Increasing rice yields and decreasing human health risk through soil silicon management

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Environmental Challenges for the 21st Century

- Global climate change
- Water security
- Food security
Global Rice Production

Each dot represents 5,000 hectares of rice

IRRI World Rice Statistics
Global rice yields are becoming stagnant

FAO STAT, 2015
Arsenic impacts global food security

- rice quantity
- rice quality
flooded rice paddy

FeOOH(s) → Fe^{2+}

As(V) → As(III)

As(III) → As(V)

Fe-mineral

Si

P

As(V)

As(III)

Fe

Si

As
Arsenic in rice: secondary route of exposure
Worldwide surveys and risk of arsenic in rice

As in rice grains (µg g⁻¹)

Minimum grain-As
Maximum grain-As

3 servings
WHO

1 serving
EPA

Countries: Bangladesh, Spain, US-Central, Cambodia, France, Egypt, Vietnam, China, Japan, Brazil, Thailand, Italy, US-California, India.
Many rice varieties

Many soil types and growing conditions
Ongoing work in the Seyfferth Lab

- Arsenic uptake, grain storage & speciation
- Rhizosphere and soil chemical processes
- Microbial community
- Expression of stress-related genes
- Greenhouse gas production & flux
Aerenchyma

Gas filled space extends from shoot to root; allows diffusion of oxygen to respiring roots

Ranathunge et al., 2004
O$_2$

Bulk soil
reduced
Fe(II),
As(III)

Mass flow/
transpiration

Rhizosphere
oxidized Fe(III), As(V)
Thin section of a root-containing soil at harvest
What role does Fe plaque have in minimizing As uptake by rice roots?
Solution conditions influence iron plaque mineral composition and quantity.
Solution conditions influence iron plaque mineral composition and quantity

deionized H₂O  Rice field H₂O

Seyfferth, 2015
Fe plaque forms discontinuous coatings
highly pigmented

minimally pigmented
rhizosphere

Fe_{(aq)}  Si_{(aq)}  As(V)_{(aq)} P_{(aq)}
Fe_{(aq)}  Si_{(aq)}  P_{(aq)}
As(III)_{(aq)}  Si_{(aq)}
Fe_{(aq)}
As(III)_{(aq)}

transpiration

root epidermis

O_2

root cortex

Si
As(III)
P
phosphate transporter

As(V)

aquaporin channel

Fe_{(aq)}
As(III)_{(aq)}
Can we change management practices to increase plant-available Si and decrease arsenic uptake?
Silicon is important for rice

Savant et al., 1997
Silicon increases rice yield

Relative rice yield (with NPK/ with NPK + Si)

Available Si in surface soil (ppm)

$r = 0.67^{**}$

Savant et al., 1997
Grain-As decreases with increasing dissolved Si

As in polished rice [μg/kg d.m.]

Silicic acid in soil solution [mg/L]

r² = 0.99****

r² = 0.98***

Bogdan et al., 2008, ES&T
Many rice paddy soils are Si-depleted

<table>
<thead>
<tr>
<th>Soil Order</th>
<th>Dominant Minerals</th>
<th>Weathering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mollisols</td>
<td>Feldspars, Vermiculites</td>
<td>Less</td>
</tr>
<tr>
<td>Vertisols</td>
<td>Smectites</td>
<td></td>
</tr>
<tr>
<td>Inceptisols</td>
<td>Smectites, Kaolinites</td>
<td></td>
</tr>
<tr>
<td>Alfisols</td>
<td>Kaolinites, Smectites</td>
<td>More</td>
</tr>
<tr>
<td>Ultisols</td>
<td>Kaolinites, Sesquioxides</td>
<td></td>
</tr>
<tr>
<td>Oxisols</td>
<td>Sesquioxides, Kaolinites</td>
<td></td>
</tr>
</tbody>
</table>

Savant et al., 1997
Many rice paddy soils are Si-depleted
What effect does increasing dissolved Si have in decreasing As accumulation in grains?

