Effects of Ozone-CO$_2$-Induced Vegetation Changes on Global Air Quality

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5th iLEAPS Science Conference 2017
Plant-Atmosphere Interactions

Stoma

O₃, SO₂, NOₓ

water travels up through trunk

water in soil

stomatal pore

CO₂

light

H₂O

glucose (C₆H₁₂O₆)
**Plant-Atmosphere Interactions**

**Lower albedo:** absorbs more shortwave radiation than bare land

**Photosynthesis:** absorbs atmospheric CO₂

**Transpiration:** transfers water and latent heat to atmosphere, cooling surface and shaping boundary-layer dynamics

**O₃, SO₂, NOₓ**
**Plant-Atmosphere Interactions**

**Lower albedo:** absorbs more shortwave radiation than bare land

**Photosynthesis:** absorbs atmospheric CO₂

**Dry deposition:** absorbs air pollutants, e.g., O₃, SO₂, NOₓ

**Transpiration:** transfers water and latent heat to atmosphere, cooling surface and shaping boundary-layer dynamics

**Biogenic emissions:** releases volatile organic compounds (VOCs) that are precursors for ozone and aerosol particles

O₃, SO₂, NOₓ
Vegetation Change Affects Air Quality and Climate

2000-2050 change in **cropland fraction** following IPCC A1B

Asynchronously coupled climate-biosphere-chemistry models

2000-2050 changes in summertime **surface ozone** (ppbv)

[Tai et al., GRL, 2013]
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- Many land use and land cover change studies only consider changes in:
  - Land/plant type distribution (category, fractional coverage) → most...
  - Vegetation structure (LAI, canopy height) → some...

[Image 35x305 to 374x431]
[Image 35x-88 to 539x290]
Vegetation Change Affects Air Quality and Climate

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  - Land/plant type distribution (category, fractional coverage) → most...
  - Vegetation structure (LAI, canopy height) → some...

- Most do not consider simultaneous changes in plant physiology under varying atmospheric conditions...

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**CO$_2$:**
- Inhibits isoprene emission
- Enhances LAI (fertilization)
- Reduces stomatal conductance (to prevent water loss)
**Effects of Ozone-CO\textsubscript{2}-Vegetation Coupling**

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**O\textsubscript{3}**:
- Reduces LAI (damage)
- Reduces stomatal conductance (damage)
In GEOS-Chem chemical transport model, we implemented:
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1. **CO₂ inhibition of isoprene emission**

![Graph showing normalized isoprene emission vs. CO₂ concentration (ppmv)].

[Possell & Hewitt 2011]
Adding CO$_2$ Effects to Atmospheric Chemistry Model

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   ![Graph showing CO$_2$ concentration vs. normalized isoprene emission]

   [Possell & Hewitt 2011]

   - Present-day level
   - 2050 level

2. Relative LAI enhancement from CO$_2$ fertilization

   CLM4.5-BGC-simulated LAI changes under 2000-2050 transient CO$_2$
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1. **CO$_2$ inhibition of isoprene emission**

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   CLM4.5-BGC-simulated LAI changes under 2000-2050 transient CO$_2$

3. **Relative stomatal conductance ($g_s$) as a function of ambient CO$_2$ concentration ($c_a$)**
1. Examine ozone changes due to RCP4.5 and RCP8.5 land use change
2. Examine additional effects of elevated CO$_2$ on top of land use change

[Wong et al., in prep]
Effects of Elevated CO$_2$ in 2050 on Surface Ozone

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**Additional effects of 2050 RCP8.5 CO$_2$ (525 ppm) on surface ozone**

- **Isoprene inhibition**: $E_{\text{isop}} \downarrow 30\%$
- **CO$_2$ fertilization**: LAI $\uparrow 10\%$
- **Stomatal conductance**: $g_s \downarrow 30\%$
- **Combined effect**

[ Wong et al., in prep ]
We previously found (using CESM) that ozone damage on stomata can induce a strong positive feedback (of up to +6 ppbv) due to:

- Reduced dry deposition
- Increased isoprene emission due to transpiration-induced increase in vegetation temperature
Effects of Ozone-Vegetation Coupling on Air Quality

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  - Reduced dry deposition
  - Increased isoprene emission due to transpiration-induced increase in vegetation temperature

Complication and caveats:
- LAI simulation in CLM4 is poor…
- Hydrometeorological feedbacks tend to mask important processes…
- Vegetation temperature calculation may be poorly constrained…

[Sadiq et al., ACP, 2017]
1. Implement Lombardozzi et al. [2015] ozone damage scheme in CLM4.5-BGC

2. Run CLM at different $[O_3]$ levels until quasi-steady state

3. Parameterize simulated relationship between $[O_3]$ and LAI ($L$) for each grid cell, month and PFT:

$$\gamma = \frac{L}{L_0} = \gamma_\infty + (1 - \gamma_\infty) e^{-k[O_3]}$$

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5. Apply \(\gamma\) as a function of mean \([O_3]\) of previous month to potential LAI at beginning of each month of GEOS-Chem simulation → dynamic \(O_3\)-LAI coupling on monthly timescale
Effects of $O_3$-LAI Coupling on Simulated Ozone

$O_3$-affected LAI – intact LAI

Resulting changes in $[O_3]$ (ppb)
Effects of O₃-LAI Coupling on Simulated Ozone

Positive feedback of up to +3 ppbv overall:

- Dry deposition ↓ (5-20%) → [O₃] ↑
- Isoprene emission ↓ (5-20%) → [O₃] ↓
- Deposition effect dominates in most regions
- In low-LAI regions, PAN transport ↓ → [O₃] ↓
Effects of $O_3$-LAI Coupling on Simulated Ozone

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Ozone feedback factor ($f$):

$$
\Delta [O_3]_{\text{total}} = \frac{\Delta [O_3]_{\text{anthropogenic}}}{1 - f}
$$

$$
f \approx 0.1 - 0.6$$
Conclusions and Future Work

Conclusions:

- Elevated CO$_2$ suppresses isoprene emission and stomatal conductance, leading to compensating effects on surface ozone.
- Combined effect of 525 ppm CO$_2$ is in the range of $-1$ to $+4$ ppb.
- O$_3$-induced damage on LAI leads to an ozone feedback of $-1$ to $+3$ ppb, and reflects compensating effects of reduced dry deposition and isoprene emission.

- **Physiological responses of plants to atmospheric changes are important for atmospheric chemistry.**

Ongoing and future work:

- Biospheric component in GEOS-Chem to fully capture CO$_2$, O$_3$ and climatic effects on photosynthesis and stomatal conductance.
- **Terrestrial Ecosystem Model in R (TEMIR) v1.0** driven by MERRA2 or GEOS-FP surface fluxes and met fields: