Air Pollution Effects on Rice Yields in South Asia

Gamze Eris, Congmeng Lyu, & Nicole Swartwood
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- Why South Asia

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Effect on Rice Yields

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Effect on Visibility and UV
Effects on Rice Yields

Temperature
Chemical Process
Expected Temperature Increases
Effects on Rice Yields

Rice Pathogens
Brief Introduction
Atmospheric Factors
Effects on Rice Yields

Conclusion
Why rice?

- Staple Crop

- 50% of calories
  - Bangladesh, Cambodia, Myanmar, Laos, Vietnam

- 20-45% of calories
  - Thailand, Philippines, Malaysia, India, Nepal, Sri Lanka

- Annually 37% of crop lost worldwide
  - 120-200 million tons

- 10-15% of losses from disease
South Asia

Southern region of the Asian continent:
- Afghanistan
- Bangladesh
- India
- Nepal
- Pakistan
- Bhutan
- Sri Lanka
- Maldives
Why South Asia?

Critical Population Group:

- Population of 1.721 billion (as of 2014)
- India projected to pass China as the world’s most populous country by 2028
- Largest working age population
- Rural to urban migration

Undernourished Population

http://www.state.gov/s/globalfoodsecurity/129573.htm
Rice & South Asia

-Staple Food

-Livelihood for 50 million households

-Cultural significance

-Rice Production
  -32% of global yield
  -37.5% of global area

-Production increased 300% since green revolution

Images courtesy of World Bank
Food Security In South Asia

Main Pollutants

By: Congmeng Lyu
Major pollutants:

Ozone
Sulfur dioxide
NOx (NO₂ mainly)
Fluorides
Ground level or “bad” ozone is not emitted directly into the atmosphere, but is created by chemical reactions of oxides of nitrogen (NOx) and volatile organic compounds (VOC) in the presence of sunlight.

\[ \text{NOx + VOC + Sunlight} = \text{OZONE} \]
Tropospheric O$_3$ distribution
Ground level $O_3$ trend

Year by year trend:
Ground level ozone concentrations are expected to rise in South Asia due to increased emissions of NOx and other ozone precursors resulting from rapid industrialization.

Month by month trends:
Ozone seasonal variation and crops cycle in South Asia
Why ozone can impact rice yields?

1. \(O_3\) enters the leaves through the stomates, and cause visible injury to the leaves.
2. Photosynthesis reduced, because chloroplast outer membrane decomposed, chlorophyll and proteins related to photosynthesis decreased.

3. Reduced carbon uptake caused by reduced photosynthesis lead to lowered carbon transport to roots, the growth of root is inhibited and consequently less nutrients will be assimilated from the ground, as a result the growth rate of rice is decreased.

4. Producing period of rice is reduced by the impact of ozone.

So rice yield is reduced.
### Ambient Air Pollution Effects on Crop

**SOME KNOWN STUDY AROUND ASIA**

<table>
<thead>
<tr>
<th>Country</th>
<th>Pollutant</th>
<th>Crop</th>
<th>Yield loss</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan (Kanto)</td>
<td>O$_3$</td>
<td>Rice</td>
<td>0–7%</td>
<td>Kobayashi (1999)</td>
</tr>
<tr>
<td>China (7 provinces) (south west)</td>
<td>SO$_2$ and acid rain</td>
<td>Vegetables</td>
<td>7.8 %</td>
<td>Feng <em>et al.</em> (1999)</td>
</tr>
<tr>
<td></td>
<td>O$_3$ (ppb) (night 15 mid day max 75)</td>
<td>Green pepper</td>
<td>''</td>
<td>''</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rice</td>
<td>''</td>
<td>Zheng <em>et al.</em> (1998)</td>
</tr>
<tr>
<td>Taiwan (S)</td>
<td>O$_3$</td>
<td>Spinach</td>
<td>''</td>
<td>Sun (1993)</td>
</tr>
<tr>
<td>Korea</td>
<td>O$_3$</td>
<td>Wheat, Soybean</td>
<td>23–27 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60–65 ppb (2020)</td>
<td>Corn, Rice, Soybean</td>
<td>2–16 %, 28–35 %</td>
<td></td>
</tr>
</tbody>
</table>
Response of O$_3$ exposure to yield of (a) rice, (b) corn, (c) spring and (d) winter wheat
Sulfur Dioxide

