Irrigation for co-benefits and tradeoffs of agricultural mitigation and adaptation: a rice case study

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AGCI Irrigation in Earth System
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6/8/2023

R. Valdivia, T. Li, G. Vellingiri, L. Arunachalam, E. Mencos, C. Rosenzweig and others. L. Arunachalam 2019
Run of show

- Climate adaptation and mitigation in agriculture
- Mitigation and adaptation in Rice: System of Rice Intensification
- Regional assessments: Vietnam, Bangladesh, and India
Mitigation and adaptation in rice

Run of show

- Modeling climate adaptation and mitigation in agriculture
  - Mitigation and adaptation in Rice: System of Rice Intensification
  - Regional assessments: Vietnam and India
Climate Change and Agriculture

The Agricultural Model Intercomparison and Improvement Project
Integrated Assessment Model Framework

1. Evaluating and Improving Models using Historical Changes

Need models that can reasonably simulate both crop growth and soil processes

Recently adapted Integrated Assessment methods to include climate mitigation and resource use (in rice systems)

Can be used to investigate “climate smart” production

2. Projecting Future Changes with improved models

Rosenzweig et al 2013: http://agmip-ie.alterra.wur.nl/
Run of show

- Modeling climate adaptation and mitigation in agriculture
- **Mitigation and adaptation in Rice: System of Rice Intensification**
- Regional assessments: Vietnam and India
Mitigation and adaptation in rice

Climate Change and Agriculture: SRI

System of Rice Intensification:

- Variety independent
- Transplant seedlings young (and quickly)
- Wider plant spacing and reduced density
- Restore SOM; organic methods
- **Alternate wetting and drying (AWD); conservation water management**
- Weed control that aerates soil
Climate Change and Agriculture: SRI

Purported benefits:

• Increases rice production

• *Strengthens resilience to climate change and variability* *(adaptation)*

• *Reduces rice contribution to climate change* *(mitigation)*
Mitigation and adaptation in rice

Climate Change and Agriculture: SRI

Rising popularity:

- ~9-13 national governments promoting and investing in SRI-like practices for **pledged climate mitigation targets**

- At state and local levels, where water is often governed, potential for **water conservation and autonomy** is major incentive

- Possible **premiums for farmers/farmer cooperatives** for adhering to SRI, as well as for diverse rice varieties
Climate Change and Agriculture: SRI

Uncertainties:

• Higher yields reported, but uncertainties around labor and gender

• Relatively high rates of dis-adoption. How many principles to be “SRI”? Complicates assessment. . .

• SRI conserves water, but changing climate induces more stress. Must test for concurrent, interactive changes across agro-climatic variables

• CH4 mitigation, but tradeoffs with CO2 and N2O

• Can SRI scale to be relevant to INDCs/NDCs per 2015 Paris Climate Agreement?
Climate Change and Agriculture: SRI

Research Questions:

- How does SRI/AWD impact production and GHG (methane) emissions under current climate conditions?

- How do these interventions fare under future climate conditions (i.e. does SRI/AWD “still work”)?
Run of show

Mitigation and adaptation in rice

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Mitigation and adaptation in rice

Regional Integrated Assessments

“Proof-of-concept” - leveraged representative data for climate-crop pilot study in Red River Delta, Vietnam (Carnegie Corp.) AWD and reduced seed rates in NDC

Pilot - leveraged existing crop field trial and socioeconomic survey data for six sites in Bangladesh (ACIAR/GRA). AWD and reduced seed rates in NDC

Full RIA - primary data collection - crop biophysical and socioeconomic HH data - in Tamil Nadu, India (Carnegie Corp.) AWD promoted in Tamil Nadu
Mitigation and adaptation in agriculture

Vietnam Proof of Concept

Red River Delta, Vietnam

Climate Smart Index across farm sites

Climate Smart Index (CSI) = Water Productivity (N) – GHG Intensity (N)

