

NOVEMBER 18, 2026

Interactive Earth system processes in CLM

Nitrogen, ozone, BVOCs, dust, and fire

Sam Rabin — Software engineer (TSS)
Danica Lombardozzi — Scientist (TSS), Assoc. Prof. (CSU)

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Land-atmosphere matter flux grab bag

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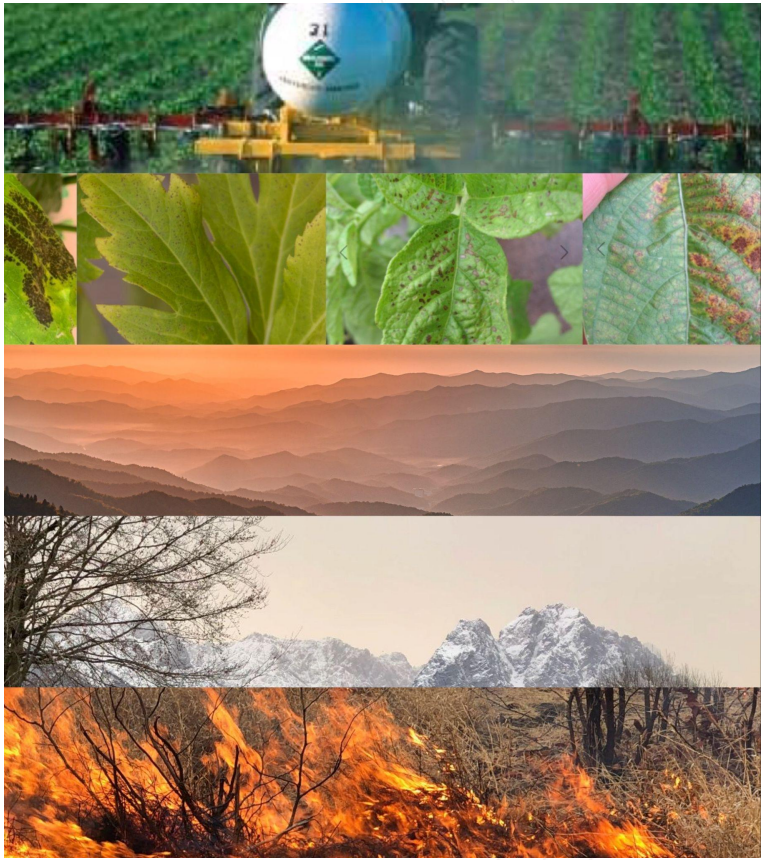


Outline

These processes are important for land in its own right

We don't *just* care about these because the atmosphere does!

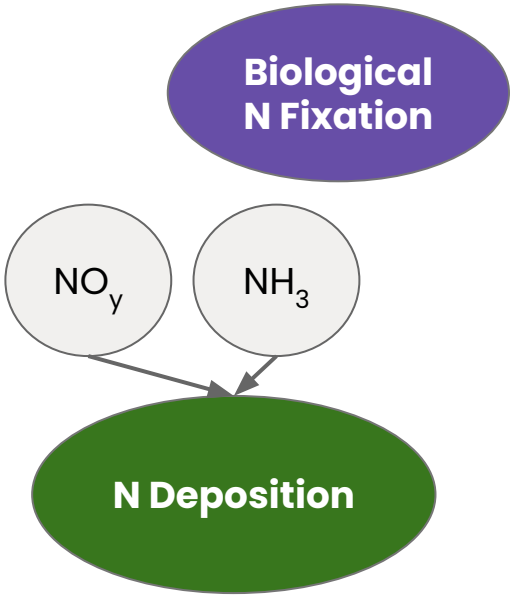
- Nitrogen deposition and gas fluxes
- Ozone
- Biogenic volatile organic compounds (BVOCs)
- Dust
- Fire



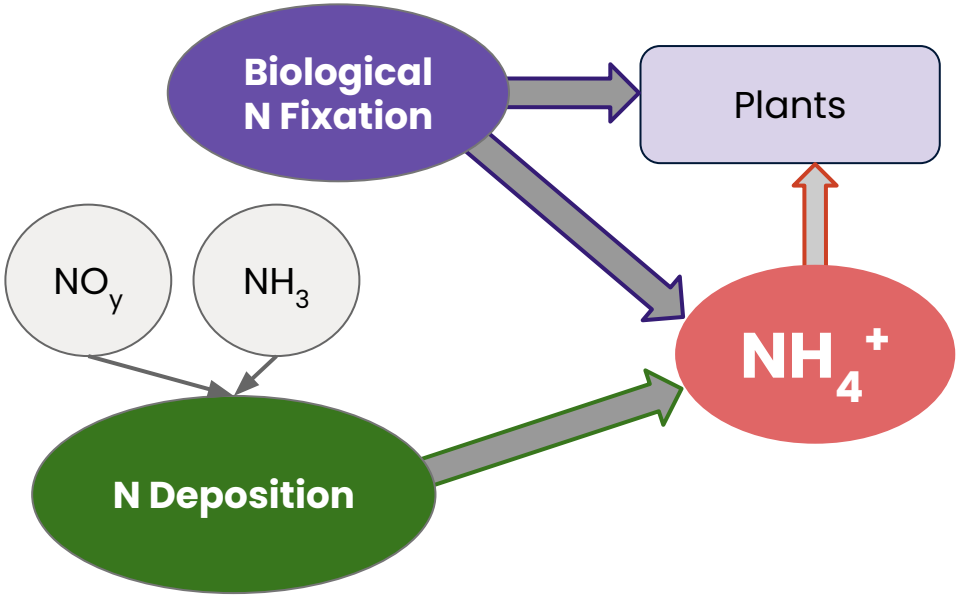
External N cycle: Deposition and gas fluxes



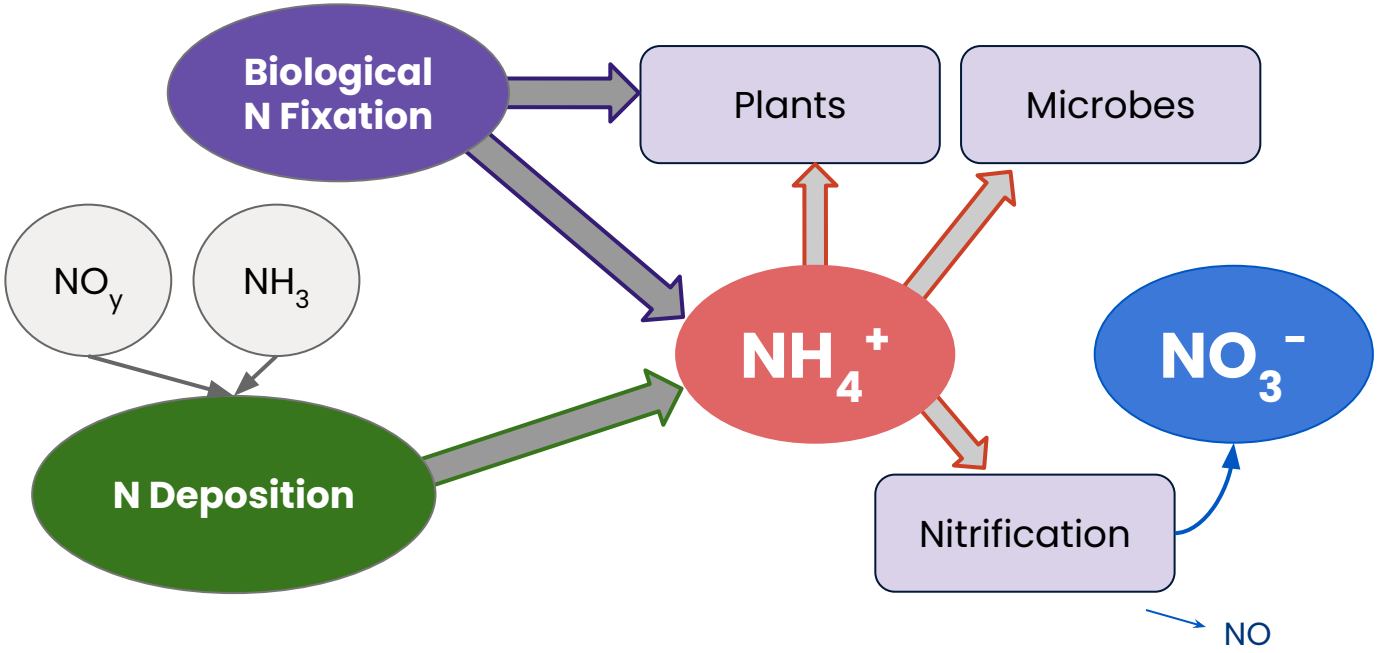
N Inputs & Flows (- ag N)



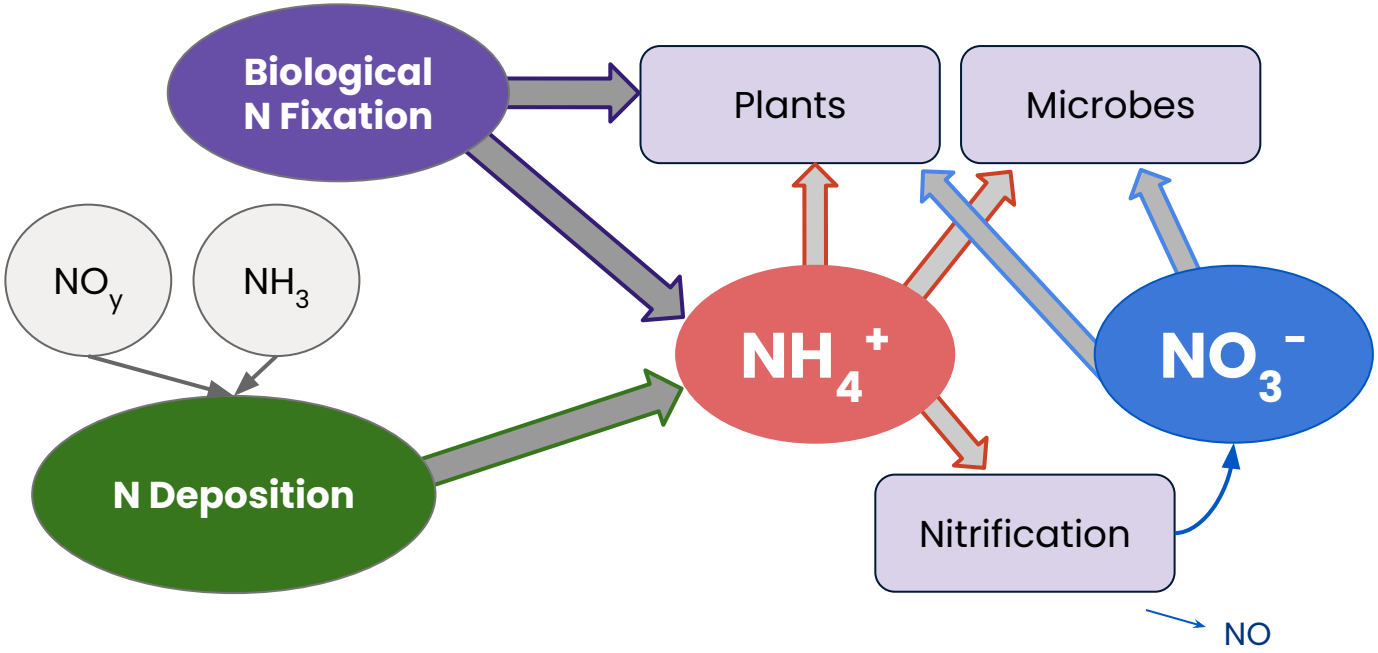
N Inputs & Flows (- ag N)



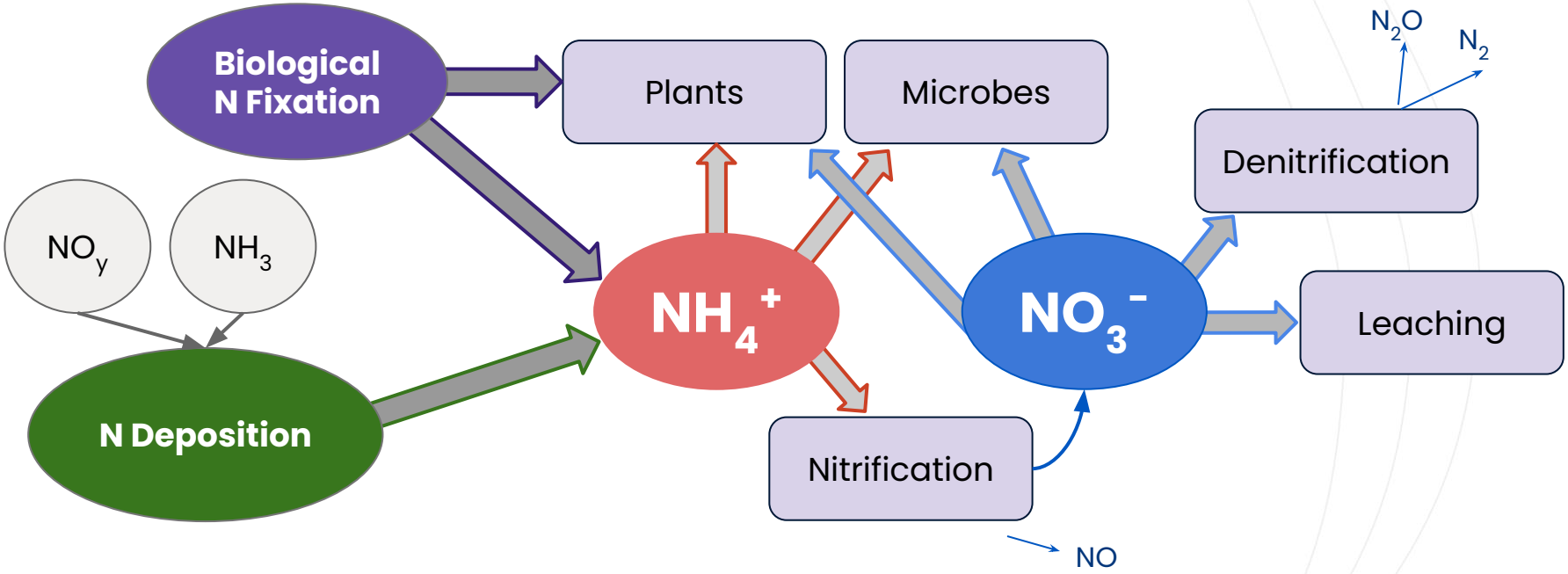
N Inputs & Flows (- ag N)