Sources of $\text{SO}_2$

- Industry
- Fires
- Mobile
- Misc.
Global SO$_2$ emission trend

Fig. 6. Comparison of SO$_2$ emissions from Asia, Europe, and the United States in different decades (data from Worldwatch Institute 1998).
Asian SO\textsubscript{2} emission trend
Simulated global distribution of SO$_2$

South Asia is under serious SO$_2$ pollution
Why $SO_2$ can impact rice yields?

**Mechanism:**

$SO_2$ enters the leaves mainly through the stomata.

1. Causes general water stress in plants by reducing stomatal opening.
2. Changes the membrane permeability by affecting structural proteins in the cell membrane.
3. Reduces the synthesis of proteins and enzymes by interferes with amino acid metabolism.
4. Inactivates many enzymes either by breaking their S-S bonds or by changing their stereo structure.
5. Reduces photosynthesis and increases respiration.
Symptoms and effects:

- Exposed leaves can begin to lose their color in irregular, blotchy white spots. Some leaves can develop red, brown or black spots.
- When the pigments in enough tissue are damaged or killed, plants can begin to lose their leaves. Crop output is greatly reduced and growth can be stunted. This is especially noticeable in young plants.
NOx

Sources of NOx

- Transportation: 61%
- Industry / Commerce: 23.3%
- Power Generation: 11.7%
- Heating/Combustion: 3.6%
- Consumer Prod./Misc: 0.4%
Trend of NOx emission in Asia
Why NOx can impact rice yields?

Mechanism:
Reduced photosynthesis: NO₂ causes formation of crystalloidal structures in the stroma of chloroplasts and swelling of thylakoid membrane.

Symptom:
Chlorosis in leaves: most of the angiosperm species produce water-soaked intravenous areas that later become necrotic.
Effects:

NO$_2$ mostly affects the leaves and seedlings. Reduced photosynthesis ultimately lead to the reduction in yields. Its effects decrease with increasing age of the plant and tissue.
Fluorides

Sources:

1. combustion of coal;
2. production of brick, tile, ceramics, and glass;
3. manufacture of aluminium and steel;
4. production of hydrofluoric acid, phosphate chemicals and fertilizers.
Why Fluorides can impact rice yields?

Mechanism:

Fluorides combine with metal components of proteins and thus interfere with the activity of many enzymes, chlorophyll and cellulose synthesis are inhibited. As a result, the cell wall composition, photosynthesis, respiration, carbohydrate synthesis, synthesis of nucleic acids and nucleotides and energy balance of the cell are affected.
Symptoms:

1. Acute symptoms of tip necrosis, occasionally with a reddish-brown band.

2. The chronic symptoms includes leaf yellowing and mottling.

3. Rice glumes were also affected, showing tip necrosis with dark brown band. If the glumes are severely affected, no grains will be formed. Dead tips of leaves and glumes become white or greyish white.
Effect:
Fluoride affects almost all the biochemical and physiological process of the plant and causes serious damage to the plant. These effects ultimately lead to the reduction in yield.
Aerosols
Direct Effects

- Reduction in total solar radiation
- Aerosol impact on the direct and the scattered radiation
- Settling of aerosols on the leaves
- Impact of the acidity of the haze

Indirect Effect

- Impact of the haze on the hydrological cycle
- Change in surface temperature from the haze
Aerosol affect on Solar Radiation

Solar Radiation (Indirect and Direct)

\[ I_{s}^{tot}(\tau_{a}) = \int I_{s}(\lambda, \tau_{a})d\lambda. \]

