氮含量以及碳/氮比值**

**Fig. 5　Contents of MBC and MBN and ratio of MBC to MBN in soil at tillering and booting stages**

[注(Note)：CK—不施氮肥 No N control；U—尿素 Urea；UI—脲酶抑制剂 Urease inhibitor；U1 ～ U5 的施氮量依次为 N 90、112.5、135、157.5、180 kg/hm$^2$ The N application rates of U1 – U5 were N 90, 112.5, 135, 157.5 and 180 kg/ha, respectively. 柱上不同小写字母代表同一时期内处理间的差异在 5% 水平显著 Different small letters above the bars mean significantly different among treatments in the same growth stage at 5% level.]

**表 1　水稻产量与两个生育期影响因子的逐步回归分析($n$ = 21)**

**Table 1　Stepwise regression between grain yield of rice and factors in tillering and booting stages**

| 生育期 Growth stage | 早稻 Early rice | | | | | 晚稻 Late rice | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 因子 Factor | 常数 Constant | 系数 Coefficient | 拟合度 $R^2$ | $P$ | 因子 Factor | 常数 Constant | 系数 Coefficient | 拟合度 $R^2$ | $P$ |
| 分蘖期 Tillering stage | $NH_4^+$-N | 3.6869 | 0.0649 | 0.6404 | <0.0001 | $NH_4^+$-N | 5.3137 | 0.0509 | 0.5375 | <0.0001 |
| 孕穗期 Booting stage | $NH_4^+$-N | 3.8585 | 0.1081 | 0.6776 | <0.0001 | $NH_4^+$-N | 5.1898 | 0.0980 | 0.6824 | <0.0001 |

注(Note)：回归方程为 $y = ax + b$ $y$ 为产量，$a$ 为系数，$x$ 为因子，$b$ 为常数 The values are fitted in the equation $y = ax + b$, $y$—Yield, $a$—Coefficient, $x$—Factor, $b$—Constant.

著差异,表明氮肥以及脲酶抑制剂对硝酸还原酶活性没有明显的影响,这与李东坡等人的报道[9,32]一致。

相同施氮量下,添加 NBPT 的处理(U5 + UI)在分蘖期土壤铵态氮含量显著低于传统施氮处理(U5)的,而孕穗期截然相反,进一步说明添加脲酶抑制剂可有效减缓生育前期尿素的水解,减少土壤中的铵态氮含量,在后期随着脲酶抑制剂的降解,尿素完全水解,因而可为需肥高峰期的水稻提供更加充分的铵态氮。水稻孕穗期耕层土壤中的铵态氮含量显著低于分蘖期,也是因为在孕穗期水稻根系庞大,对养分的吸收强度和数量急剧增加[22],导致土壤中的铵态氮含量骤降。土壤中硝态氮含量始终较低,不足铵态氮含量的 2%,且不受施氮量的影响,这与 Wang[33]等人报道一致;另外,硝态氮含量没有明显的变化,可能与稻田长期淹水以及水稻为喜铵作物有关。

本研究结果中,在水稻分蘖期和孕穗期的处理间微生物量碳、氮含量均无显著差异,证明了添加 NBPT 对微生物无明显副作用[9,34]。同一时期内微生物量碳、氮含量存在极显著正相关关系,这与 Mandal 等[35]的报道一致。土壤微生物量碳、氮含量以及土壤酶活性受到多种因素的影响[29],在作物生长期,微生物生物量会因为作物的生长、气候变化而发生短暂的季节性波动[36],本研究中,晚稻的两个生育期之间微生物量碳、氮含量存在显著差异,孕穗期土壤微生物量碳、氮含量显著高于分蘖期,显示了季节变化的影响[24,37],早稻则无此差异,这可能由于晚稻生长期间,温度较高,水稻生长旺盛,根系分泌物较多,土壤微生物活性较高等诸多因素导致。

通过对稻田土壤的七项指标在分蘖期和孕穗期与产量的关系进行逐步回归分析发现,只有土壤铵态氮含量对产量的影响显著,且孕穗期的影响大于分蘖期的,因此,通过添加脲酶抑制剂,有效地实现了尿素水解后移,增加了孕穗期土壤铵态氮的供应,可能是其节约氮肥与增产显著的主要原因。本研究中,对不同处理的水稻产量和氮素回收率分析结果也证明了添加脲酶抑制剂的有效性。在同样产量目标下,添加 1% 的脲酶抑制剂可以节省 25% 的尿素,今后可继续深入研究添加脲酶抑制剂的节肥潜力。

**参 考 文 献:**


[1] 朱德峰,陈惠哲,徐一成,张玉屏. 我国双季稻生产机械化制约因子与发展对策[J]. 中国稻米, 2013, 19(4): 1-4.
Zhu D F, Chen H Z, Xu Y C, Zhang Y P. Limiting factors and countermeasures of mechanization for double-cropping rice [J]. China Rice, 2013, 19(4): 1-4.