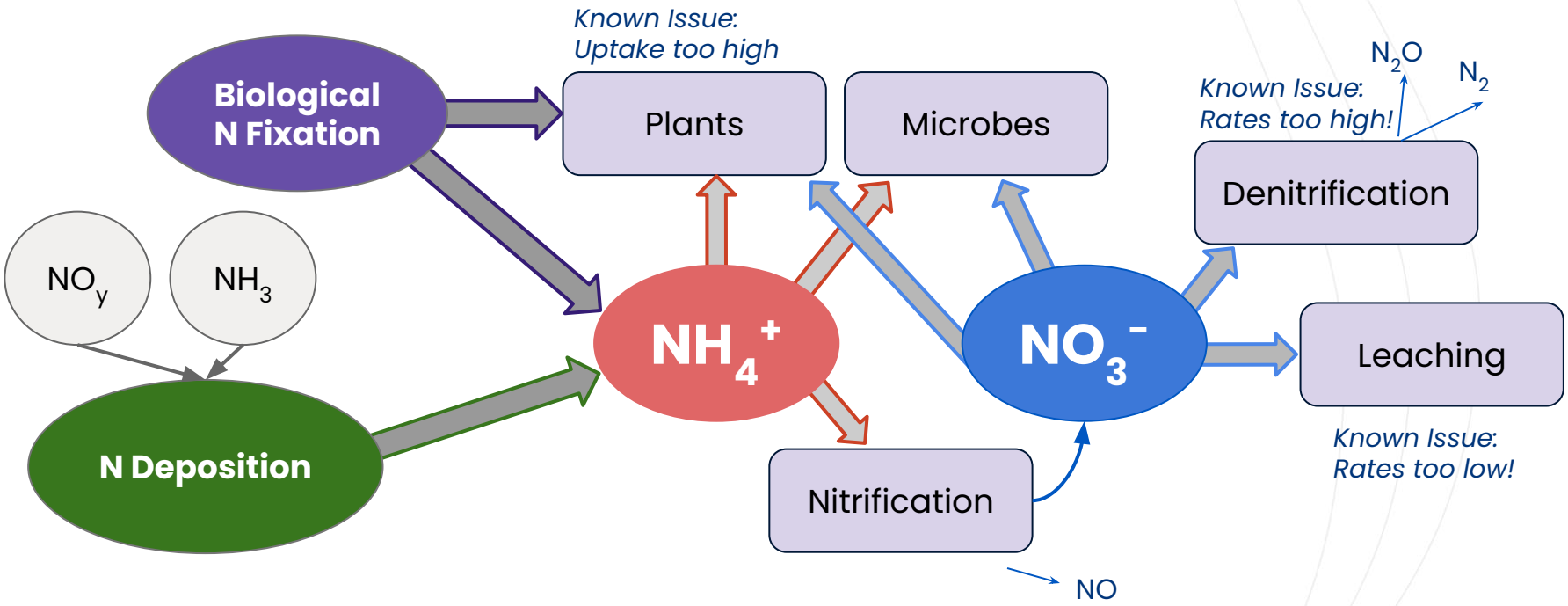
N Inputs & Flows (- ag N)



N Inputs & Flows (- ag N)

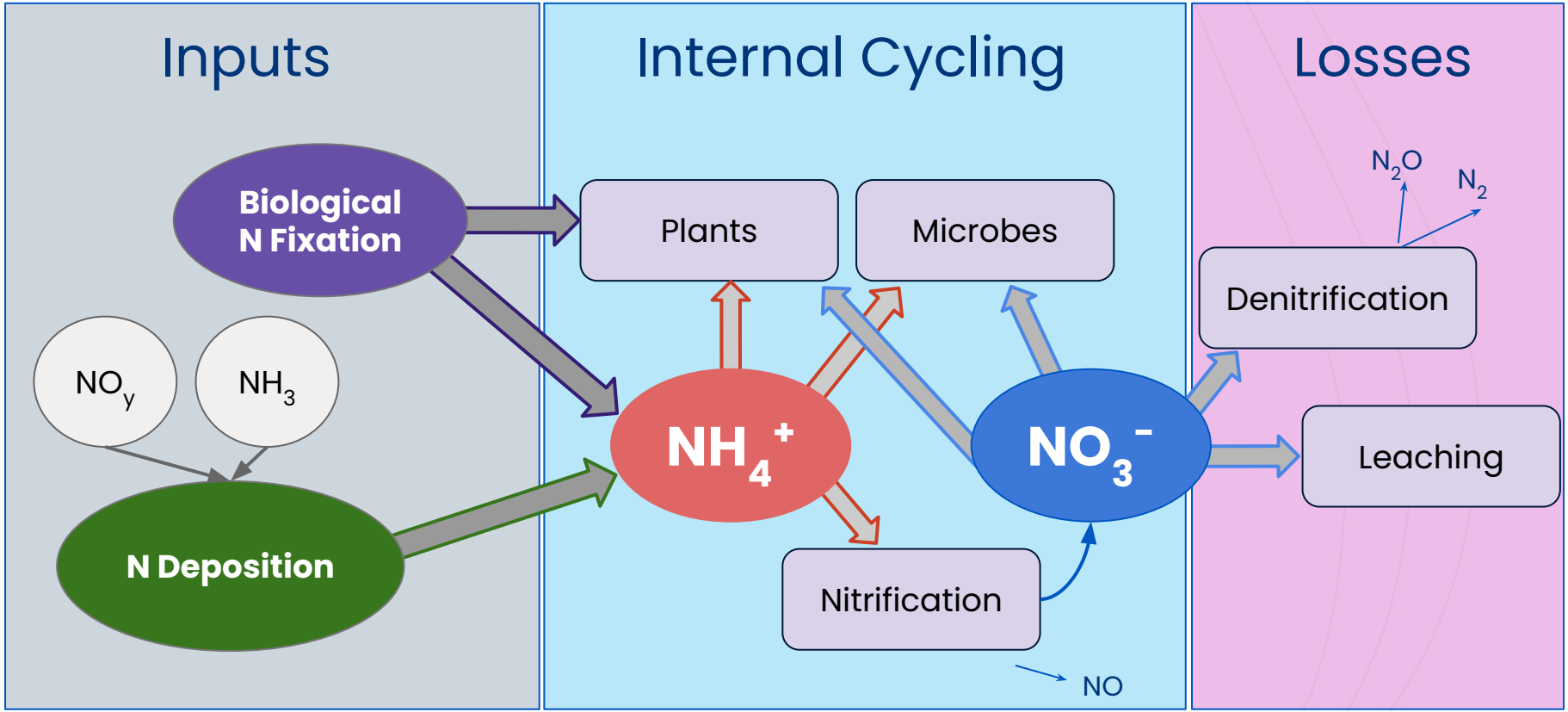


N Inputs & Flows (- ag N)



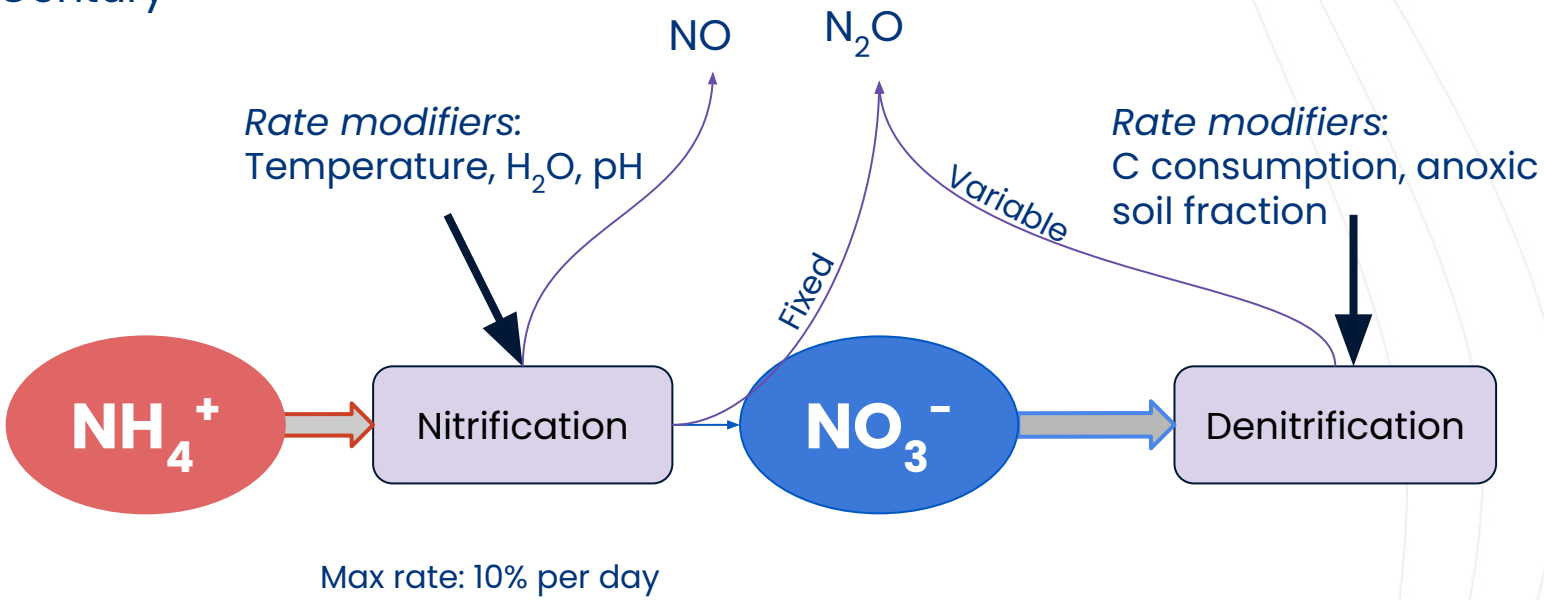
Cheng et al. 2019

N Inputs & Flows (- ag N)