Aerosol: Absorbs and scatters solar light

Aerosol optical depth

\[ I_{s}^{dir}(\lambda, \tau_{a}) = I_{0}(\lambda)\exp(-\tau_{a}(\lambda) + \tau_{g}(\lambda))/\cos(\theta). \]

Single scattering albedo

\[ \omega_{a}(\lambda) = \sigma_{sp}(\lambda)/\sigma_{sp}(\lambda). \]

Figure 8.1: Aerosol effect on diffuse and global surface fluxes (direct aerosol forcing) in the PAR (Photosynthetically Active Radiation, 400-700 nm) spectral region. Calculations are made for the case of grassland using the INDOEX aerosol model (Satheesh et al., 1999; Podgorny et al., 2000).
How solar radiation effect crops

- Regulating carbon assimilation by plants by solar radiation
- Water loss to the atmosphere
Crop yield vs Solar Irradiance

**Fig. 5.** Scatterplots of measured yields of rice cultivated in Texas as a function of accumulated surface solar irradiance received during a 40-day critical sunlight period. Commercial and experimental fields are shown with different symbols and trend lines. Commercial fields exhibit a higher correlation ($R^2 = 0.83$) compared to experimental fields ($R^2 = 0.54$).

Chameide W.L. et al, PNAS, 1999
Rice and Wheat

![Graph showing crop yield change as a function of total surface solar irradiance.](image)

Fig. 6. Model-calculated percentage change in crop yields as a function of the assumed total surface solar irradiance, with 100% representing the observed irradiance. The calculations were carried out by using conditions appropriate for Nanjing (see Table 3).

<table>
<thead>
<tr>
<th>Weather data*</th>
<th>Sow date</th>
<th>Harvest date</th>
<th>Mean yield for base model*, kg/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>1969-1979</td>
<td>November 9</td>
<td>June 8</td>
</tr>
<tr>
<td>Rice</td>
<td>1970-1979</td>
<td>May 10</td>
<td>September 25</td>
</tr>
</tbody>
</table>

*Input weather data consisted of averages of observations made during the indicated years. The data were obtained from Nanjing Agricultural Sciences (courtesy of Jin Zhigang).

*Base model represents the simulation using 100% of the observed total surface solar irradiance.
Winter Wheat

Figure 8.3: Winter wheat crop yield in New Delhi environment versus radiation change at the surface.
Rice

Figure 8.5: Percent change in biomass and yield of rice (rabi season) due to the direct effect of haze.
Sugar cane

Figure 8.6: Percent change in cane yield.
Rice

Table 2  Simulated rice photosynthesis, grain yield, ground biomass and total biomass change rate as daily radiation increased/decreased by 10% & 20% respectively compared with observations

<table>
<thead>
<tr>
<th>Radiation changes (the whole growing season)</th>
<th>+ 20%</th>
<th>+ 10%</th>
<th>0</th>
<th>- 10%</th>
<th>- 20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change rate of photosynthesis (%)</td>
<td>+ 9.5%</td>
<td>+ 5%</td>
<td>0</td>
<td>- 5.4%</td>
<td>- 11.2%</td>
</tr>
<tr>
<td>Change rate of grain yield (%)</td>
<td>+ 9.2%</td>
<td>+ 4.8%</td>
<td>0</td>
<td>- 5.4%</td>
<td>- 10.9%</td>
</tr>
<tr>
<td>Change rate of ground biomass(%)</td>
<td>+ 8.6%</td>
<td>+ 4.4%</td>
<td>0</td>
<td>- 4.9%</td>
<td>- 10.2%</td>
</tr>
<tr>
<td>Change rate of total biomass(%)</td>
<td>+ 9.1%</td>
<td>+ 4.7%</td>
<td>0</td>
<td>- 5.3%</td>
<td>- 10.8%</td>
</tr>
</tbody>
</table>
Soybean

\[ NPP(\text{grams C}/m^2/s) = \text{Photosynthesis} - \text{Respiration} \]

**Figure 2.** Integrated daily direct and diffuse PAR irradiance at 30°N on July 15 under various aerosol optical depths and cloudless sky, cloud optical depth 2, and cloud optical depth 10. Data are based on NCAR Tropospheric Ultraviolet and Visible Radiation Model calculations.