[2] 巨晓棠,张福锁. 关于氮肥利用率的思考[J]. 生态环境, 2003, 12(2): 192-197.
Ju X T, Zhang F S. Thinking about nitrogen recovery rate[J]. Ecology and Environment, 2003, 12(2): 192-197.

[3] 朱兆良. 农田中氮肥的损失与对策[J]. 土壤与环境, 2000, 9(1): 1-6.
Zhu Z L. Loss of fertilizer N from plants-soil system and the strategies and techniques for its reduction [J]. Soil and Environmental Sciences, 2000, 9 (1): 1-6.

[4] Trenkel M E. Characteristics and types of slow- and controlled-release fertilizers and nitrification and urease inhibitors [A]. Trenkel M E. Slow- and controlled-release and stabilized fertilizers: an option for enhancing nutrient use efficiency in agriculture[C]. Paris: International Fertilizer Industry Association (IFA). 2010: 56.

[5] Chien S H, Prochnow L I, Cantarella H. Recent developments of fertilizer production and use to improve nutrient efficiency and minimize environmental impacts [J]. Advances in Agronomy, 2009, 102: 267-322.

[6] Byrnes B H, Freney J R. Recent developments on the use of urease inhibitors in the tropics[A]. Springer Netherlands: Ahmad N. Nitrogen Economy in Tropical Soils [C]. Trinidad: Kluwer Academic Publishers, 1996: 251-259.

[7] Alberto S C, Laura S M, Lourdes G T *et al*. Gaseous emissions of $N_2O$ and NO and $NO_3^-$ leaching from urea applied with urease and nitrification inhibitors to a maize (*Zea mays*) crop [J]. Agriculture, Ecosystems and Environment, 2012, 149: 64-73.

[8] Xiang S, Doyle A, Holden P A *et al*. Drying and rewetting effects on C and N mineralization and microbial activity in surface and subsurface California grassland soils [J]. Soil Biology and Biochemistry, 2008, 40 (9): 2281-2289.

[9] Chaiwanakupt P, Freney J R, Keerthisinghe D G *et al*. Use of urease, algal inhibitors, and nitrification inhibitors to reduce nitrogen loss and increase the grain yield of flooded rice (*Oryza sativa* L.)[J]. Biology and Fertility of Soils, 1996, 22(1-2): 89-95.

[10] 孙庆元,张雪崧,王艳红. 土壤脲酶抑制剂正丁基硫代磷酰三胺的作用基团研究[J]. 土壤, 2007, 39(3): 492-495.
Sun Q Y, Zhang X S, Wang Y H. Functional groups of soil urease inhibitor NBPT[J]. Soils, 2007, 39(3): 492-495.

[11] Luo Q X, Freney J R, Keerthisinshe D G *et al*. Inihibition of urease activity in flooded soils by phenylphosphorodiamidate and N-(n-butyl) thiophosphoricariamides [J]. Soil Biology and

Biochemistry, 1994, 26(8): 1059-1065.

[12] Grant C A, Bailey L D. Effect of seed-placed urea fertilizer and N-(n-butyl) thiophosphoric triamide (NBPT) on emergence and grain yield of barley[J]. Canadian Journal of Plant Science, 1999, 91(79): 491-496.

[13] Malhi S S, Oliver E, Mayerle G *et al*. Improving effectiveness of seedrow-placed urea with urease inhibitor and polymer coating for durum wheat and canola[J]. Communications in Soil Science and Plant Analysis, 2003, 34(11-12): 1709-1727..

[14] Freney J R, Keerthisinghe D G, Phongpan S *et al*. Effect of urease, nitrification and algal inhibitors on ammonia loss and grain yield of flooded rice in Thailand[J]. Fertilizer Research, 1995, 40: 225-233.

[15] Abdallahi M M, N'Dayegamiye A. Effects of two incorporations of green manures on soil physical and biological properties and on wheat (*Triticum aestivum* L.) yields and N uptake [J]. Canadian Journal of Soil Science, 2000, 80(1): 81-89.

[16] Kandeler E, Gerber H. Short-term assay of soil urease activity using colorimetric determination of ammonium[J]. Biology and Fertility of Soils, 1988, 6(1): 68-72.

[17] Abdelmagid H M, Tabatabai M A. Nitrate reductase activity of soils[J]. Soil Biology and Biochemistry, 1987, 19(4): 421-427.

[18] 鲁如坤. 土壤农业化学分析法[M]. 北京: 中国农业科技出版社,2000.
Lu R K. Analytical methods of soil and agro-chemistry[M]. Beijing: China Agricultural Science and Technology Press, 2000.

[19] Wu J, Joergensen R G, Pommerening B *et al*. Measurement of soil microbial biomass C by fumigation-extraction automated procedure[J]. Soil Biology and Biochemistry, 1990, 22(8): 167-169.

[20] Vance E D, Brggke P C, Jenkinson D S. An extraction method for measuring soil microbial biomass C[J]. Soil Biology and Biochemistry, 1987, 19(6): 703-707.

[21] Brookes P C, Landman A, Pruden G *et al*. Chloroform fumigation and the release of soil nitrogen: A rapid direct extraction method to measure microbial biomass nitrogen in soil [J]. Soil Biology and Biochemistry, 1985, 17(6): 837-842.