300 µg/L As (80/20 As(III)/As(V))
2 Si treatments: Diatomaceous Earth (Si_L) and Silica gel (Si_H)
2 soil types: Vertisol and Ultisol
2 rice cultivars: M206 and IR66

Seyfferth and Fendorf, 2012
Pore-water Si and As

Silica gel (Si_H)
Diatomaceous Earth (Si_L) & Control

Seyfferth and Fendorf, 2012
High Si treatment decreases As in grains

Seyfferth and Fendorf, 2012
Add Si to soil

Si\textsubscript{aq}

“high Si”

more Si released to bulk solution

Si\textsubscript{aq}

As\textsubscript{(aq)}

As release to solution

competition for root uptake

more Si released to solution

Si\textsubscript{aq}

As\textsubscript{(aq)}

As\textsubscript{(aq)}

Si\textsubscript{aq}

Si\textsubscript{aq}

Si\textsubscript{aq}

Si\textsubscript{aq}

Si\textsubscript{aq}

Fe-mineral

Si

As

As

As
Practical solutions for rice farmers?
Si amendments for farmers in developing countries?

FH = 11% Si by weight

RHA = 37% Si by weight
RHA
Rice husk ash

FH
Fresh rice husk

Evanise Penido
UFLA
At 1% w/w incorporation, there was no difference between RHA and FH amendments.
What happens when we incorporate rice husk (FH), rice husk ash (RHA) or rice straw (RS) into flooded soil?
Highest dissolved silicon in husk-amended pots
Highest dissolved arsenic in straw-amended pots

Penido et al., accepted
FH and RHA are most promising choices for Si amendments

Penido et al., accepted
What impact does the incorporation of fresh husk (FH) or rice husk ash (RHA) have on As in grains?

Si-rich rice amendments with no additional As
FH = fresh rice husk
RHA = rice husk ash

Seyfferth et al., in Review
Higher rice yield with RHA amendment

Seyfferth et al., in Review

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>+FH</th>
<th>+RHA</th>
</tr>
</thead>
<tbody>
<tr>
<td>total # grains</td>
<td>351 ± 24</td>
<td>352 ± 51</td>
<td>356 ± 19</td>
</tr>
<tr>
<td>% unfilled grains</td>
<td>47 ± 17</td>
<td>59 ± 10</td>
<td>27 ± 10</td>
</tr>
</tbody>
</table>
FH amendment leads to highest Si but also highest As in pore water when plants are present.

Seyfferth et al., in Review
RHA and FH either do not change or decrease total grain As concentrations

Seyfferth et al, in Review
25 – 50% decrease of inorganic As in grains with fresh husk amendments

Seyfferth et al., in Review

Jessica Mann

Seyfferth et al., in Review
Strong negative relation between pore-water Si concentration and inorganic grain As

\[ r^2 = 0.735^{**} \]

\[ r^2 = 0.618^{**} \]

Seyfferth et al., in Review
Both inorganic grain As and straw As decrease as straw Si increases
RHA and FH do not increase, and sometimes decrease, Cd levels in rice grains

Seyfferth et al, in Review.
Neither RHA or FH incorporation affect methane production.
### Experiments with elevated arsenic

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Calcium silicate</th>
<th>Ash</th>
<th>Husk</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total grains</strong></td>
<td>105 ± 94</td>
<td>37 ± 16</td>
<td>345 ± 109</td>
<td>485 ± 78</td>
</tr>
<tr>
<td><strong>% unfilled</strong></td>
<td>72 ± 14</td>
<td>94 ± 5</td>
<td>44 ± 17</td>
<td>16 ± 6</td>
</tr>
</tbody>
</table>

Teasley and Seyfferth, *In Prep*
Greenhouse gas flux measurements

Fred Teasley
RICE Facility at the University of Delaware
RICE Facility at the University of Delaware
Silicon can improve rice quantity and quality