**Figure 3.** Instantaneous canopy NPP at various levels of total irradiance, as a function of the amount of irradiance that is diffuse. Data are based on Norman canopy model with the base case assumptions of Table 2 and a solar zenith angle of 45°.
Acid Rain

Slower growth, injury, or even death of forests, by damaging leaves

Limiting nutrients available to trees

Exposing the trees to toxic substances slowly released from the soil
Increased Temperature
Air Pollution & Increased Temperatures

Figure 7-1 Rise in the concentrations of greenhouse gases since the 18th century

Jacob, 1999.
Predicted Temperature Changes in South Asia


Table 3: Temperature Change (°C) in South Asian Countries for 2030, 2050, and 2080 from 2000 Baseline, under Different IPCC Emission Scenarios

<table>
<thead>
<tr>
<th>Country</th>
<th>2030</th>
<th>2050</th>
<th>2080</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A2</td>
<td>A1B</td>
<td>B1</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>0.9</td>
<td>1.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Bhutan</td>
<td>1.5</td>
<td>1.9</td>
<td>1.7</td>
</tr>
<tr>
<td>India*</td>
<td>0.6–1.8</td>
<td>0.9–2.4</td>
<td>0.7–2.0</td>
</tr>
<tr>
<td>Maldives</td>
<td>0.9</td>
<td>1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>Nepal</td>
<td>1.6</td>
<td>2.0</td>
<td>1.7</td>
</tr>
<tr>
<td>Sri Lanka</td>
<td>1.0</td>
<td>1.1</td>
<td>1.0</td>
</tr>
</tbody>
</table>

A1B, A2, and B1 = projected scenarios from IPCC Special Report on Emission Scenarios; RCM = regional climate model.

* For India, range of temperature change is for 28 states and 3 union territories.
Increased Minimum Temperatures → Decreased Rice Yields

Peng et al. PNAS 2004
Temperature and Rice → Mechanism Unclear

<table>
<thead>
<tr>
<th>Year</th>
<th>Treatment</th>
<th>CO₂ conc. μmol mol⁻¹</th>
<th>Light intensity μmol m⁻² s⁻¹</th>
<th>Relative humidity %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>NAT</td>
<td>350.1a†</td>
<td>1005.2a</td>
<td>72.5a</td>
</tr>
<tr>
<td></td>
<td>HAT</td>
<td>349.3a</td>
<td>957.0a</td>
<td>72.1a</td>
</tr>
<tr>
<td>2007</td>
<td>NAT</td>
<td>349.6a</td>
<td>987.6a</td>
<td>74.0a</td>
</tr>
<tr>
<td></td>
<td>HAT</td>
<td>348.8a</td>
<td>947.1a</td>
<td>73.6a</td>
</tr>
</tbody>
</table>

† Numbers within a column followed by the same letter for a year are not significantly different at P = 0.05.

Rice Pathogens
Major Rice Pathogens

Sheath Blight (Rhizoctonia solani)

Rice Blast (Magnaporthe oryzae)
What factors?

- increased atmospheric CO2
- heavy and unseasonal rains
- increased humidity
- drought
- cyclones and hurricanes
- warmer winter temperatures

J.Luck et. al, Plant Pathology 2011
Increased Temperatures and Pathogens

Temperature emerged as the primary determinant of plant pathogen incidence and severity (Luo Agric. & Forest Meteorology, 2015).