Nitrification & Denitrification

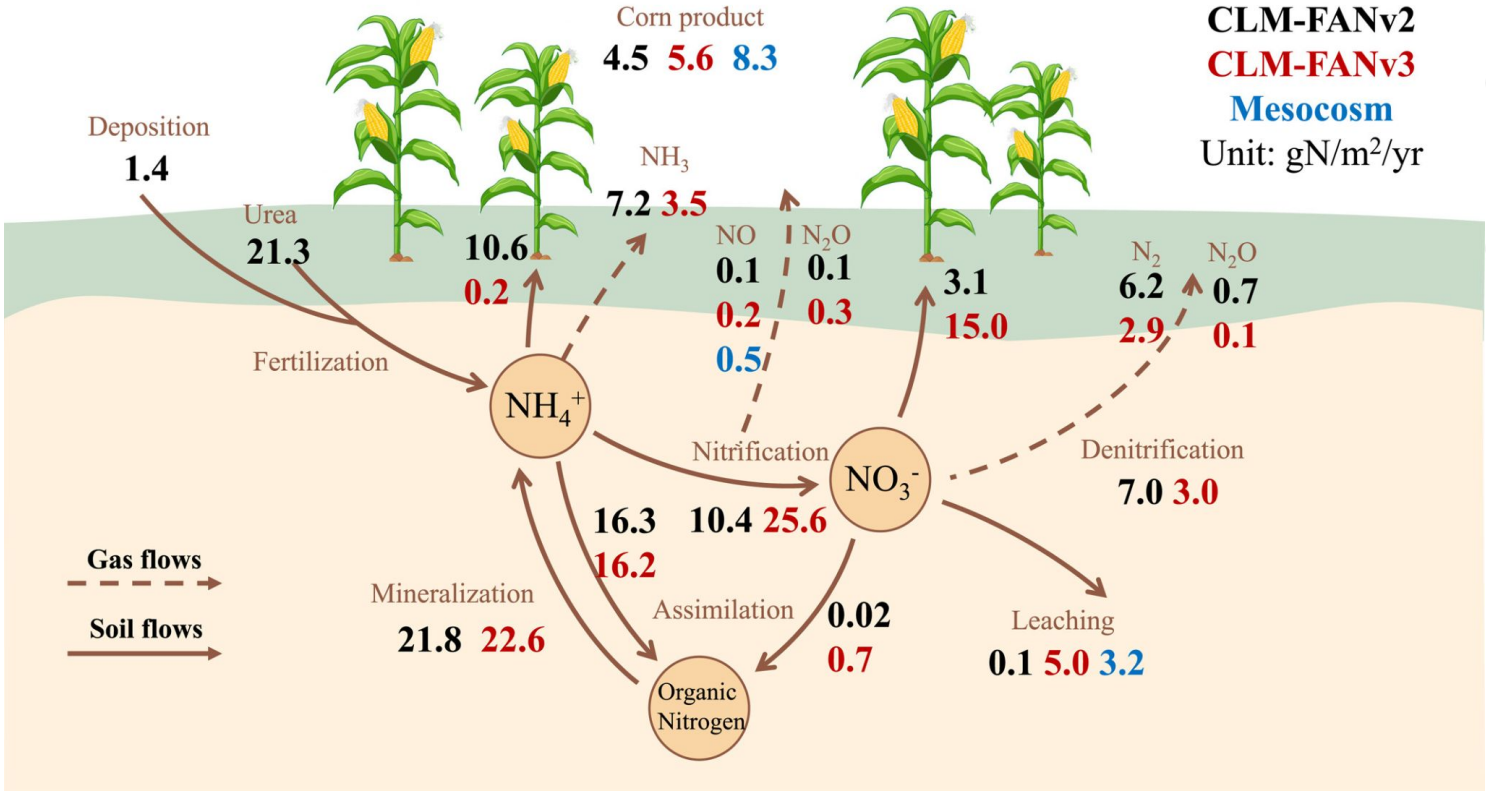
Based on Century



Max rate: 10% per day

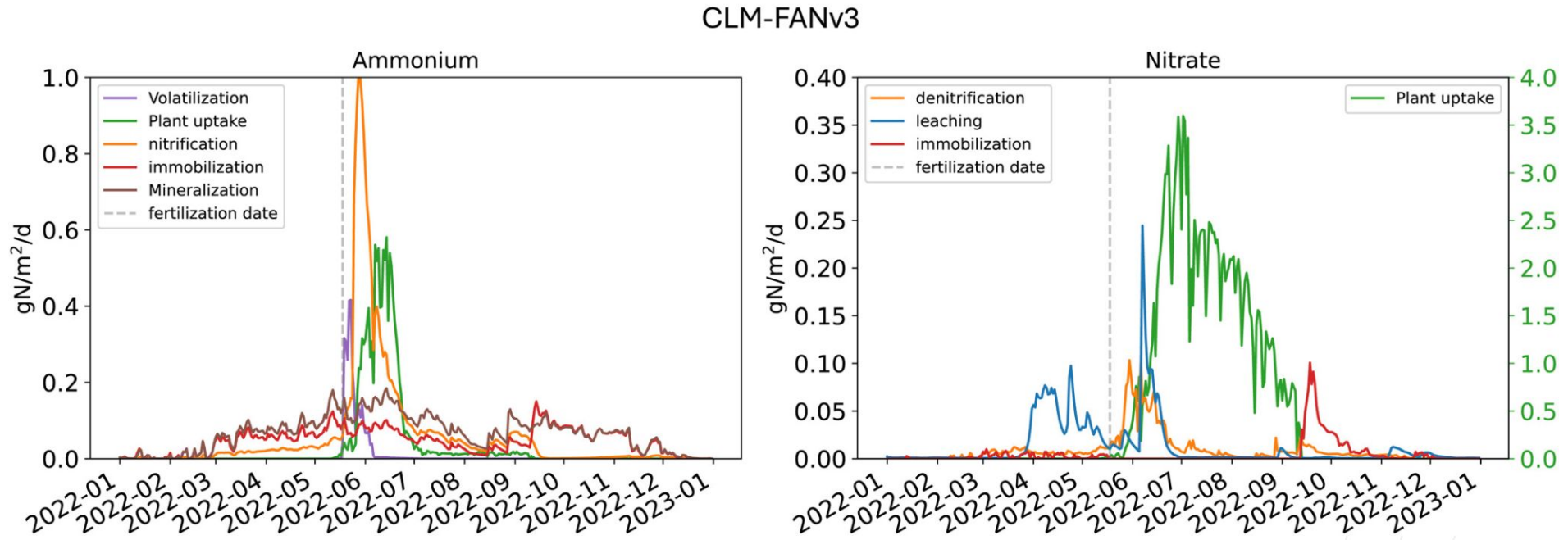
Flows of Agricultural Nitrogen (FAN)

FAN is an optional module that you can turn on in CLM



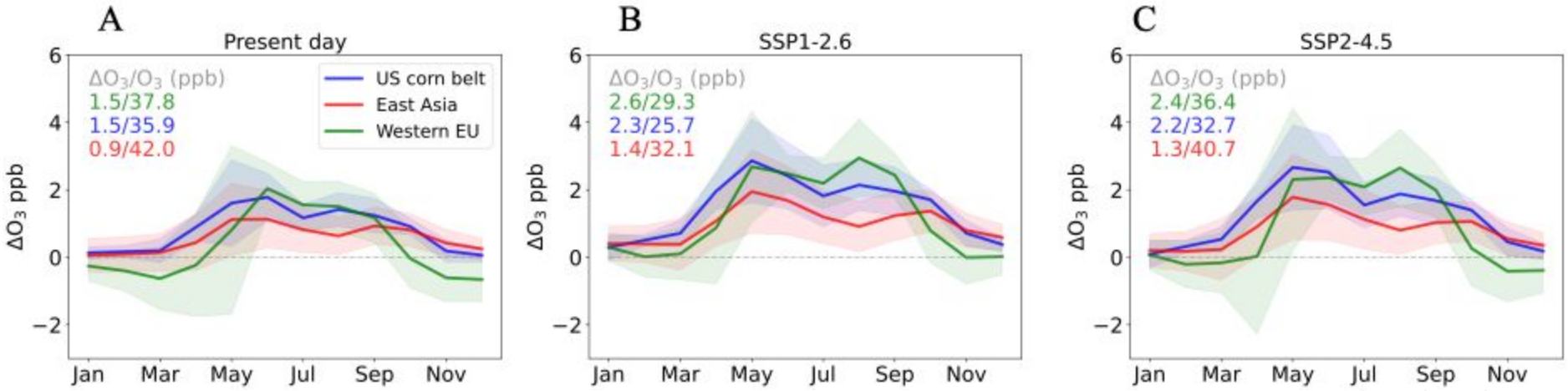
Luo et al. 2026

N transformations after fertilization event



Luo et al. 2026

Soil NOx emissions increase ozone concentrations



Luo et al. in review

Ozone

Milkweed



Coneflower



Potato

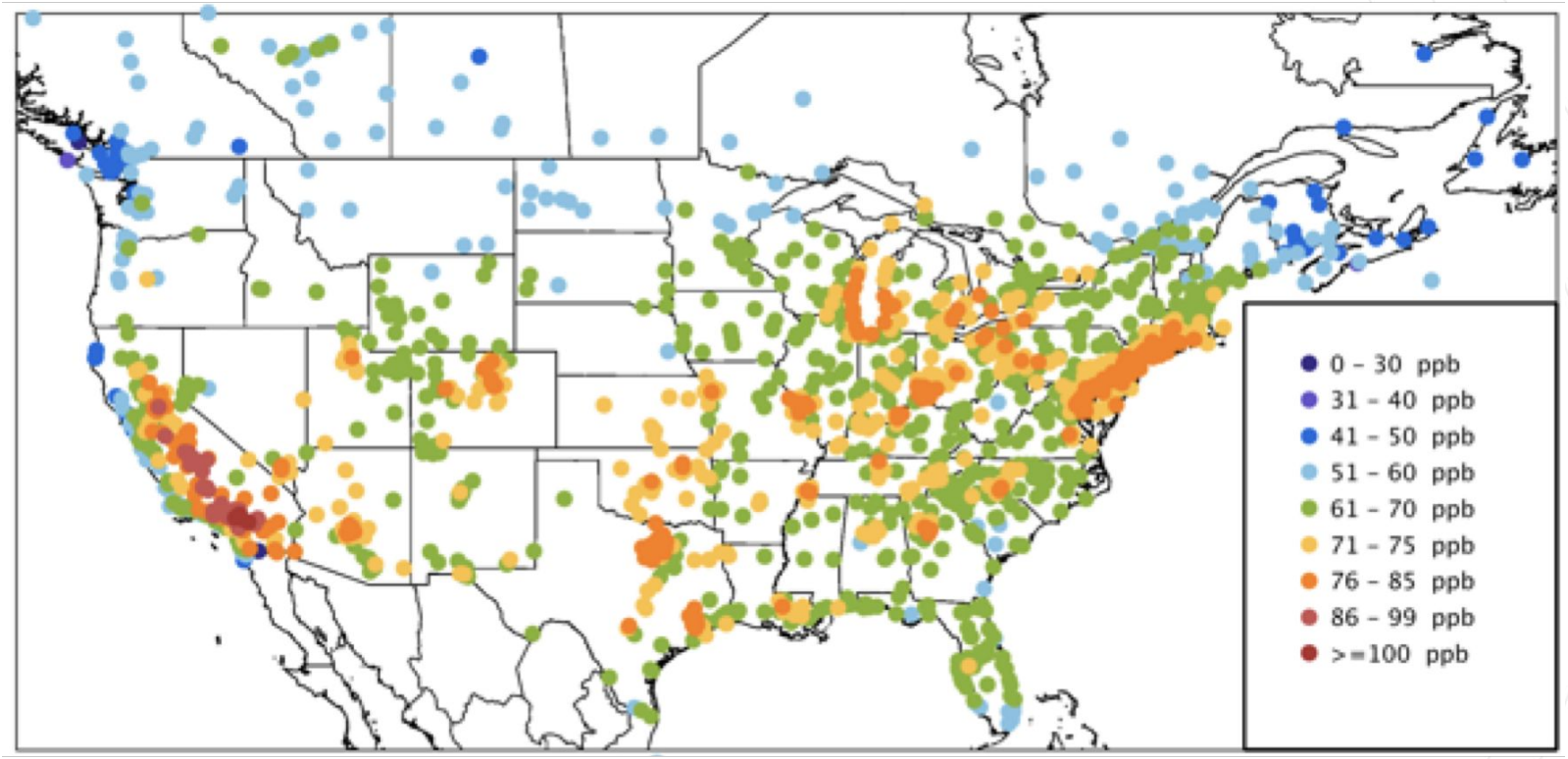


Snap bean



Visible damage caused by ozone. Photos are from NSF-NCAR's Ozone Bioindicator Garden where ambient ozone concentrations are high enough to cause the damage shown in these photos.

U.S. EPA limit for **ozone**: 70 ppb over 8 hours



2010-2014 TOAR Data, courtesy of Owen Cooper, NOAA

Why does EPA regulate ozone?