[22] 黄见良, 邹应斌, 彭少兵, 等. 水稻对氮素的吸收、分配及其在组织中的挥发损失[J]. 植物营养与肥料学报, 2004,10(6): 579-583.
Huang J L, Zou Y B, Peng S B *et al*. Nitrogen uptake, distribution by rice and its losses from plant tissues[J]. Journal of Plant Nutrition and Fertilizer, 2004, 10(6): 579-583.

[23] 雍太文,杨文钰,向达兵,等. 不同种植模式对土壤氮素转化及酶活性的影响[J]. 应用生态学报, 2011, 22(12): 3227-3235.
Yong T W, Yang W Y, Xiang D B *et al*. Effects of different planting modes on soil nitrogen transformation and related enzyme activities[J]. Chinese Journal of Applied Ecology, 2011, 22(12): 3227-3235.

[24] Geisseler D, Horwath W R. Short-term dynamics of soil carbon, microbial biomass, and soil enzyme activities as compared to longer-term effects of tillage in irrigated row crops[J]. Biology and Fertility of Soils, 2009, 46(1): 65-72.

[25] 和文祥,朱铭莪,张一平. 汞、镉对土壤脲酶活性影响的研究 Ⅰ. 尿素浓度[J]. 应用生态学报, 2002, 13(2): 191-193.
He W X, Zhu M G, Zhang Y P. Effects of mercury and cadmium on the activity of urease in soils Ⅰ. Urea concentration[J]. Chinese Journal of Applied Ecology, 2002, 13(2): 191-193.

[26] Rachhpal S, Nye P H. The effect of soil pH and high urea concentrations on urease activity in soil[J]. Journal of Soil Science, 1984, 35(4): 519-527.

[27] 郭天财, 宋晓, 马冬云, 等. 施氮量对冬小麦根际土壤酶活性的影响[J]. 应用生态学报, 2008, 19(1): 110-114.
Guo T C, Song X, Ma D Y *et al*. Effects of nitrogen application rate on soil enzyme activities in wheat rhizosphere[J]. Chinese Journal of Applied Ecology, 2008, 19(1): 110-114.

[28] Moyo C C, Kisseli D E., Cabrera M L. Temperature effects on soil urease activity[J]. Soil Biology and Biochemistry, 1989, 21(7): 935-938.

[29] 马晓霞, 王莲莲, 黎青慧, 等. 长期施肥对玉米生育期土壤微生物生物量碳氮及酶活性的影响[J]. 生态学报, 2012, 32(17): 5502-5511.
Ma X X, Wang L L, Li Q H *et al*. Effects of long-term fertilization on soil microbial biomass carbon and nitrogen and enzyme activities during maize growing season [J]. Acta Ecologica Sinica, 2012, 32(17): 5502-5511.

[30] Zhong W H, Cai Z C, Zhang H. Effects of long-term application of inorganic fertilizers on biochemical properties of a rice-planting red soil[J]. Pedosphere, 2007, 17 (4): 419-428.

[31] Bhattacharyya P, Chakrabarti K, Chakraborty A. Microbial biomass and enzyme activities in submerged rice soil amended with municipal solid waste compost and decomposed cow manure [J]. Chemosphere, 2005, 60: 310-318.

[32] 李东坡, 梁成华, 武志杰, 等. 玉米苗期施用缓/控释氮素肥料养分释放特点与土壤生物活性研究[J]. 沈阳农业大学学报, 2006, 37(1): 48-52.
Li D P, Liang C H, Wu Z J *et al*. Characteristics of releasing nutrition and soil biological activities at maize seedling stage for using slow/controlled release nitrogen fertilizers[J]. Journal of Shenyang Agricultural University, 2006, 37(1): 48-52.

[33] Wang Y, Ke X, Wu L *et al*. Community composition of ammonia-oxidizing bacteria and archaea in rice field soil as affected by nitrogen fertilization [J]. Systematic and Applied Microbiology, 2009, 32(1): 27-36.

[34] Ajwa H A, Dell C J, Rice C W. Changes in enzyme activities

and microbial biomass of tallgrass prairie soil as related to burning and nitrogen fertilization [J]. Soil Biology and Biochemistry, 1999, 31: 769-777.

[35] Mandal A, Patra A K, Singh D *et al*. Effect of long-term application of manure and fertilizer on biological and biochemical activities in soil during crop development stages[J]. Bioresource Technology, 2007, 98(18): 3585-3592.

[36] Mahmood T, Ali R, Hussain F, Tahir G R. Seasonal changes in soil microbial biomass carbon under a wheat-maize cropping system receiving urea and farmyard manure in different combinations[J]. Pakistan Journal of Botany, 2005, 37(1): 105-117.

[37] Franzluebbers A J, Hons F M, Zuberer D A. Seasonal changes in soil microbial biomass and mineralizable C and N in wheat management systems[J]. Soil Biology and Biochemistry, 1994, 26(11): 1469-1475.