- Reduce Winter Kill → Increase Populations

- Increased number of reproductive generations per season (Cruz et al, 2007)

- Increased geographical range of pathogens (Dixon, 2012).
Carbon Dioxide and Pathogens

Increased canopy size and density →
greater biomass with greater nutritional quality →
promotion of foliar disease such as mildews, leaf spots, and blights (Coakley et al., 1999).

### Table 3. Panicle blast incidence (%) under ambient and elevated CO₂ conditions

<table>
<thead>
<tr>
<th>Year</th>
<th>Ambient</th>
<th>Elevated&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.1</td>
<td>2.6&lt;sup&gt;*&lt;/sup&gt;</td>
</tr>
<tr>
<td>1999&lt;sup&gt;c&lt;/sup&gt;</td>
<td>23.9</td>
<td>20.3</td>
</tr>
<tr>
<td>2000</td>
<td>47.4</td>
<td>46.3</td>
</tr>
</tbody>
</table>

<sup>a</sup> Statistical differences between the [CO₂]e levels were determined with the paired t test within each year. Means followed by * are significant at P < 0.05 between ambient and elevated conditions.

<sup>b</sup> Panicle blast incidence occurred naturally and was determined by estimating the disease severity through field observations on 15 September 1998.

<sup>c</sup> Rice plants were artificially inoculated on 9 August 1999 and 2000. The number of healthy and infected spikelets was counted for each plant. Disease incidence was determined by calculating the percentage of diseased spikelets.

### Table 4. Sheath blight incidence and severity under ambient and elevated CO₂ concentrations in the field<sup>a</sup>

<table>
<thead>
<tr>
<th>Year</th>
<th>N&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Diseased plants (%)&lt;sup&gt;d&lt;/sup&gt;</th>
<th>Lesion height (%)&lt;sup&gt;e&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ambient CO₂</td>
<td>Elevated CO₂</td>
<td>Ambient CO₂</td>
</tr>
<tr>
<td>1999</td>
<td>High</td>
<td>3.2</td>
<td>10.1&lt;sup&gt;*&lt;/sup&gt;</td>
</tr>
<tr>
<td>2000</td>
<td>High</td>
<td>20.1</td>
<td>40.3&lt;sup&gt;*&lt;/sup&gt;</td>
</tr>
<tr>
<td>2000</td>
<td>Low</td>
<td>13.4</td>
<td>10.3</td>
</tr>
</tbody>
</table>

<sup>a</sup> Statistical differences between the [CO₂]e levels were determined with the paired t test within each year. Means followed by * are significant at P < 0.05 between ambient and elevated conditions within each year and nitrogen (N) rate.

<sup>b</sup> Disease incidence and severity was assessed on 29 July 1999 and 10 August 2000 in the field.

<sup>c</sup> N was applied as ammonium sulfate at rates of 15 and 4 g/m² for high- and low-N subplots, respectively. Normal rate of N application was 8 g/m².

<sup>d</sup> Percentage of hills with more than one lesion.

<sup>e</sup> Height of the uppermost lesion above the soil surface relative to the plant height.
# Carbon Dioxide and Pathogens

## TABLE 3 - Effect of enriched CO₂ concentration on rice blast severity expressed by area under disease progress curve (AUDPC) in leaves of three rice cultivars (Agulha Precoce, Shao Tiao Tsao and Caloro)

<table>
<thead>
<tr>
<th>Years</th>
<th>Cultivars</th>
<th>AUDPC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C¹</td>
</tr>
<tr>
<td>2007</td>
<td>Agulha Precoce</td>
<td>11.96c¹</td>
</tr>
<tr>
<td>2008</td>
<td>Agulha Precoce</td>
<td>13.15a</td>
</tr>
<tr>
<td></td>
<td>Shao Tiao Tsao</td>
<td>19.96a</td>
</tr>
<tr>
<td></td>
<td>Caloro</td>
<td>25.62b</td>
</tr>
<tr>
<td>2009</td>
<td>Agulha Precoce</td>
<td>9.31b</td>
</tr>
<tr>
<td></td>
<td>Shao Tiao Tsao</td>
<td>6.11ab</td>
</tr>
<tr>
<td>Means</td>
<td></td>
<td>14.35b</td>
</tr>
</tbody>
</table>