Ozone impacts our health

EPA Primary Standard







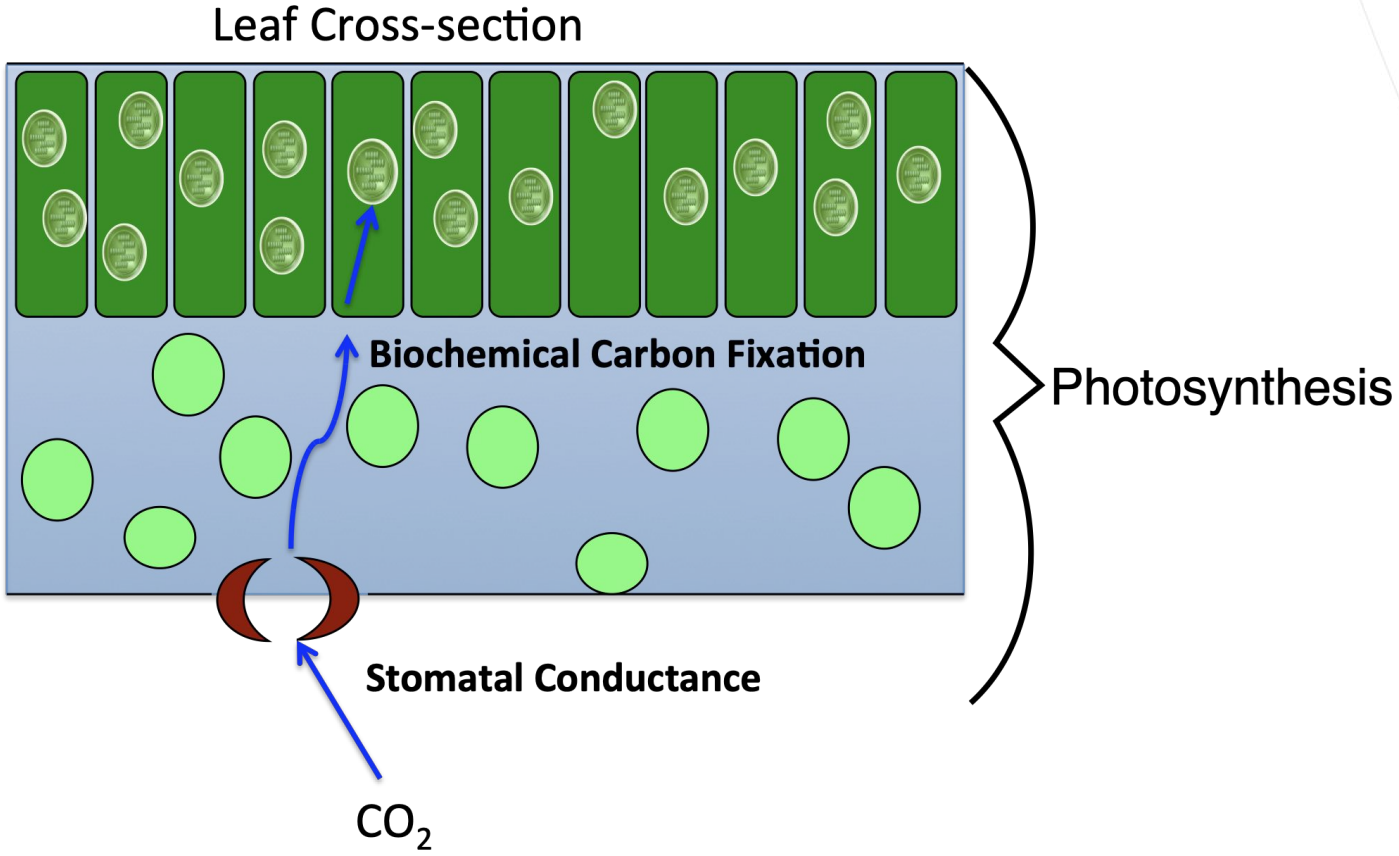
Pentax Medical Company

Ozone impacts our ecosystems

EPA Secondary Standard

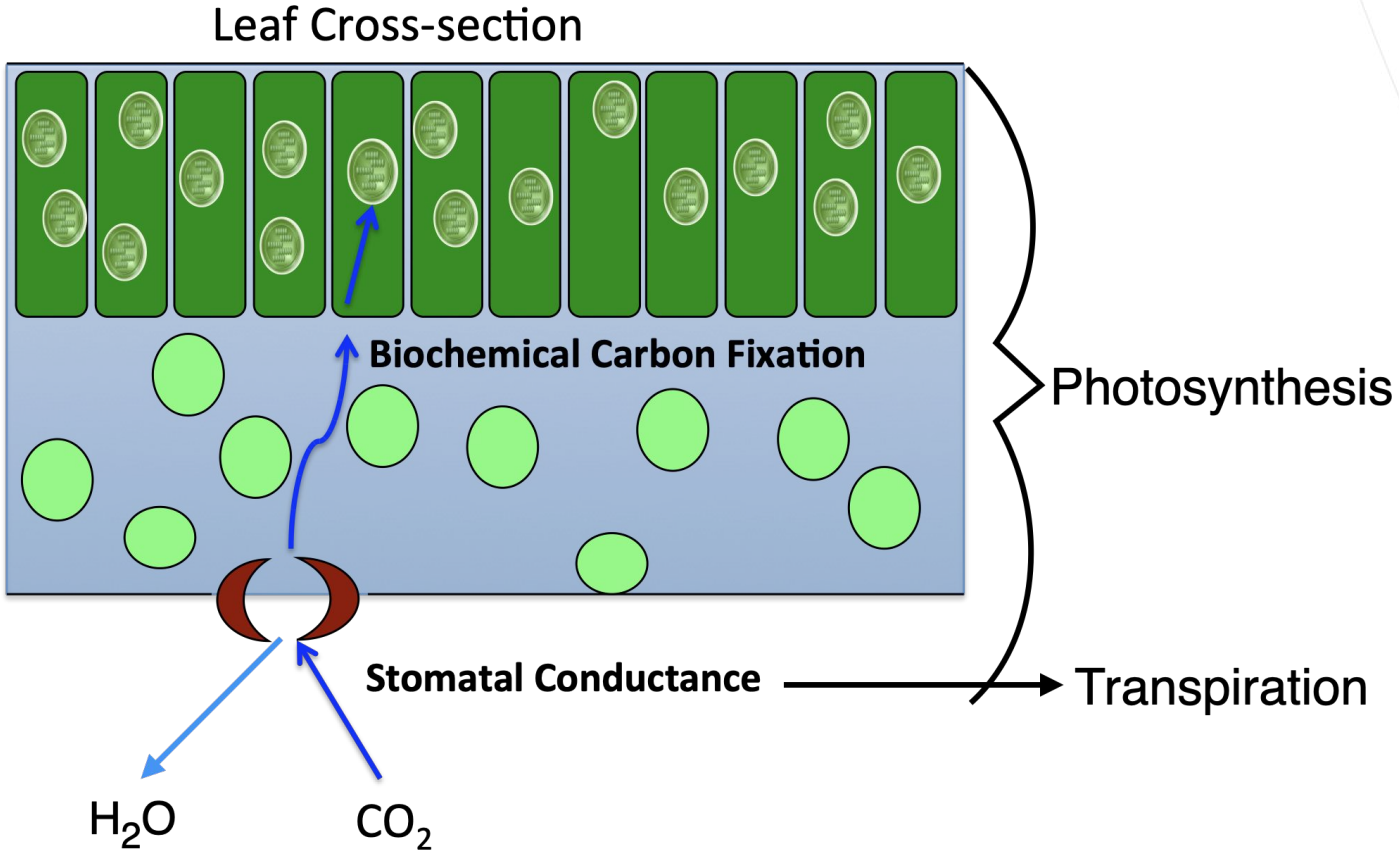


How does ozone damage leaves?



Adapted from Lombardozzi et al. 2013, *BGS*

How does ozone damage leaves?



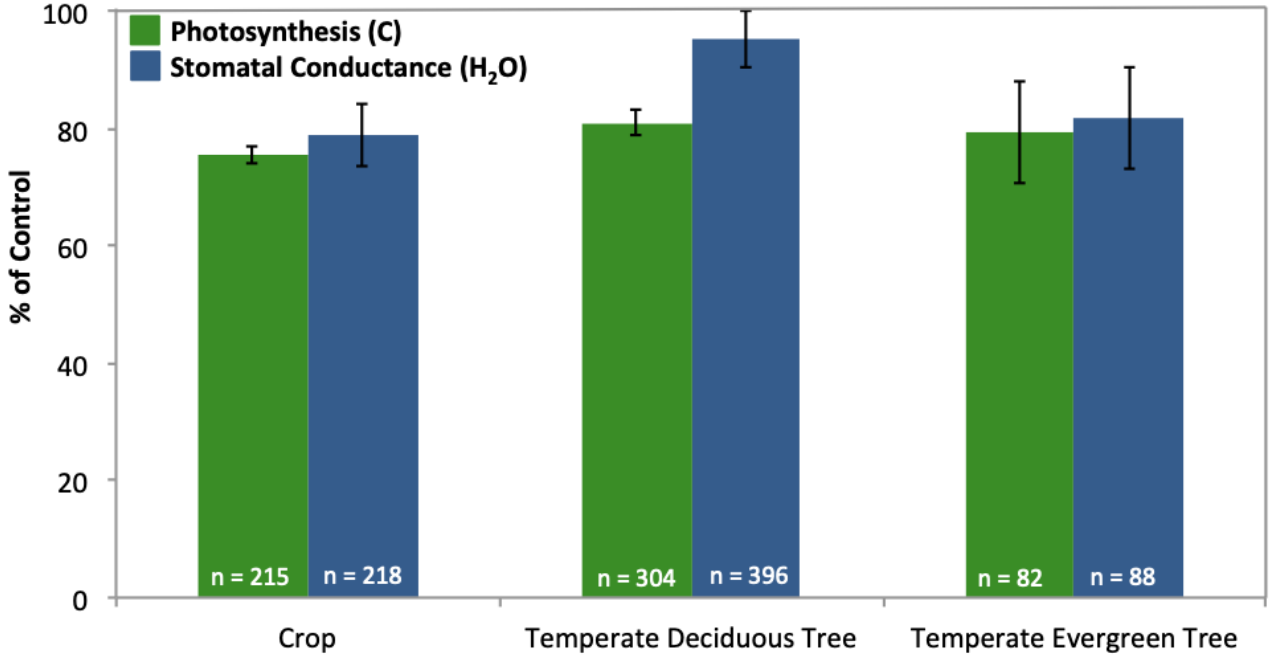
Adapted from Lombardozzi et al. 2013, *BGS*



Open-top Chamber Experiment. Credit: S. Cook-Patton

Mean **photosynthetic** change = **-21%** *

Mean **conductance** change = **-11%**

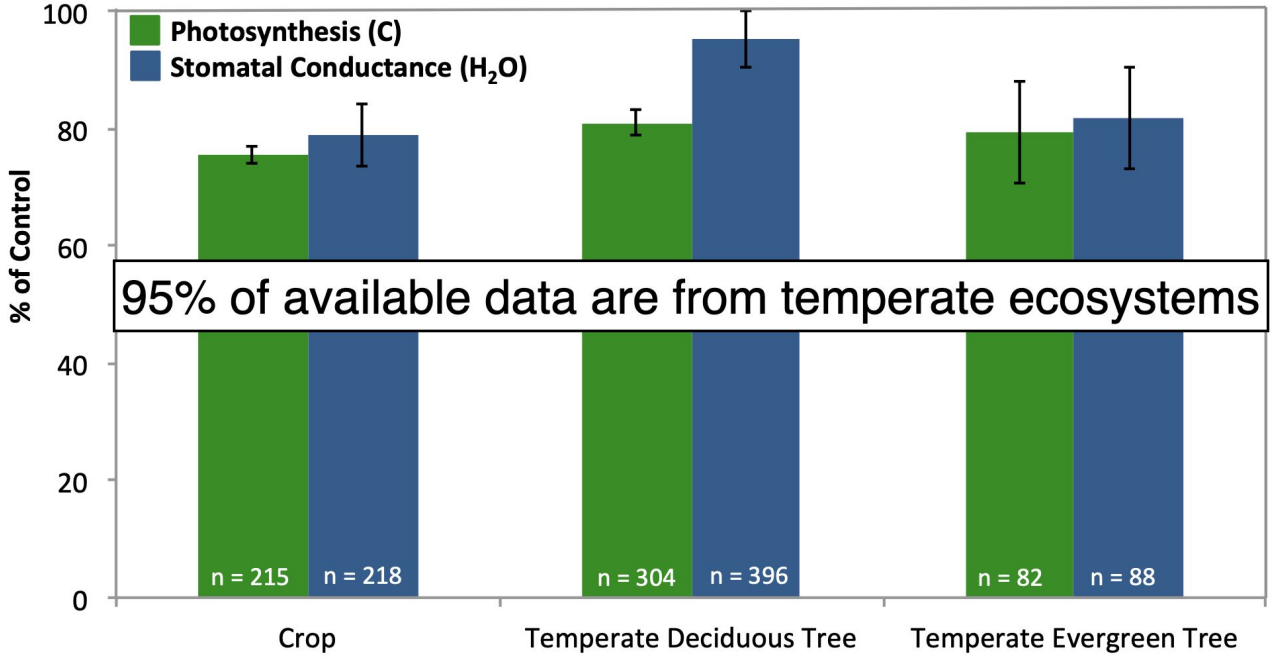


Data adapted from Lombardozzi et al., 2013 *BGS*

* Similar to Wittig et al. 2007, *Plant Cell Environ*; Feng et al. 2008 *GCB*; Morgan et al. 2003, *Plant Cell Environ*

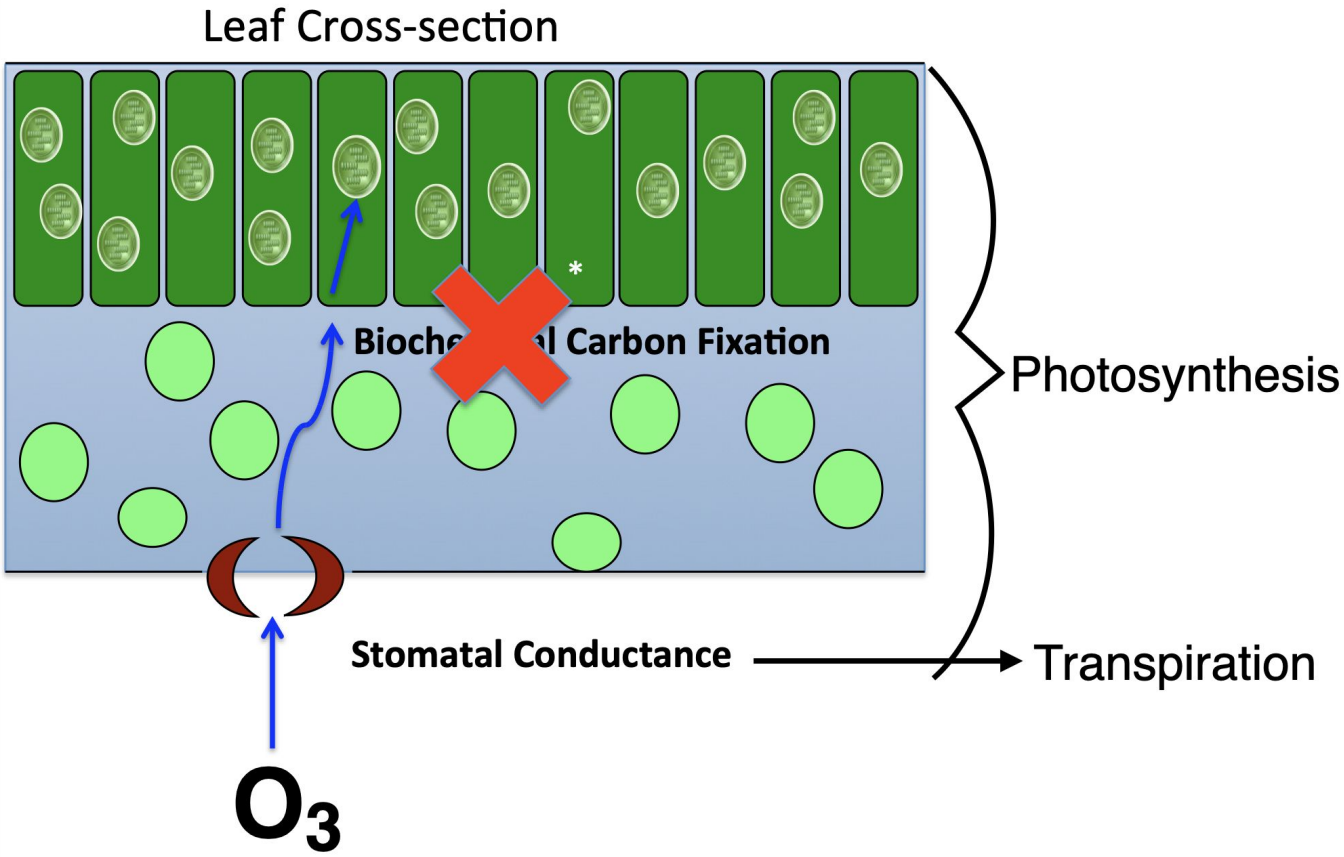
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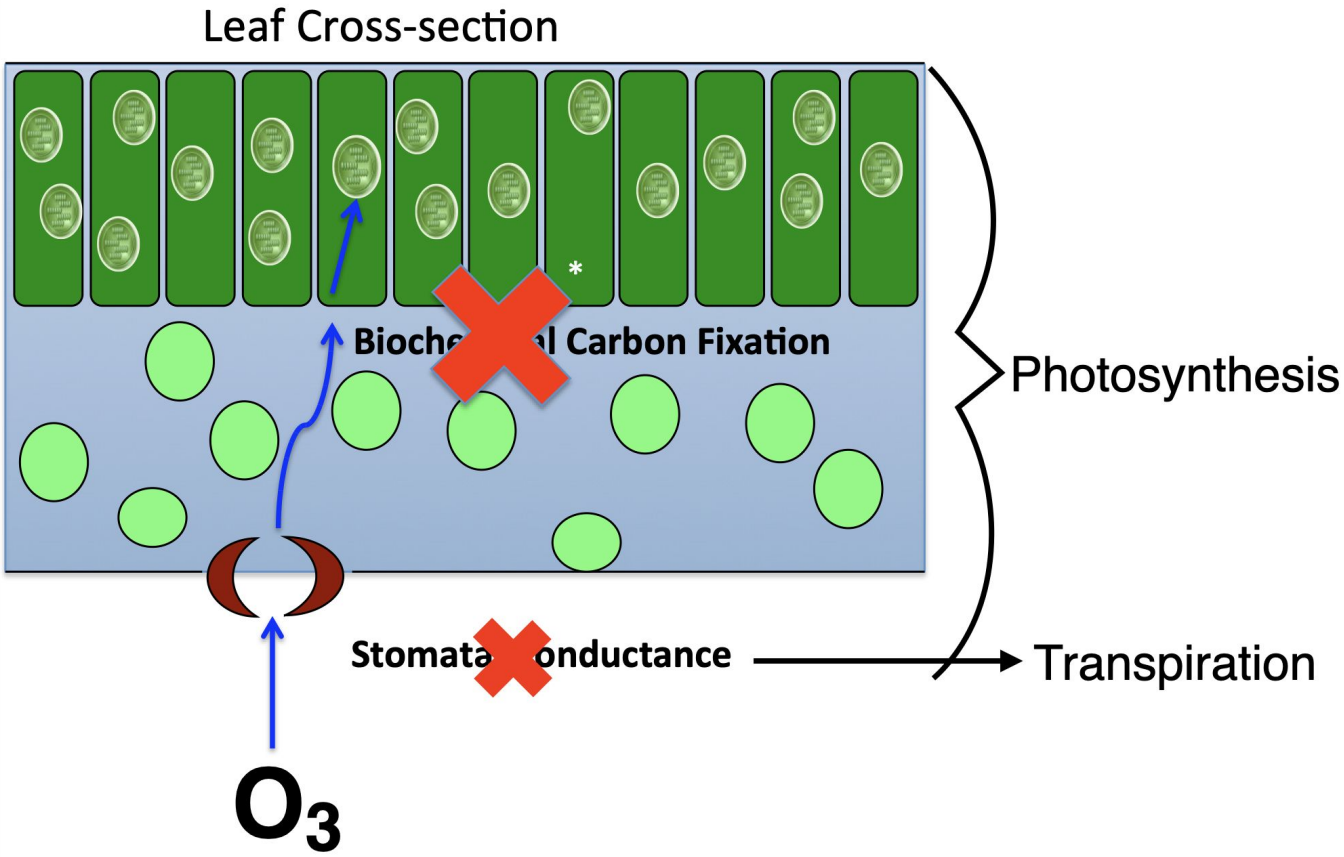