SRI interventions can enhance “climate smartness” under current climate conditions

However, their efficacy can change under future climate conditions

The choice of climate future can impact CSI score
Mitigation and adaptation in agriculture

Bangladesh Pilot

All management systems face increases in methane emissions under climate change

However, there is still socioeconomic benefits from adopting more climate smart rice farming practices

For this and Vietnam, the impacts of climate extremes - and implications for shifts in management in response to extremes (e.g. “disadoption”) - were not investigated...
India Full RIA (just starting)

Field Trial Design

Number of Treatments: 6
Replications: 4
Timeframe: Transplanting late Oct 2021, ~130 day varieties

T1 (partial SRI): Square planting (25 cm x 25 cm) of 2 leaf stage single seedling
T2 (partial SRI): T1 + Cono-weeding four times on 15, 25, 35 and 45 days after planting
T3 (partial SRI): T1 + Alternate wetting and Drying (AWD) method of irrigation
T4 (complete SRI): T2 + Alternate wetting and Drying (AWD)
T5 (conventional): 21 days old seedling @ 2 – 3 seedlings / hill -15 cm x 10 cm
T6 (conventional with AWD): T5 + Alternate wetting and Drying (AWD) method of irrigation
Mitigation and adaptation in rice

## India Full RIA (just starting)

Coimbatore experimental results

<table>
<thead>
<tr>
<th></th>
<th>Plant population/ sq.m</th>
<th>Productive tiller per hill</th>
<th>No. of filled grains per panicle</th>
<th>Grain yield (kg/ha)</th>
<th>CH4 (mg m²/day)</th>
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</thead>
<tbody>
<tr>
<td>T1 (part SRI)</td>
<td>16</td>
<td>18.6</td>
<td>120.6</td>
<td>4253.9</td>
<td>481.37</td>
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<tr>
<td>T2 (part SRI)</td>
<td>16</td>
<td>21.2</td>
<td>132.9</td>
<td>5822.5</td>
<td>450.69</td>
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<tr>
<td>T3 (part SRI)</td>
<td>16</td>
<td>21.3</td>
<td>130.1</td>
<td>5326.5</td>
<td>417.36</td>
</tr>
<tr>
<td>T4 (full SRI)</td>
<td>16</td>
<td>27.5</td>
<td>136.2</td>
<td>6904.1</td>
<td>323.3</td>
</tr>
<tr>
<td>T5 (con)</td>
<td>33</td>
<td>12.2</td>
<td>120.2</td>
<td>5439.1</td>
<td>526.84</td>
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<tr>
<td>T6 (con+AWD)</td>
<td>33</td>
<td>12.4</td>
<td>121.2</td>
<td>5490.0</td>
<td>439.33</td>
</tr>
</tbody>
</table>

In prep, with G. Vellingiri, A. Lakshmanan, R. Valdivia and T. Li
Mitigation and adaptation in rice

**India Full RIA (just starting)**

**Farmer Rice Area vs Income**

**Farmer Yields**
Mitigation and adaptation in rice

Takeaways

What needs to be incorporated?
- More work with coupled model frameworks, coupled with representations of farming populations, management systems, and constraints

To whom is this useful?
- Model communities - study co-benefits and trade-offs of combined mitigation and adaptation
- Stakeholder communities, particularly those units focused on promoting and/or disseminating interventions

Longer-term challenges
- Farmer behavior (although not entirely irreducible! See floods/decision-making from space)

- Roberto Valdivia (OSU)
- Tao Li (IRRI)
- Geetha Vellingiri, Laxman Arunachalam, Bhuvana (TNAU)
- Cynthia Rosenzweig, Erik Mencos, Jonas Jaegermeyr (NASA GISS/CU)
- Many others from Bangladesh and Vietnam
Vietnam Pilot: biophysical intervention impact

Climate Smart Index (CSI):

\[
CSI = WP_{(N)} - GHGI_{(N)}
\]

\[
GHGI_{(N)} = \frac{GHGI_{obs} - GHGI_{min}}{GHGI_{max} - GHGI_{min}}
\]

\[
WP_{(N)} = \frac{WP_{obs} - WP_{min}}{WP_{max} - WP_{min}}
\]

SRI-like interventions improve CSI; climate change depresses CSI across all management.