*C, control; OTC-A, open-top chambers with ambient CO₂; OTC+CO₂, OTC with elevated CO₂.*

²Means followed by the same letter in rows do not differ significantly (Tukey $p \leq 0.05$).
CO2 and Increased Plant Growth

- grew rice under higher CO2 in Sri Lanka

- looking at rice specifically grown under temps >30 degrees C

- found an increase in grain yields
  - increased biomass production overall

- increase in RUE (Radiation use efficiency)

- seed yields were 24% and 39% higher than ambient

Table 6: Panicle growth rates (PGR) and overall crop growth rates (CGR) of rice grown under elevated (ca. 570 μmol mol-1) and ambient CO2 (ca. 370 μmol mol-1) in open top chambers and in open field conditions in Maha (January to March) and Yala (May to August) seasons of 2001

<table>
<thead>
<tr>
<th>Period (days after transplanting)</th>
<th>PGR (g m⁻² d⁻¹)</th>
<th>CGR (g m⁻² d⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Elevated CO₂</td>
<td>Ambient CO₂</td>
</tr>
<tr>
<td></td>
<td>38-54</td>
<td>54-67</td>
</tr>
<tr>
<td></td>
<td>10.3 a</td>
<td>40.6 a</td>
</tr>
<tr>
<td></td>
<td>7.4 b</td>
<td>23.9 b</td>
</tr>
<tr>
<td></td>
<td>10.5 a</td>
<td>19.3 b</td>
</tr>
<tr>
<td></td>
<td>37.6 a</td>
<td>79.3 a</td>
</tr>
<tr>
<td></td>
<td>30.1 b</td>
<td>26.5 b</td>
</tr>
<tr>
<td></td>
<td>40.2 a</td>
<td>5.9 c</td>
</tr>
</tbody>
</table>

Maha

<table>
<thead>
<tr>
<th>Period (days after transplanting)</th>
<th>PGR (g m⁻² d⁻¹)</th>
<th>CGR (g m⁻² d⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Elevated CO₂</td>
<td>Ambient CO₂</td>
</tr>
<tr>
<td></td>
<td>Yala</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40-53</td>
<td>53-60</td>
</tr>
<tr>
<td></td>
<td>4.9 a</td>
<td>9.0 a</td>
</tr>
<tr>
<td></td>
<td>4.8 a</td>
<td>10.3 a</td>
</tr>
<tr>
<td></td>
<td>4.6 a</td>
<td>13.44 a</td>
</tr>
<tr>
<td></td>
<td>20.7 a</td>
<td>12.9 b</td>
</tr>
<tr>
<td></td>
<td>18.3 a</td>
<td>32.5 a</td>
</tr>
<tr>
<td></td>
<td>20.7 a</td>
<td>29.4 a</td>
</tr>
</tbody>
</table>

Yala

For each parameter, means connected horizontally by the same letter are not significantly different at p = 0.05.
Conclusion

As shown in our presentation, air quality will have direct, primary indirect, and possibly even secondary indirect effects on crop growth.

While we described several levels of effects in this presentation, there are many we omitted: extreme weather events, droughts, salinity infiltration, and more.

Major atmospheric pollutants, such as ozone, sulfur dioxide, NOx and fluorides have significant impact on rice yields, especially, ozone can cause most of the damage.

All of these four pollutants have a common mechanism to reduce rice yields, that is inhibiting photosynthesis.

Aerosol affect crop productivity/yield by scattering and absorbing solar irradiation


Kim, Kwang-Hyung. 2015. Predicting potential epidemics of rice leaf blast and sheath blight in South Korea under RCP 4.5 and RCP 8.5 climate change scenarios using a rice disease epidemiology model, EPRICE. Agricultural and Forest Meteorology, 203:191-207.