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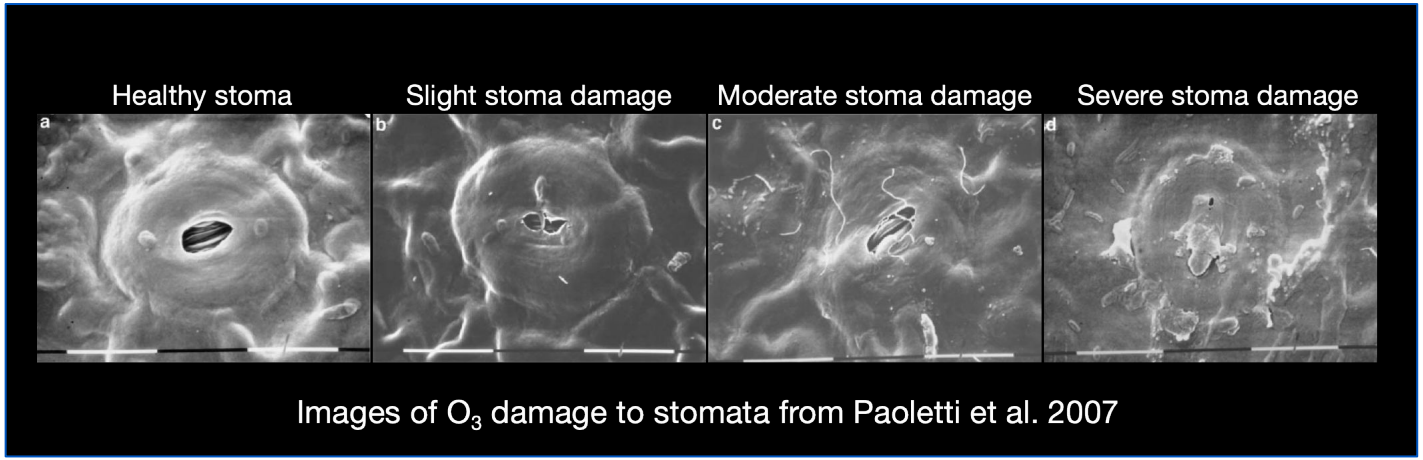
* Bortier et al. 2000, *New Phtyol*; Francini et al. 2007, *Environ Exp Bot*; Fiscus et al. 1997, *J. Exp Bot*; Heagle et al. 1996 *J. Environ Qual*; Noormets et al. 2001, *Plant Cell Environ*; Sharma et al. 2003, *Ekologia,* Lombardozzi et al. 2012, *Oceologia,* Lombardozzi et al. 2014, *Biogeosciences*



* Bortier et al. 2000, *New Phtyol*; Francini et al. 2007, *Environ Exp Bot*; Fiscus et al. 1997, *J. Exp Bot*; Heagle et al. 1996 *J. Environ Qual*; Noormets et al. 2001, *Plant Cell Environ*; Sharma et al. 2003, *Ekologia,* Lombardozzi et al. 2012, *Oceologia,* Lombardozzi et al. 2014, *Biogeosciences*

Medlyn Stomatal Conductance

$$g_s = g_0 + 1.6\left(1 + \frac{g_1}{\sqrt{VPD}}\right)\frac{\text{Photosynthesis}}{[CO_2]}$$

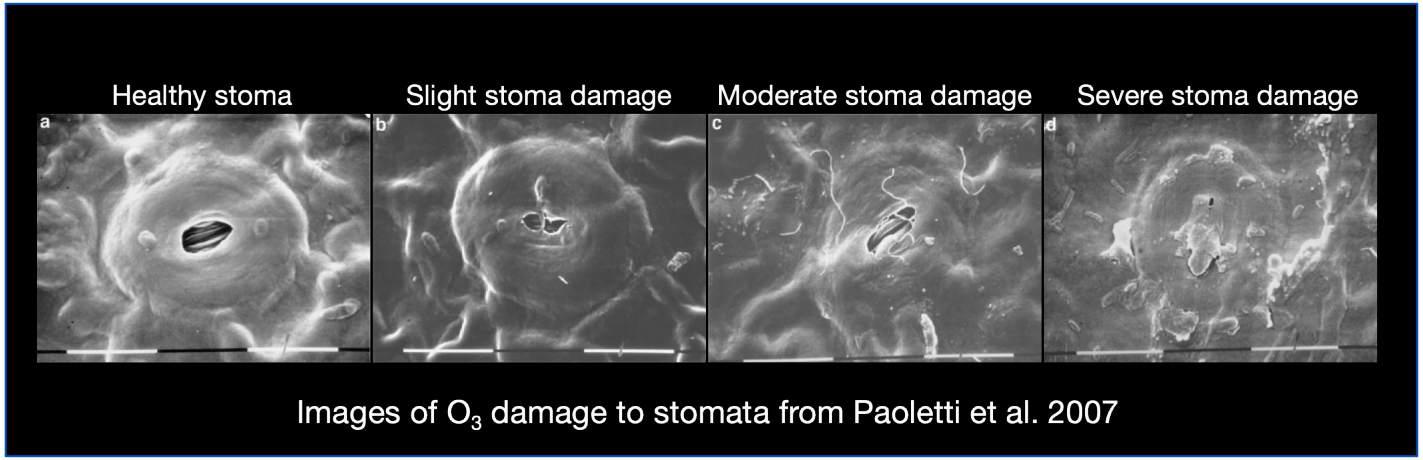


Images of O_3 damage to stomata from Paoletti et al. 2007

Medlyn Stomatal Conductance

Undamaged

#1 $g_s = g_0 + 1.6\left(1 + \frac{g_1}{\sqrt{VPD}}\right)\frac{\text{Photosynthesis}}{[CO_2]}$



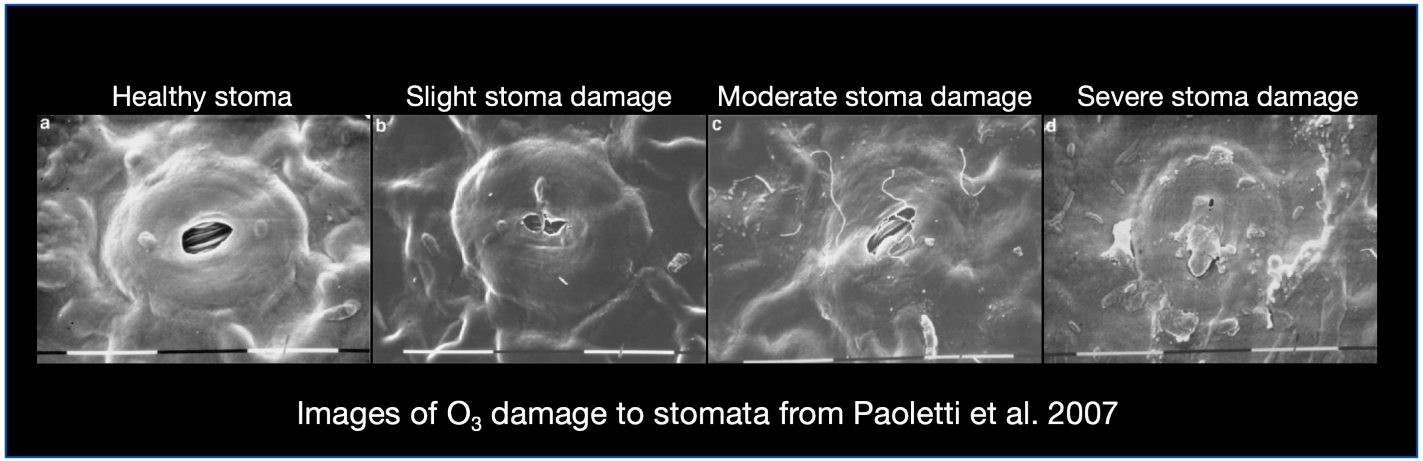
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Medlyn Stomatal Conductance

Undamaged

#1 $g_s = g_0 + 1.6\left(1 + \frac{g_1}{\sqrt{VPD}}\right)\frac{\textbf{Photosynthesis}}{[CO_2]}$ #2

Photosynthesis* = Photosynthesis x O_3 damage



Images of O_3 damage to stomata from Paoletti et al. 2007

Medlyn Stomatal Conductance

Undamaged

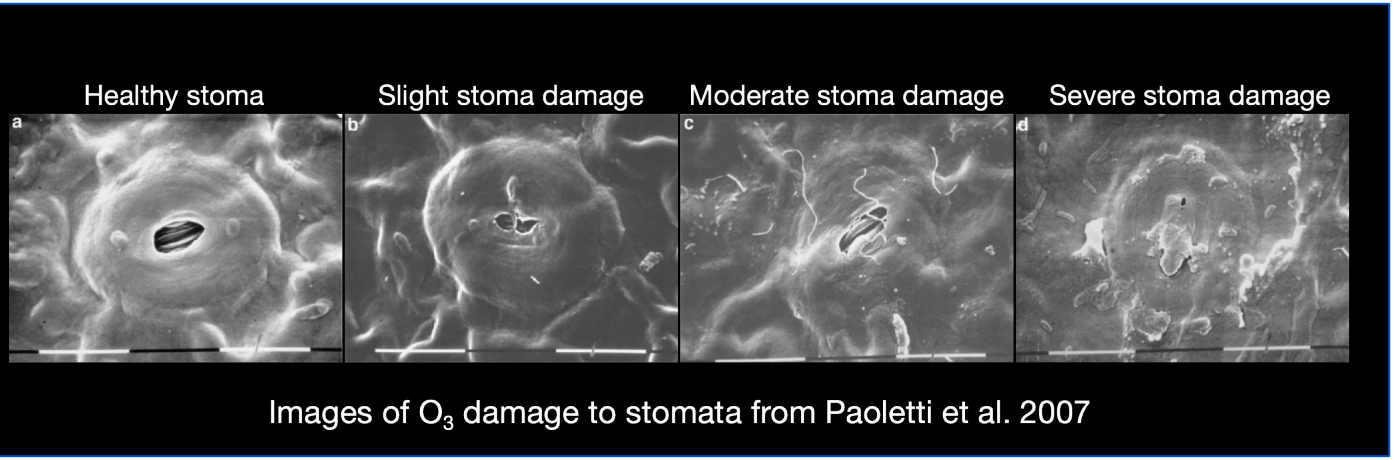
#1 $g_s = g_0 + 1.6\left(1 + \frac{g_1}{\sqrt{VPD}}\right)\frac{\textbf{Photosynthesis}}{[CO_2]}$

#2

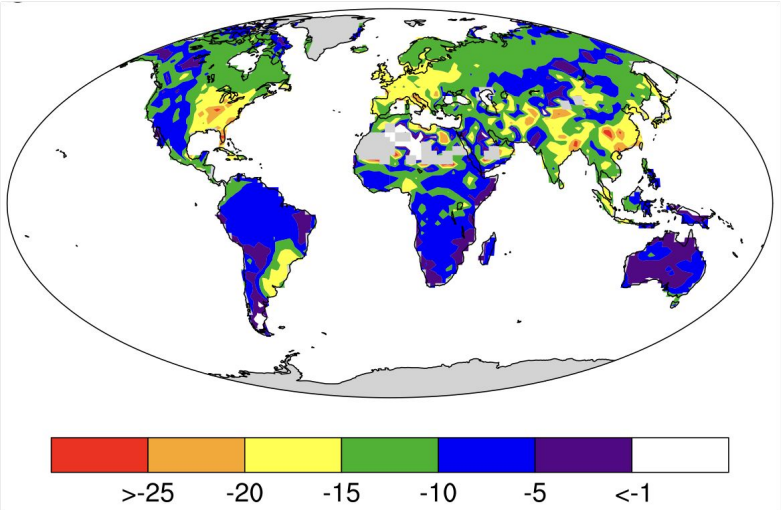
Photosynthesis* = Photosynthesis x O_3 damage

