RECENT DEVELOPMENTS IN YIELD INCREASING THEORY FOCUSING ON NITROGEN USE EFFICIENCY

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ABSTRACT

Increasing the yield potential of rice in response to global population increases and arable land decreases is a crucial research target. The approaches to meeting this goal are new varieties development together with innovative crop managements. Particularly, water scarcity is a challenge for the future in rice-growing regions, and alternate wetting and drying (AWD) rice cultivation and aerobic rice cultivation have been developed to address this issue (Bouman et al. 2007). To innovate the rice production system adapted to low fertilizer input is another approach for the future of our resource limited globe. For this purpose, we have been trying to clarify the genetic factor(s) of root N uptake characteristics and root system development. Obara et al. (2011) mapped and verified the quantitative trait locus/loci (QTL) for root elongation in response to exogenous NH₄⁺ concentration and estimated the candidate gene responsible for that QTL by comparative mapping with genes for NH₄⁺ uptake and nitrogen metabolism. Rice breeding program with DNA marker by using genes related to beneficial root trait as well as other traits such as plant architecture and yield components will be carried out by close collaboration with crop physiologist and agronomists in the JIRCAS project entitled “Rice innovation for environmentally sustainable production systems (2011-2015)”.

Kirk et al. (2001) simulated the uptake of nitrogen near root surface and estimated the significant uptake of NO₃⁻ (one third of N uptake) by rice root even under the submerged condition, although rice plant was believed to take up nitrogen mainly as NH₄⁺ under submerged soil condition. The production of NO₃⁻ is attributed to the nitrification of NH₄⁺ near root surface where oxygen is transported from atmosphere through aerenchyma. The synergistic effect of NH₄⁺ and NO₃⁻ on N uptake was shown where NO₃⁻ seems more favorable than NH₄⁺ in terms of its uptake and storage/assimilation (Kronzucker et al.1999). Duan et al. (2006) supported this estimate by using hydroponically grown rice plants. According to their results, there is also a varietal differences in the effect of NO₃⁻ on biomass production and grain yield when both nitrogen sources are applied. Analysis by Michaelis-Menten kinetics showed that NO₃⁻ affect Vmax rather than Km of NH₄⁺ uptake (Duan et al. 2007). This suggests the beneficial effect of NO₃⁻ on NH₄⁺ transporters. The molecular biological study on the mechanism of this NO₃⁻ effect was also carried out (Zhao et al. 2008).

We examined the response of several rice varieties under NH₄⁺, NO₃⁻, and partial nitrate nutrition (NH₄⁺/NO₃⁻) in solution culture (Senoo et al. 2007). Result showed that rice varieties can be grouped by their biomass production; improved varieties have relatively low physiological N use efficiency (PNUE) while some native varieties have higher PNUE, especially under partial nitrogen nutrition. The increase in biomass production was attributable both to the higher N uptake and higher PNUE with NO₃⁻ nutrition.

Submerged paddy field condition has been believed to show the higher yield potential of lowland rice than upland conditions. However, recent investigations by Kato et al. (2009) and Katsura et al. (2010) have suggested the possibility that upland condition without severe water stress could be more appropriate to show the potential ability of rice plant. Katsura et al. (2010) showed the significantly higher radiation use efficiency (RUE) as well as higher fraction of radiation intercepted under upland conditions compared to submerged ones. Thakur et al. (2010) assessed the physiological effects of saturated water management practice comparing with submerged soil conditions and showed higher intercepted radiation during the reproductive stage as well as increase of rooting depth and RUE for saturated water management. These findings suggest the involvement of nitrate uptake for such improved RUE.
The genetic and physiological study of partial nitrogen nutrition in rice plant could contribute to the increase of nitrogen use efficiency of rice plant, hence yield increase under lower nitrogen application environment would be feasible if the aerobic or at least non-severe reductive soil condition without water stress could be achieved by proper water saving management of paddy field.