Relative to baseline management some SRI interventions still do “better”, but climate scenario-model uncertainty is high.
Climate Change and Agriculture: Rice

- Globally, **rice directly feeds over 3B people**, and is a major internationally traded food commodity.
- Unmitigated climate change, inclusive of heatwaves, drought, air pollution, variable and declining water resources, **may reduce rice yields by 10% or more and reduce nutrient content**.
- Rice is also responsible for ~10% of agricultural **GHG emissions (primarily CH4)**, and proportionally accounts for large GHG footprints in key rice-exporting countries (mainly across South, Southeast, and East Asia).
- Rice systems also have a **high demand for freshwater**, and as production increases (movement toward 3x cropping in some areas) this demand will grow.
Vietnam proof of concept

Red River Delta, Vietnam

20% of rice area, mostly small-holders. Many farmers already use younger seedlings (1-2 weeks) and AWD

Used a calibrated/validated rice growth model (Oryza) coupled to soil biogeochemistry model (DNDC) to compare 3 SRI-like interventions against baseline management at 83 sites:

**INV1:** Most reduced planting density, most reduced urea, higher ammonium

**INV2:** Least reduced planting density, reduced urea, higher ammonium

**INV3:** Younger seedlings, moderately reduced planting density, slight increases in urea and reduced ammonium

**Future climate:** T,P changes imposed from 5 CMIP5 ESMs, RCP8.5 2050s
Mitigation and adaptation in rice

Vietnam Pilot: biophysical intervention impact

Top Row: Violin plots of SRI interventions’ performance across sites relative to baseline management and 1980-2010 climate conditions

Bottom Row: Same as top but using 5 future climate scenario-models

Yield SOC20 CO2eq WUE CH4

INV1; INV2; INV3
Vietnam Takeaways

**Preliminary conclusions** *(analyses still under development)*

- Most rice interventions that leverage SRI-like principles (in this region) boost yields relative to baseline management practices under both current and future climate conditions.

- However, “win/wins” with mitigation and water use occur less frequently, and depend heavily on baseline management conditions.

- Future climate conditions show a large spread depending on “climate” used.

**Next steps** *(currently underway)*

- Systematic sensitivity testing varying over CTWN independently and together -> help to identify mechanistic responses to treatments.

- Identify site attributes (and interaction with management) that enable win/wins, and quantify total impact/contributions of these sites.

In prep, with Tao Li and Roberto Valdivia
Mitigation and adaptation in rice

Bangladesh Pilot

Leveraged farm household data - RCT survey data collected by BRAC and Monash University between 2014-2016

Compared three rice management systems:
- Conventional, continuous flood (Conv.CF)
- Conventional, AWD (Conv.AWD)
- Full SRI with AWD (SRI.AWD)

Identified two main strata across three regions:
- Gopalganj, Kishoreganj & Lalmonirhat
  - “Smaller” farms <0.5Ha, larger farms >0.5Ha

Climate Projections for 2050, SSP2-4.5:
- (0): Current
- (P) KAIST: Hotter model, higher precipitation
- (X) MIROC6: Less hot, less increased precipitation
Mitigation and adaptation in rice

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<table>
<thead>
<tr>
<th>Type of analysis</th>
<th>Scenario</th>
<th>System 1</th>
<th>System 2</th>
</tr>
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<tbody>
<tr>
<td>Impacts of climate change on current rice systems</td>
<td>1</td>
<td>Conv.CF.OX</td>
<td>Conv.CF.PX</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Conv.CF.OX</td>
<td>Conv.CF.RX</td>
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<tr>
<td></td>
<td>3</td>
<td>Conv.AWD.OX</td>
<td>Conv.AWD.PX</td>
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<tr>
<td></td>
<td>4</td>
<td>Conv.AWD.OX</td>
<td>Conv.AWD.RX</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>SRI.AWD.OX</td>
<td>SRI.AWD.PX</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>SRI.AWD.OX</td>
<td>SRI.AWD.RX</td>
</tr>
<tr>
<td>Adaptation - current climate</td>
<td>7</td>
<td>Conv.CF.OX</td>
<td>Conv.AWD.OX</td>
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<tr>
<td></td>
<td>8</td>
<td>Conv.CF.OX</td>
<td>SRI.AWD.OX</td>
</tr>
<tr>
<td>Adaptation - Future climate GPXF</td>
<td>9</td>
<td>Conv.CF.PX</td>
<td>Conv.AWD.PX</td>
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<tr>
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<td>10</td>
<td>Conv.CF.PX</td>
<td>SRI.AWD.PX</td>
</tr>
<tr>
<td>Adaptation - Future climate GRXF</td>
<td>11</td>
<td>Conv.CF.RX</td>
<td>Conv.AWD.RX</td>
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<tr>
<td></td>
<td>12</td>
<td>Conv.CF.RX</td>
<td>SRI.AWD.RX</td>
</tr>
</tbody>
</table>
Mitigation and adaptation in rice

**Bangladesh Pilot: biophysical impacts**

SRI with AWD on average increases yields and WUE, and decreases CH4, across districts/sites. There exists spatial heterogeneity not shown here, particularly related to soils.
Bangladesh Takeaways

- Some dependency on climate scenarios. Hotter climate models (XP) reduces farm net returns, increase poverty rates, and increase GHG emissions at most sites. However, a less warm future may have small positive impacts on farm income at many sites.

- Adoption of Conventional AWD or SRI-AWD under current or future climate can reduce GHG emissions and well as overall WUE at most sites.

- AWD also shows potential co-benefits increasing income and reducing poverty rates, and when coupled with SRI the co-benefits are somewhat larger (more analyses TBD).

- In practice, farmers and stakeholders report important factors that limit the full benefits of AWD and SRI systems, including water access and control seasonally and due to other reasons.
India: mitigation and adaptation RIA

‘19/’21/’22: Crop field trials in Coimbatore and Madurai, Tamil Nadu, India for biophysical data

‘21-’22: Household survey data for socioeconomic analysis
Mitigation and adaptation in rice

India: field trials

Farmer Rice Area vs Income

Farmer Yields
Supplementary
Vietnam Pilot: Climate

Future climate model selection for Red River Delta - CMIP5 RCP8.5 mid-century

30-year crop model simulations for baseline (1981-2010) using nearest station data

Imposed mean changes from RCP8.5 mid-century (2041-2060 relative to baseline) conditions using subset of five GCMs

Yield results averaged over 30 years of experiment for each site and each management package ("management-sites")
Future climate model selection for Bangladesh - SSP2-4.5 2050s

Bangladesh and India work will be using updated CMIP6 projections via the NASA Earth Exchange (NEX) Global Daily Downscaled Projections (GDDP) dataset, using bias-correction spatial disaggregation.