#3

g_s* = g_s x O_3 damage



Images of O_3 damage to stomata from Paoletti et al. 2007

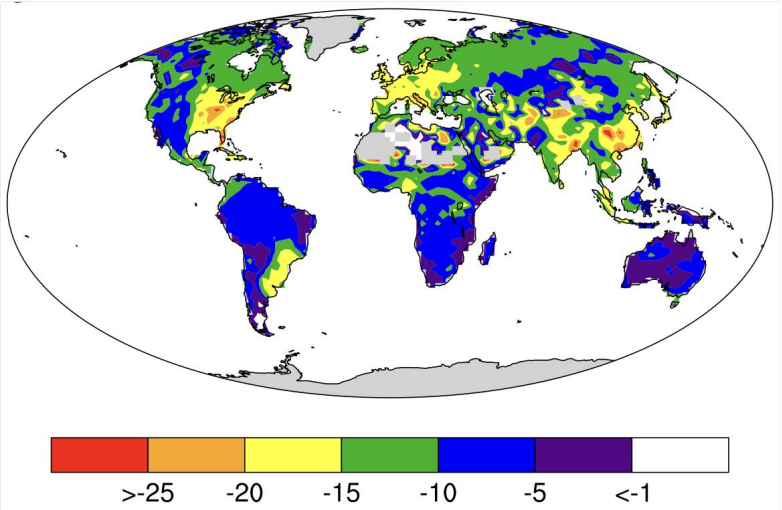


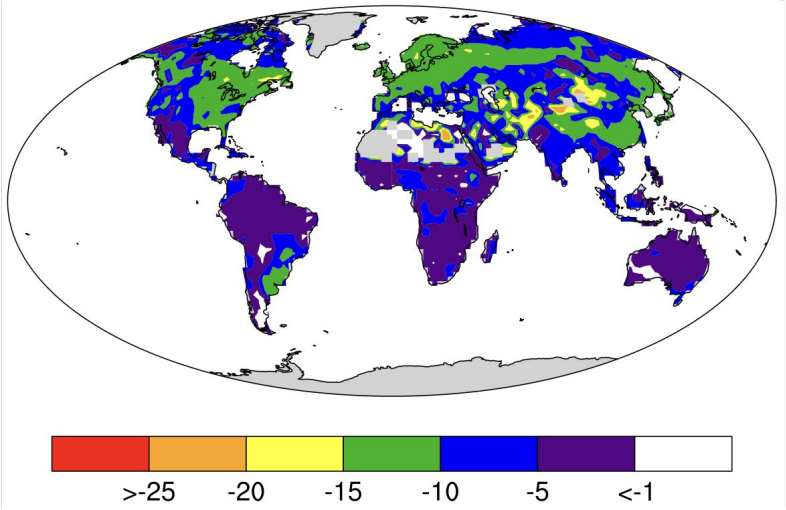
Decrease in **Photosynthesis** due to O_3 (%)

(decrease in C gain)

Significance:

1) *Ozone reduces C stored in our ecosystems*
2) *Regions with the largest reductions are agricultural hotspots*





Decrease in **Photosynthesis** due to O_3 (%)

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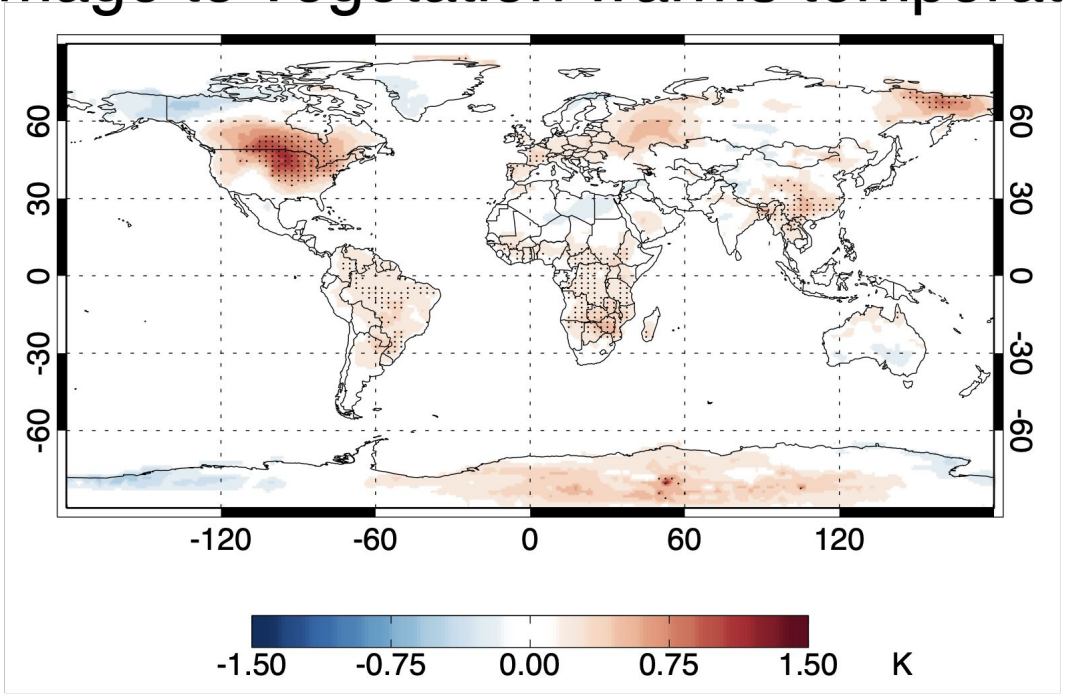
Decrease in **Transpiration** due to O_3 (%)

(decrease in H_2O loss)

Significance:

1) *Reduces evaporative cooling & increases surface runoff*
2) *Decoupling of C & H_2O cycling*

Damage to vegetation warms temperatures

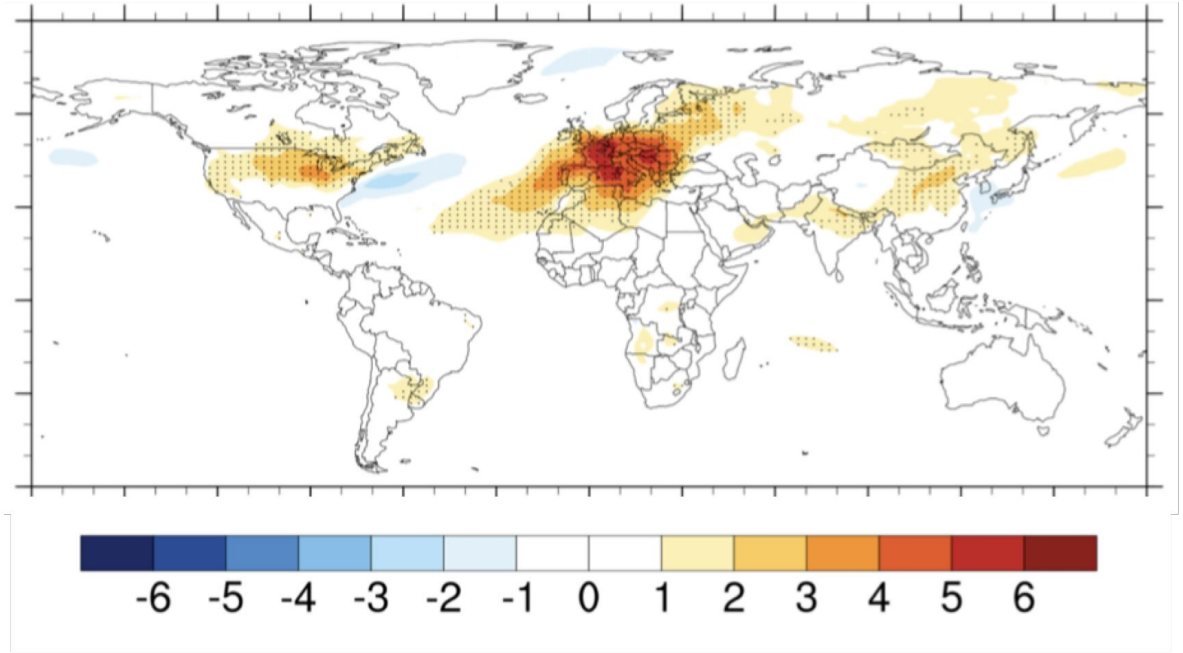


Change in Surface Temperature due to O_3 (K)

conductance —> evaporative cooling —> temperatures

Arnold, Lombardozzi, et al. *GRL* 2018

Damage to vegetation increases [O_3]



Change in summertime O_3 concentration (ppb)

40% - 100% of changes: reduced g_s decreases dry deposition

0-60% of changes: warmer leaf temperatures increase isoprene emissions

Sadiq et al. (2017) *ACP*

https://github.com/ESCOMP/CTSM

Where you can find most of the ozone damage code

CTSM / src / biogeophys / **OzoneMod.F90**

Code | Blame | 784 lines (665 loc) · 32.4 KB

```
83    ! !PRIVATE TYPES:
84    integer, parameter :: stress_method_lombardozzi2015 = 1
85    integer, parameter :: stress_method_falk = 2
86
```

Method I shared today. Includes all data available through 2011

Alternative method that modifies Jmax instead of photosynthesis (unpublished). Data only available for broadleaf trees

Updated dataset with linear & non-linear functions in Li et al. 2024 GMD. Tested in CLM. *Not yet included in CLM code base (?)*

NCAR Community Earth System Model
OPERATED BY UCAR

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CESM Home / CESM Documentation & Tools / CESM2 Component Configuration Settings / CESM2.2.2 CLM Namelist Definitions

CESM2.2.2 CLM Namelist Definitions

Show 10 entries

Search: ozone

Variable	Namelist Group	Category	Entry Type
use_ozone	clm_inparm	physics	logical

Valid Values [.true., .false.]

Possible Default Values

Description and out-of-the-box Default

Toggle to turn on ozone stress

Variable	Namelist Group	Category	Entry Type

Showing 1 to 1 of 1 entries (filtered from 413 total entries)

Previous 1 Next

https://docs.cesm.ucar.edu/models/cesm2/settings/current/clm5_0_nml.html

Make sure ozone concentrations are specified!

If ozone is on but a file is not specified, concentrations default to 100 ppb

Example streams file to specify an ozone file:
/glade/work/oleson/ctsm5.1.dev112/cime/scripts/
ctsm51_ctsm51d112_1deg_GSWP3V1_hourlyO3_SSP245/user_nl_datm_streams
(note that this example is for a single point simulation)

Find O_3 files in `$DIN_LOC_ROOT (/glade/campaign/cesm/cesmdata/cseg/inputdata)`

Biogenic volatile organic compounds (BVOCs)



"Early autumn dusk on **Smoky Mountains"**

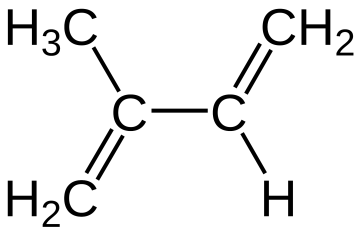
Don Sniegowski (Flickr); CC BY-NC-SA 2.0

Types of BVOCs

~1 PgC/yr

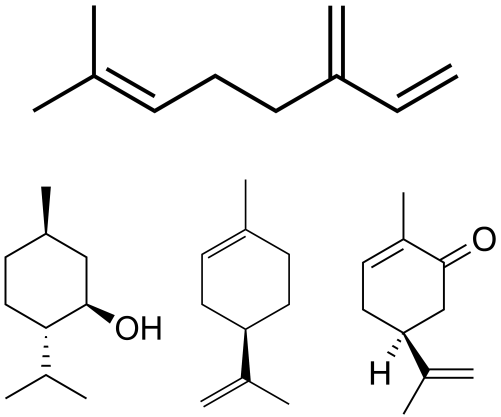
~400-600 TgC/yr

Isoprene (C_5H_8)



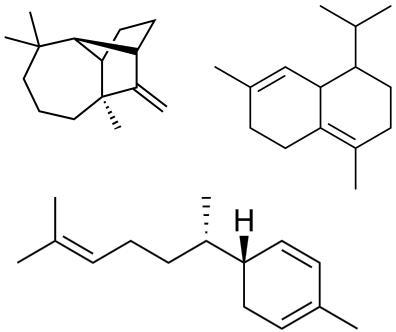
~30-480 TgC/yr

Monoterpenes/ monoterpenoids ($C_{10}H_{16}$...)



~260 TgC/yr

Sesquiterpenes ($C_{15}H_{24}$)



~260 TgC/yr

Others

Numbers from Laothawornkitkul et al. (2009); molecular diagrams from Wikipedia

Why do plants make them?

Herbivory

Some BVOCs are emitted in response to plants being eaten or having insect eggs laid in them.

These emissions can have a **toxic / repellent effect** on herbivores.

Can **"warn"** other plant tissues and even other plants!

Mutualisms

Emissions during herbivory can attract **predators** and parasitoids of herbivores!

Flowers can emit BVOCs to **attract pollinators**... including humans!

Abiotic stresses

Protect against **high-temperature stress** by strengthening membranes and other protein complexes.

Protect against **oxidative stress** by "scavenging" reactive species (OH^-, O_3, NO_x).

Mechanisms are... complex and **not well-understood**.

????

"Burn off" excess energy?

"Accidental" by-products of synthesizing other compounds?

What are their impacts?

Climate

BVOCs, especially in the presence of air pollution (NO_x), contribute to **secondary organic aerosol** formation.

Aerosols reflect and scatter incoming sunlight—**cooling** effect.

Also serve as **cloud condensation nuclei**, affecting albedo (reflectivity) and precipitation.

BVOCs can increase the lifetime of **methane** (a potent greenhouse gas).

Air quality

BVOCs can also enhance **tropospheric ozone** formation.

BVOCs, SOAs, and ozone are important components of **photochemical smog**.

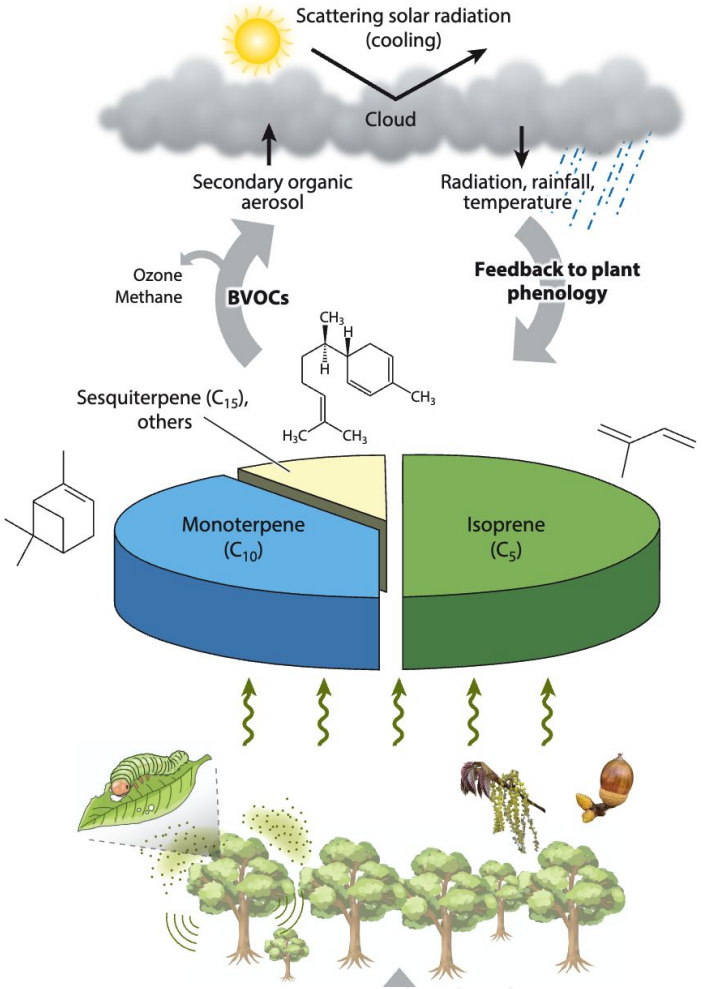


Figure from Satake et al. (2024)

How do we model BVOC emissions?