**KEYWORDS**
Nitrogen, Root system, Aerobic soil, AWD, Yield potential, Radiation use efficiency

**REFERENCES**
Recent developments in yield increasing theory focusing on Nitrogen Use Efficiency

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JIRCAS

Background and Objectives

• To solve the problems of rice cultivation in developing countries

• Innovation of rice production through research collaboration in breeding and crop management with a new concept

Strategy

• To meet a pressing demand from developing countries such as in Africa

• Long-term measures for future demand

Use conventional techniques well adapted and updated

Innovation based on technology breakthrough

• Increase of nitrogen use efficiency (NUE) is one of the keys to establish a new system

Points of talk

1. Introduction of Rice Innovation Project

2. Strategy to improve Nitrogen Use Efficiency

3. A breakthrough concept - Nitrate hypothesis

Rice innovation Project (2011-2015)

Rice innovation for environmentally sustainable production systems

1. Resistance to blast disease

- Durable protection system
- Genetic improvement of resistance under a blast research network

2. High productive rice under limited nitrogen fertilizers

- Increasing spikelet No. per panicle with high grain filling
- High dry matter production

- Different root systems
- Genetic improvement for nitrogen use efficiency

3. Increasing the adaptability for environmental stresses

- P. Zn deficiency
- Fe toxicity
- Ozone

- Survey and the selection of DNA markers for tolerant gene(s), and development of breeding materials

Way of improving NUE

• To improve Agronomic N use efficiency (ANUE)

1. Breeding high yield variety

2. Proper adjustment of fertilizer application by plant and soil diagnosis

3. Breeding of root traits which leads to a larger rhizosphere volume

• To improve Physiological N use efficiency (PNUE)

1. Discovering the phenomena showing high PNUE and elucidate the physiological mechanism and genetic bases in it
Genetic improvement for nitrogen use efficiency - relating to the root length

- QTLs for root elongation in response to exogenous NH$_4^+$ concentration was mapped and verified.
- The candidate gene responsible for the QTL was estimated by comparative mapping with genes for NH$_4^+$ uptake and nitrogen metabolism.

Obara et al. (2011)

Identification of novel QTL for root length traits

<table>
<thead>
<tr>
<th>Chromosome</th>
<th>QTL</th>
<th>LOD</th>
<th>A.E. (mm)</th>
<th>R$^2$(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chr. 1</td>
<td>qRL2.1</td>
<td>3.9</td>
<td>11.2</td>
<td>11.2</td>
</tr>
<tr>
<td>Chr. 2</td>
<td>qRL2.2</td>
<td>6.4</td>
<td>16.1</td>
<td>16.1</td>
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<tr>
<td>Chr. 3</td>
<td>qRL3.1</td>
<td>6.0</td>
<td>15.3</td>
<td>15.3</td>
</tr>
<tr>
<td>Chr. 4</td>
<td>qRL4.2</td>
<td>5.0</td>
<td>13.8</td>
<td>13.8</td>
</tr>
<tr>
<td>Chr. 5</td>
<td>qRL5.1</td>
<td>5.5</td>
<td>14.5</td>
<td>14.5</td>
</tr>
<tr>
<td>Chr. 6</td>
<td>qRL6.2</td>
<td>5.5</td>
<td>14.5</td>
<td>14.5</td>
</tr>
</tbody>
</table>

Different response of variety to N concentration in nutrient solution

- 31 rice varieties from Indica, Japonica and local, improved were water cultured by using various concentration of (NH$_4^+$+NO$_3^-$) mixture from 1mg to 80 mg N L$^{-1}$.
- Relative dry weight (RDW) was analyzed by cluster analysis

RDW(%) = (DM of treatment with N / DM of treatment without N) × 100

Namai et al. (2009)

Strategy to improve NUE from crop management aspects

- Nutritional diagnosis for nitrogen
- Site-specific management
- Aerobic soil management with little water stress

Cluster analysis based on dry matter response to N
Effect of N sources on biomass production