This dataset includes 35 Global Circulation Models (GCM) from the Coupled Model Intercomparison Project Phase 6 (CMIP6) for the period from 2015 to 2100, and historical experiments for the period of 1950-2014.
DNDC-ORYZA & Modelling Evaluation Process

ORYZA rice module
- Phenology
- Photosynthesis
- Evapotranspiration
- Respiration
- Allocation & growth
- Root growth & senescence
- Yield formation
- N & W uptake
- Abiotic stress

Central Interface Module
- Simulation configuration
- Daily calculation management
- Nutrient and water transfers
- Management of cropping status

Management Module
- Water (irrigation)
- Fertilizer
- Tillage
- Residue

Environmental Driver Module
- Soil physical, chemical & hydraulic characters
- Daily weather

DNDC Soil Module (C, N, P life cycling)
- Mineralization
- Nitrification
- Denitrification
- Hydrolysis
- Absorption
- Desorption
- Decomposition
- Fermentation
- GHGs

Model calibration & parameterization
Model validation & uncertainty identification
Management & cropping system scenario formation
Simulation & analysis for targets

Courtesy Tao Li
Climate Change and Agriculture: Vietnam Pilot
Uncertainties in predicting rice yield by current crop models under a wide range of climatic conditions

MMM of crop models can reproduce experimental yield data, with an uncertainty of less than 10% of measured yields. However, individual models are not very consistent in reproducing experimental and regional yields.

Temperature (and CO2 in the longer term)-mediated physiological and reproductive effects (e.g. grain set and harvest index) vary widely across models (and several models do not fully capture the effects of temperature extremes at reproductive stages).
Crops and Drops

DNDC developments

Decomposition/carbon pools

Figure 5. SOC pools and decomposition processes in DNDC.
DNDC developments

Figure 6 The framework for simulating soil biogeochemistry and methane dynamics in the modified DNDC.
## Vietnam Pilot

<table>
<thead>
<tr>
<th>Rice management components</th>
<th>Base1</th>
<th>Base2</th>
<th>Base3</th>
<th>INV1</th>
<th>INV2</th>
<th>INV3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spring season</strong></td>
<td></td>
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<tr>
<td>Establishment</td>
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<td></td>
</tr>
<tr>
<td>Transplanting density (#/m²)</td>
<td>135</td>
<td>123</td>
<td>145</td>
<td>60</td>
<td>110</td>
<td>109</td>
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<tr>
<td><strong>Tillage</strong> &lt;sup&gt;1&lt;/sup&gt;</td>
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<tr>
<td>2 20cm mouldboard preplant + 1 10cm disk after harvest</td>
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<tr>
<td>2 10cm disk preplant</td>
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<tr>
<td>2 20cm mouldboard and disk preplant</td>
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<tr>
<td>20cm mouldboard preplant + 1 10cm disk after harvest</td>
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<tr>
<td>1 10cm disk preplant</td>
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<tr>
<td><strong>Fertilizing (kg/ha)</strong></td>
<td></td>
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<tr>
<td>Urea &lt;sup&gt;2&lt;/sup&gt;</td>
<td>54.0 (3 splits)</td>
<td>54.0 (3 splits)</td>
<td>81.0 (2 splits + 2 slow release)</td>
<td>25.6 (1)</td>
<td></td>
<td></td>
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<tr>
<td>Ammonium &lt;sup&gt;2&lt;/sup&gt;</td>
<td>63.0 (2)</td>
<td>63.0(2)</td>
<td>63.0(2)</td>
<td>82.8(4)</td>
<td>83.3(1)</td>
<td>81.1 (1+2s)</td>
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<tr>
<td>Organic &lt;sup&gt;3&lt;/sup&gt;</td>
<td>43.5(46)</td>
<td>4.6(70)</td>
<td>47.8 (46)</td>
<td>45.7 (46)</td>
<td>27.9(86)</td>
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<td>Irrigation &lt;sup&gt;4&lt;/sup&gt;</td>
<td>A(2, 5)</td>
<td>A(2, 5)</td>
<td>A(2, 5)</td>
<td>A(5, 6)</td>
<td>A(5, 6)</td>
<td>A(4, 5)</td>
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</table>
Climate Change and Agriculture: Vietnam Pilot

1920 simulations with Baseline management under 30 years of historical weather data

Factorial experiments varying over:

CO2 levels (ppm): 360, 450, 540, 630, 720

Tmax/Tmin levels (change in °C): -2, 0, +2, +4, +6, +8

Precipitation level (% of baseline): 25%, 50%, 75%, 100%, 125%, 150%, 175%, 200%

Fertilizer N levels (% of nitrate baseline): 0%, 25%, 50%, 75%, 100%, 125%, 150%, 200%
Better representations of:

- Root distribution relative to water and nutrients in soils (instead of uniform distribution across the soil column)
- Soil temperature limits on photosynthesis
- Water uptake under water stress conditions and inclusion of drought tolerance factor
- Allocation of photosynthate to roots under stress
Socioeconomic modeling

Systems are being used in heterogeneous populations, resulting in distributions of gains and losses.

Opportunity cost, system choice and adoption
Opportunity cost $\omega = V_1 - V_2$ follows distribution $\phi(\omega)$

$V_1 =$ returns to system 1
$V_2 =$ returns to system 2

Map of a heterogeneous region

In prep, with G. Vellingiri, A. Lakshmanan, R. Valdivia and T. Li
The effects of future climate conditions on baseline management
CBE FIELD TRAIL

SOWING

EMERGENCE

CONOWEEDING -35 DAP

Transplanting video – SRI METHOD

Conoweeding video – CBE field

53 DAS (2.12.2021)
<table>
<thead>
<tr>
<th>Location</th>
<th>Crop</th>
<th>Variety</th>
<th>Duration</th>
<th>Date of Sowing</th>
<th>Date of Transplanting</th>
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</thead>
<tbody>
<tr>
<td>COIMBATORE</td>
<td>Rice</td>
<td>IW Ponni</td>
<td>135 days</td>
<td>09.10.2021</td>
<td>22.10.21 &amp; 29.10.21</td>
</tr>
<tr>
<td>MADURAI</td>
<td>Rice</td>
<td>VGD 1 (ADT43 / Seeragasamba)</td>
<td>127 - 132 days</td>
<td>17.09.2021</td>
<td>01.10.2021 &amp; 08.10.2021</td>
</tr>
</tbody>
</table>
Vietnam Pilot: intervention Impact (Current)

Mean relative changes of 3 interventions on baseline (current climate conditions)

Right: Violin plots of interventions across sites relative to mean across baseline management-sites

Negative values = decrease,
Positive values = increase
Vietnam Pilot: intervention Impact (Future)

Mean relative changes of 3 interventions on baseline (future climate conditions)

**Right:** Violin plots of interventions across sites relative to mean across baseline management-sites

Negative values = decrease,

Positive values = increase
Framing key “wins” and “losses” across variables: CO2 equivalent vs Yield

Points plotted here represent impact of interventions relative to baselines at respective sites

Right: for future climate, points are also plotted for five different climate models (here undifferentiated)
Vietnam Pilot: co-benefits and trade-offs

Framing key “wins” and “losses” across variables: methane vs water use efficiency (WUE)

Points plotted here represent impact of interventions relative to baselines at respective sites
**Right:** for future climate, points are also plotted for five different climate models (here undifferentiated)
Vietnam Pilot

Preliminary climate-crop results from Red River Delta, Vietnam

Red River Delta is 20% of Vietnamese rice producing area, mostly small-holders

Leveraged representative AgResults’ data on prevailing ("baseline") management systems and interventions

https://agresults.org/projects/vietnam
Vietnam Pilot

Experimental design - summarize interventions here, not general

Used a previously calibrated/validated rice growth model (Oryza) coupled to soil biogeochemistry model (DNDC)

Compared 3 SRI-type interventions against 3 representative “baseline” systems:

Establishment: Interventions used the same or reduced seedling age at the time of transplanting compared to baseline management, and transplanting densities were significantly reduced

Fertilizer: Interventions enhanced organic fertilizer applications and/or increased the proportion of slow-release nitrogen fertilizer

Irrigation: Interventions used AWD with increased # of cycles and/or the length of the AWD drying period