The Model of Emissions of Gases and Aerosols from Nature (MEGAN)

- 150 different BVOCs
- Grouped into 15 (?) categories that go to CAM in atmosphere-coupled runs
- CAM makes secondary organic aerosols

$$F_i = \gamma_i \sum_j \epsilon_{i,j} \chi_j$$

Flux of compound ***i***

Activity factor of compound ***i*** given *actual* conditions (0 – ∞)

Emissions factor of compound ***i*** from PFT ***j*** at "standard conditions"

Fractional area of PFT ***j***

See also: CLM Tech Note section on BVOCs

How do we model BVOC emissions?

Activity factor of compound ***i*** given actual conditions (0 – ∞)

$$\gamma_i = 0.3 \times LAI \times \gamma_{P,i} \times \gamma_{T,i} \times \gamma_{A,i} \times \gamma_{SM,i} \times \gamma_{C,i}$$

Leaf area index

Effect of **light**

Effect of **temperature**

Effect of **leaf age**

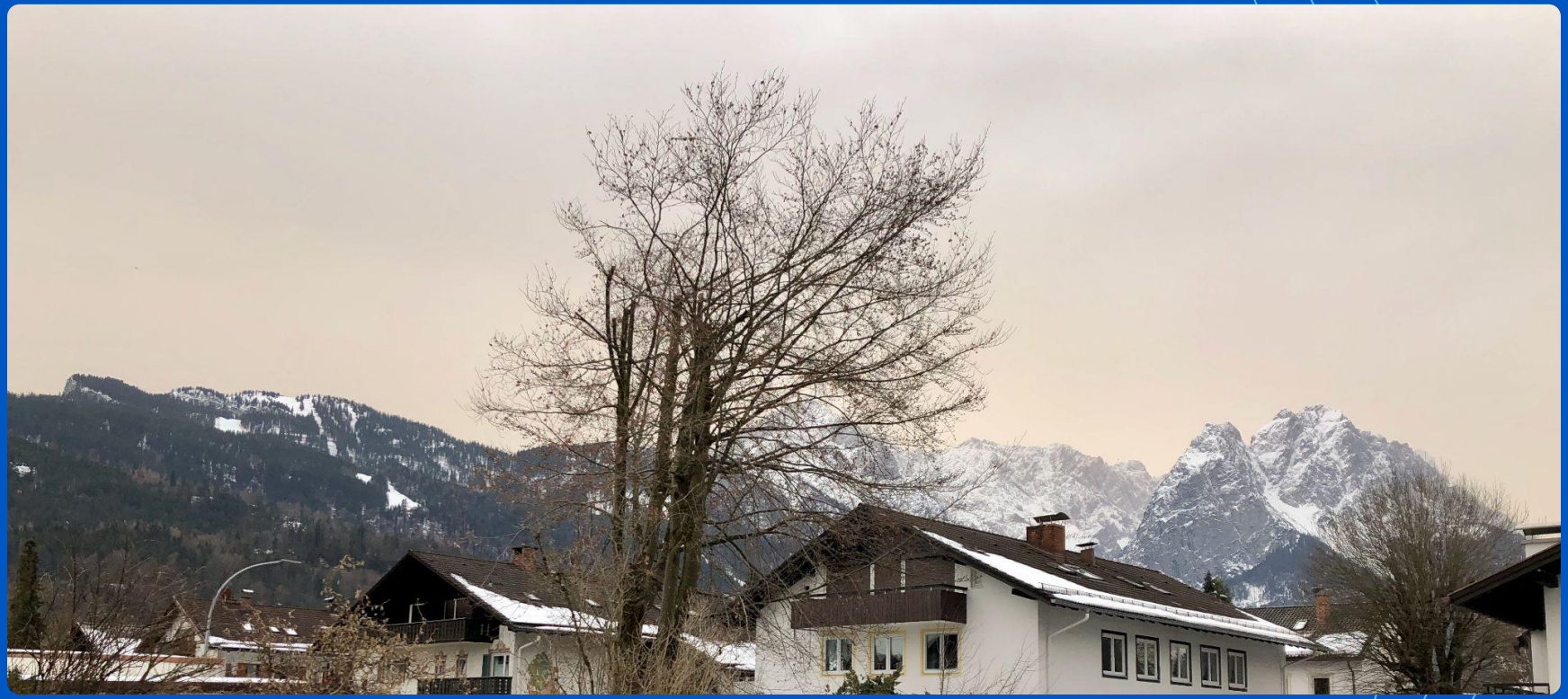
Effect of **soil moisture / drought**

Effect of **CO2**

Isoprene only

See also: CLM Tech Note section on BVOCs

Dust



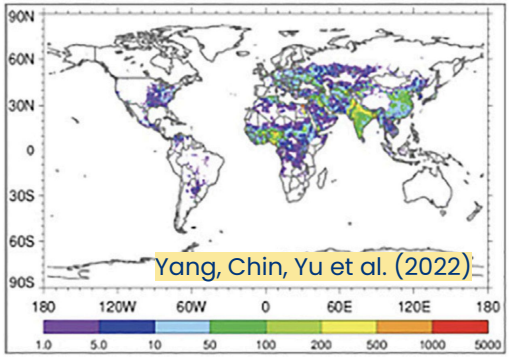
Saharan dust over Garmisch-Partenkirchen, Germany

Slide lightly adapted from **Danny Leung**

Why dust is important in Earth system modeling

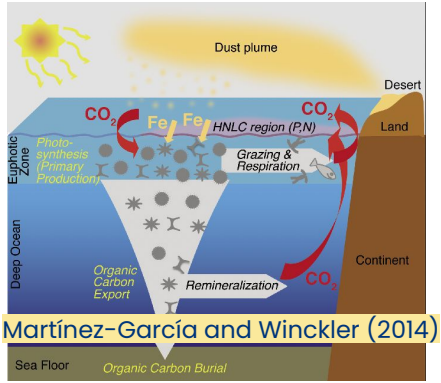
Human health

2019 dust-attributable mortality (total: ~ 721 000)



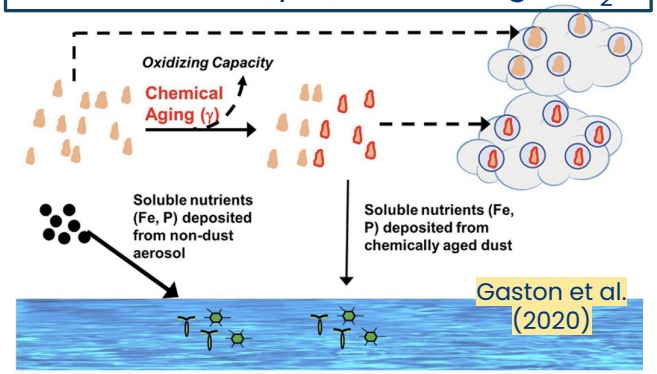
Yang, Chin, Yu et al. (2022)

Ocean BGC: dust iron boosts marine photosynthesis



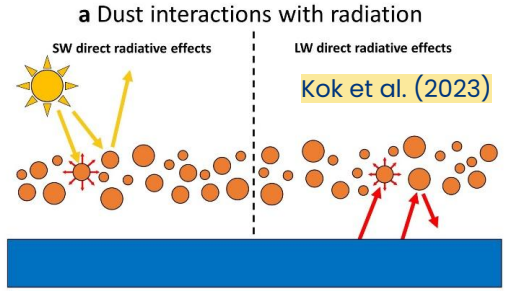
Martínez-García and Winckler (2014)

Atmospheric chemistry: Reacts with acidic air pollutants (e.g., SO_2)

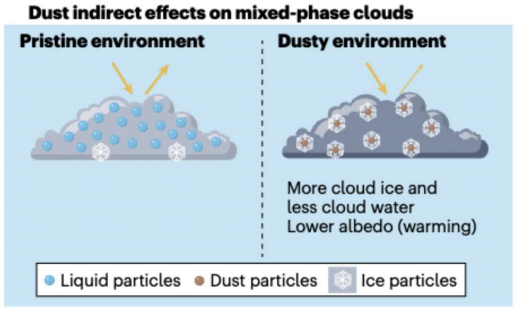


Gaston et al. (2020)

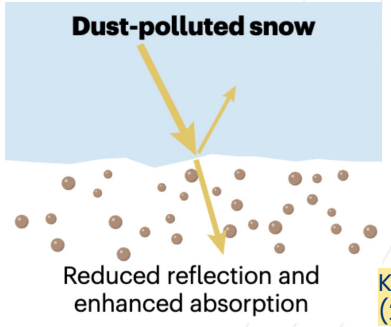
Radiative effects: reflects sunlight and cool the atmosphere



Kok et al. (2023)



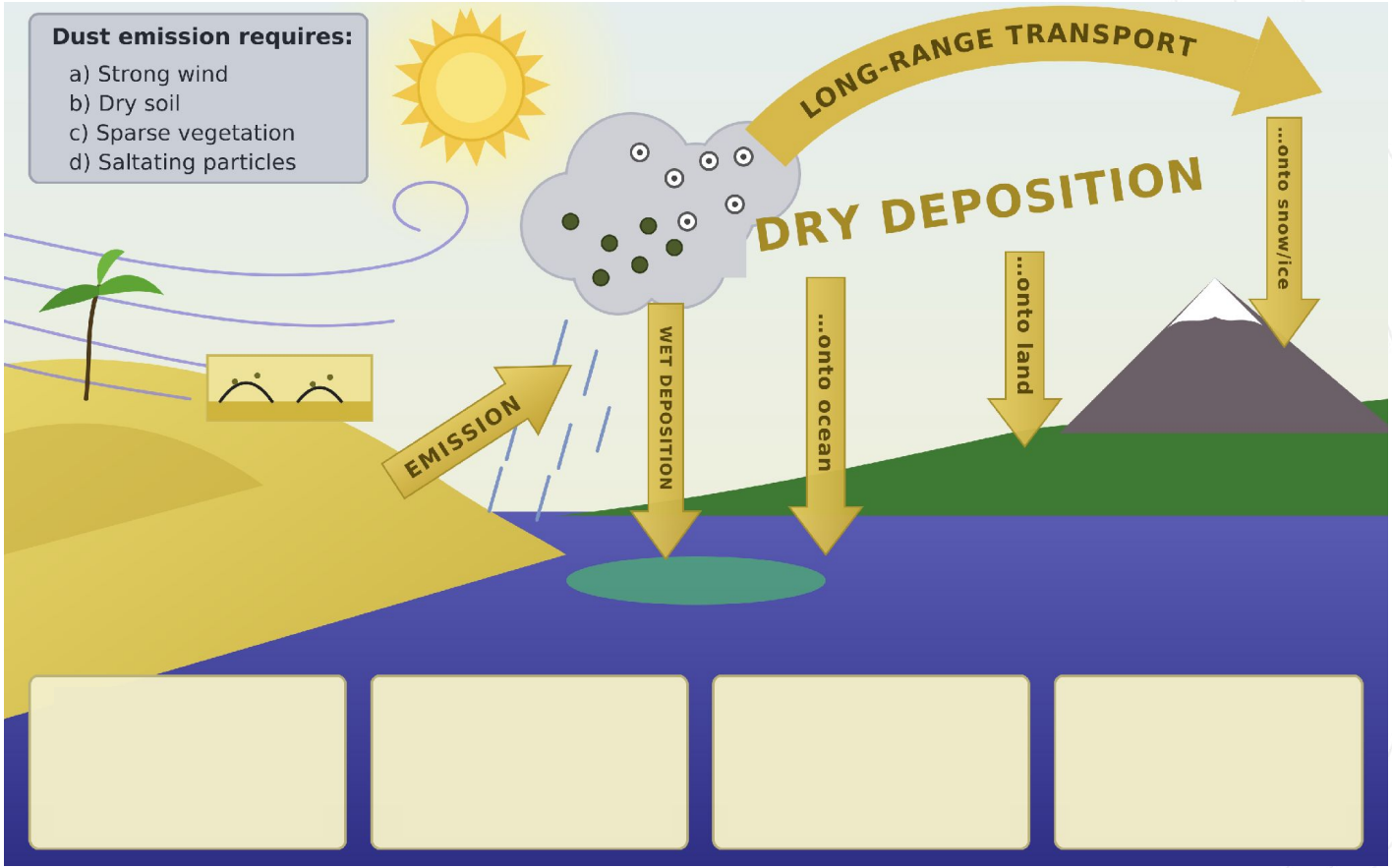
Cryosphere: reduce snow albedo



Kok et al. (2023)

Slide lightly adapted from **Danny Leung**

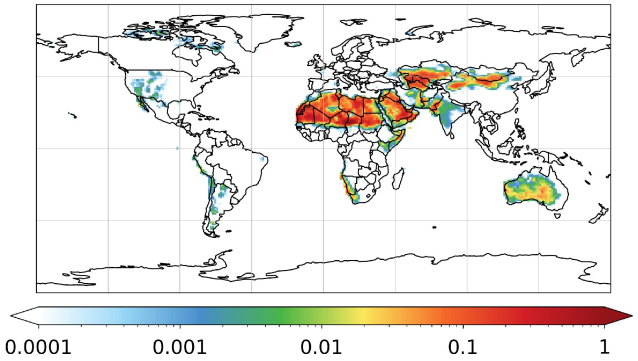
Global mineral dust cycle that CESM simulates