Methods

- 30 rice cultivars were water-cultured with NH₄⁺, NO₃⁻ and NH₄⁺ + NO₃⁻ mixture
- Relative dry weight (RDW) and PNUE was measured

Senoo et al. (2007)

Effect of different N sources on biomass production

Senoo et al. (2007)

Effect of N sources: NO₃⁻ / NH₄⁺ (%)
Effect of N sources: \( \frac{(NH_4^+ + NO_3^-)}{NH_4^+} \) (%)

<table>
<thead>
<tr>
<th>Group</th>
<th>Nup</th>
<th>PNUE</th>
<th>RDW</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>125</td>
<td>1</td>
<td>125</td>
</tr>
<tr>
<td>II</td>
<td>119</td>
<td>2</td>
<td>115</td>
</tr>
<tr>
<td>III</td>
<td>151</td>
<td>8</td>
<td>158</td>
</tr>
<tr>
<td>IV</td>
<td>129</td>
<td>9</td>
<td>128</td>
</tr>
<tr>
<td>V</td>
<td>117</td>
<td>10</td>
<td>116</td>
</tr>
<tr>
<td>All</td>
<td>126</td>
<td>30</td>
<td>126</td>
</tr>
</tbody>
</table>

Partial N nutrition increased N uptake, PNUE and biomass production significantly.

**Effect of NO\textsubscript{3}\textsuperscript{-} uptake on NH\textsubscript{4}\textsuperscript{+} uptake**

- Co-provision of NH\textsubscript{4}\textsuperscript{+} and NO\textsubscript{3}\textsuperscript{-} (Partial N nutrition) increase the total N uptake.
  
  Kronzucker et al. (1999), Kirk et al. (2001)

- Partial N nutrition enhance the uptake of NH\textsubscript{4}\textsuperscript{+}
  
  Duan et al. (2006, 2007), Zhao et al. (2008)

**Proposed NO\textsubscript{3}\textsuperscript{-} effects on the growth of rice plant (1)**

- Positive correlation between Nitrate reductase activities (NRA) and biomass production
  
  Barlaan and Ichii, Breeding Sci. (1996)

- Nitrate could be stored in vacuole of shoot tissue and estimated to move to leaf tissue when NO\textsubscript{3}\textsuperscript{-} was depleted
  

**Proposed NO\textsubscript{3}\textsuperscript{-} effects on the growth of rice plant (2)**

- Field experiment with NO\textsubscript{3}\textsuperscript{-} application suggested the delayed biomass increase compared to NH\textsubscript{4}\textsuperscript{+} application in vegetative stage
  

- Hybrid rice with higher NUE contains more NO\textsubscript{3}\textsuperscript{-} than conventional cultivar between late tillering and heading stage
  
  Yang et al., Int. Rice Res. Notes (1999)
NO$_3^-$ sources in soil and its uptake

- There are three possible NO$_3^-$ sources in paddy soil
  1) surface oxidized layer and irrigated water
  2) rhizosphere
  3) surface soil and bulk soil (if aerated)

Rice productivity under aerobic soil management

- Upland condition without severe water stress could be more appropriate to show the potential productivity of rice plant.

- Significantly higher radiation use efficiency (RUE) as well as higher fraction of radiation intercepted under aerobic conditions compared to submerged ones.

Hypothetical scheme for a possible high yield potential by aerobic soil management

- Increase of dry matter production
- Increase of radiation use efficiency
- Increase of radiation interception
- Increase of NH$_4^+$ and NO$_3^-$ uptake
- Better canopy structure
- Better development of root system
- Auxin?

Future research to be addressed

1. Seek for the optimum conditions under aerobic soil culture for the increased N uptake
   Aerobic condition without water stress is worthy to be explored

2. Clarify the physiological mechanism and genetic bases for the increased PNUE under NO$_3^-$ uptake
   Is there any positive effect of NO$_3^-$ uptake on photosynthesis?

Goal: Genetic improvement of NUE together with an establishment of a suitable soil management

Thank you for your attention!