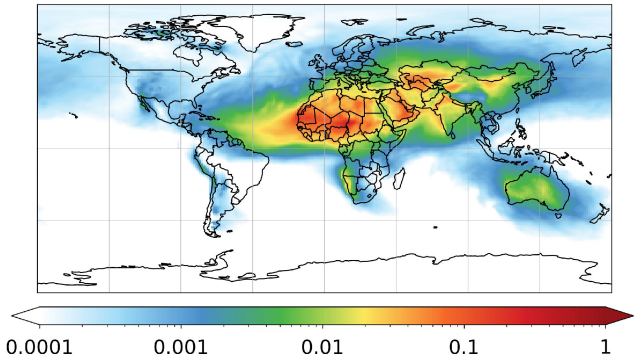
Slide lightly adapted from **Danny Leung**

CESM3 dust cycle in fully coupled CESM
(CLM in BGC–CROP mode)

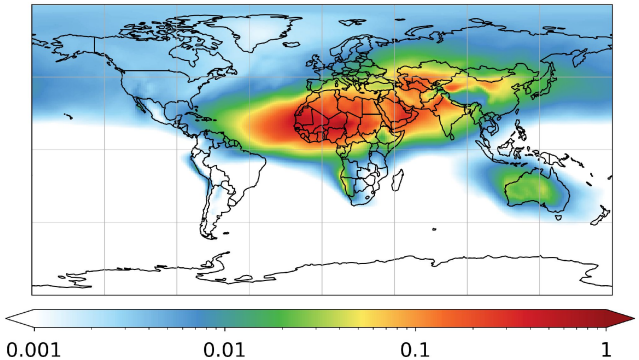
Dust flux to atmosphere (kg/m^2/yr)



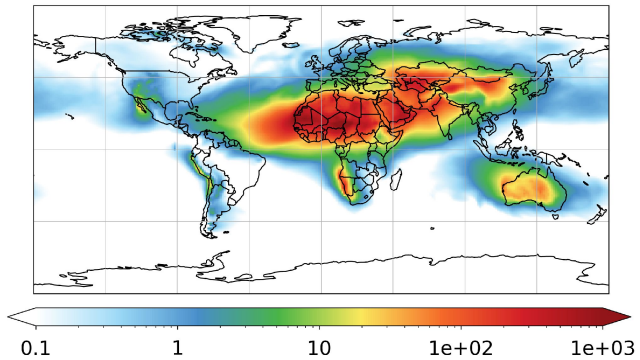
Dust flux to land (kg/m^2/yr)



Dust aerosol optical depth (unitless)



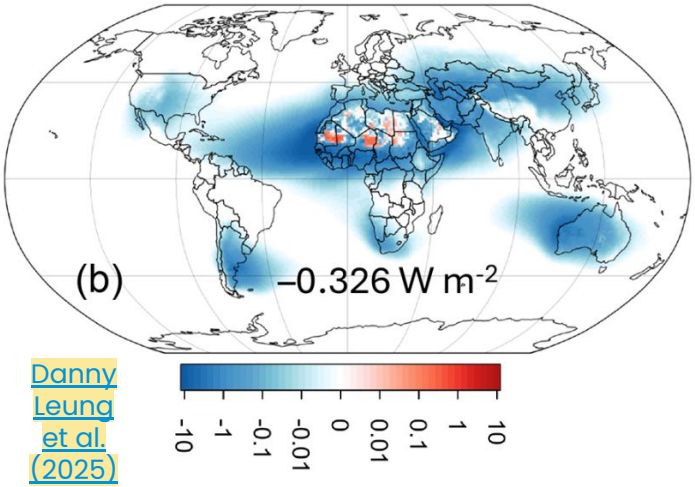
Dust aerosol surface conc. (μg m^{-3})



Slide lightly adapted from **Danny Leung**

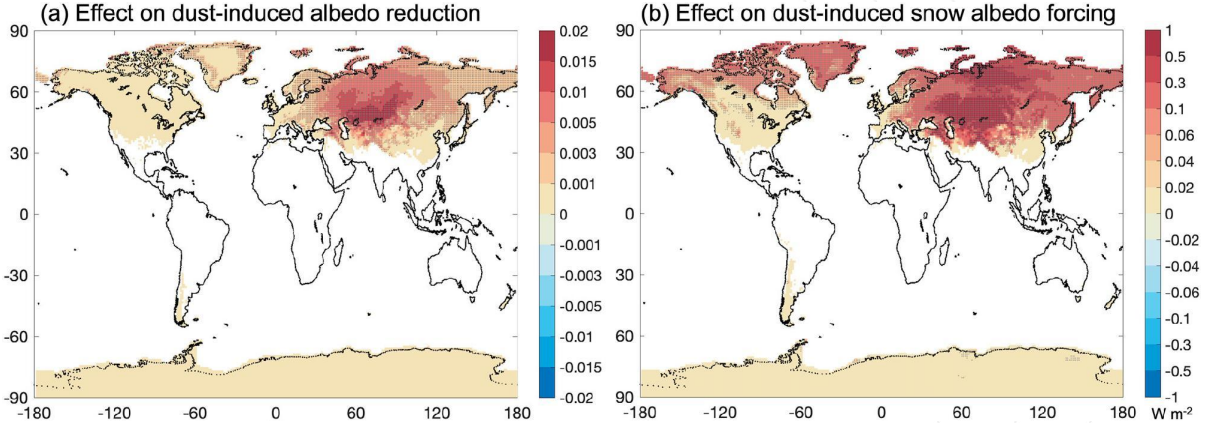
Dust impacts on global radiative effects

Dust-induced global cooling due to scattering sunlight simulated in CAM



Danny Leung et al. (2025)

Dust-induced warming due to mixing with albedo simulated by CLM



Cenlin He et al. (2024)

Dust scatters sunlight back to space, **cooling the atmosphere by 0.326 W m^{-2}**.

Dust depositing in and mixing with snow darkens the land surface and reduces snow albedo. This **warms the Earth by 0.1 W m^{-2}**.

See also: CLM Tech Note section on dust

Fire



An **experimental burn** in Kruger National Park, South Africa

Fire's many roles in the Earth system

Ecosystem structure and function

Some ecosystems **rely on fire** for their persistence, while others **are very fire-sensitive**.

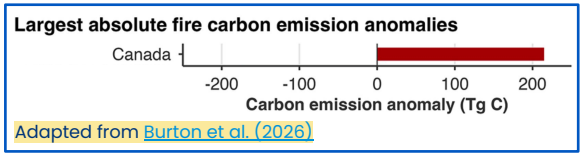




Carbon cycling

CO_2 emissions from extreme fire seasons can be a big part of national GHG totals.

Some CO_2 will be re-absorbed during recovery… **When? How much?**



Adapted from Burton et al. (2026)

Aerosols

Fires emit aerosols that, as previously discussed, **can cool the Earth**.

Fires also emit **black carbon** which can have a **warming effect** in the atmosphere.

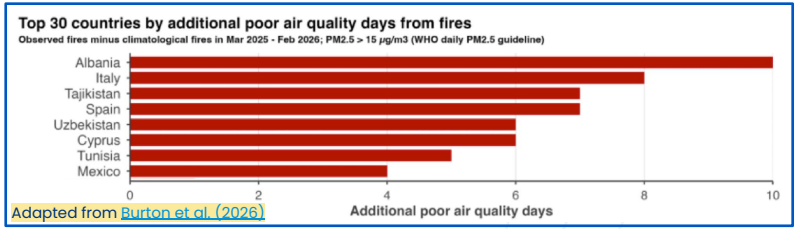
Black carbon can also **darken ice**, increasing melt rates.

Direct impacts to people

Wildfires can **destroy property**, including valuable land (ecosystems), structures, etc.

Suppression is **expensive** and limited in effectiveness.

Smoke causes asthma and other **respiratory illnesses**.

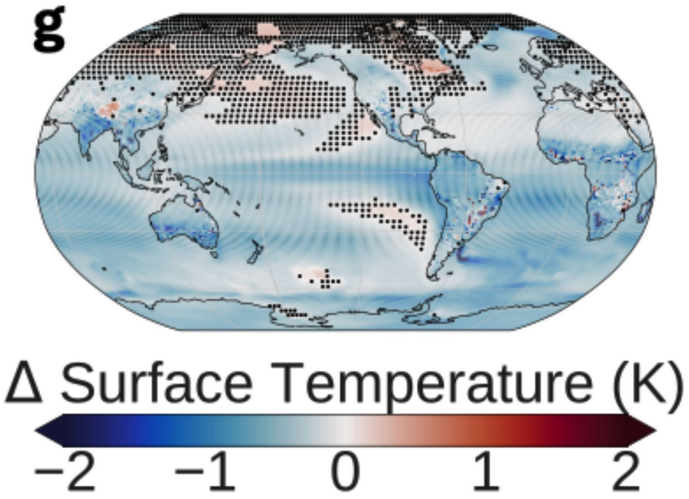


Adapted from Burton et al. (2026)

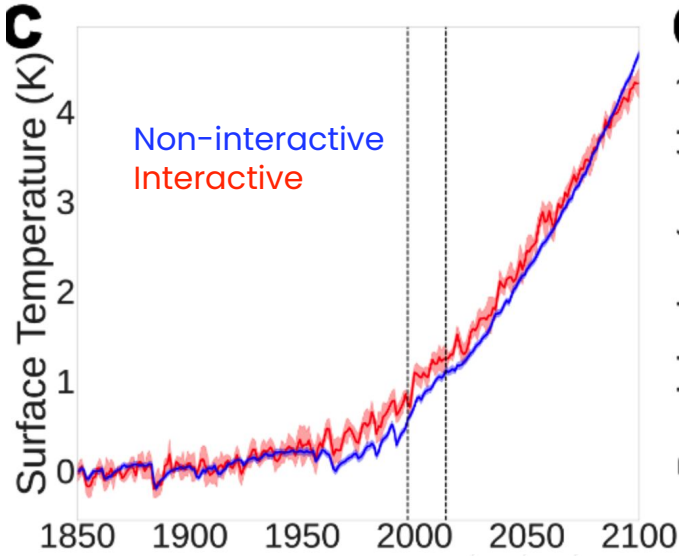
Fire in CESM

We've recently begun running CESM with CLM's fire feeding the atmosphere.

Difference in 1860-1900 mean surface temp:
Interactive fire makes things cooler



Mean surface temp anomaly over time:
Interactive fire effect varies



Leister et al. (submitted)

The [global] fire [modeling] triangle



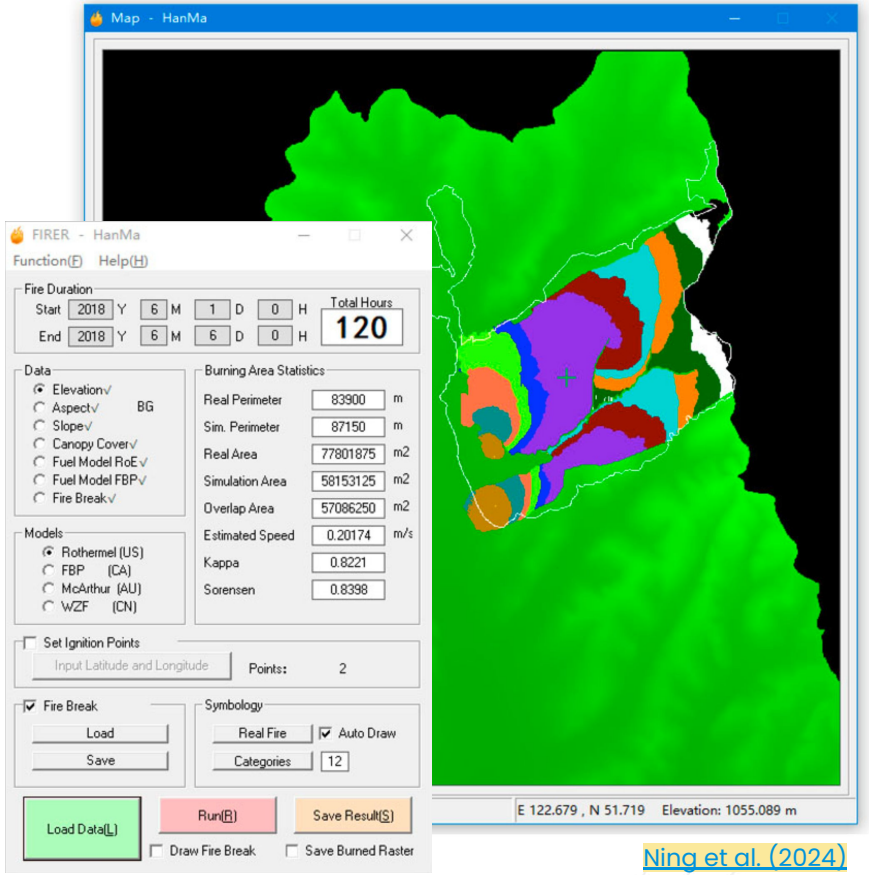
Physical fire spread models

Advantages

- Explicit modeling of radiative and convective heat transfer
- Account for fine-scale variation in fuel and microclimate
- Simulate impact of spread barriers, spot fires, etc.

Disadvantages

- Assume *an* ignition
- Processes happen at high spatial and temporal scales CLM doesn't represent
- Computationally expensive
- Often require data that aren't available worldwide



Ning et al. (2024)

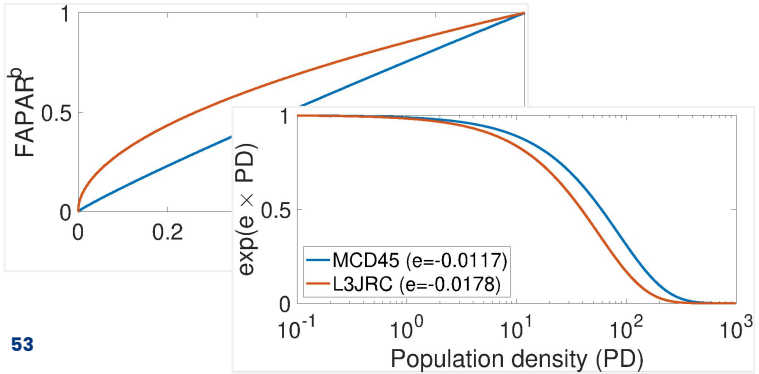
Empirical fire models

Advantages

- Simple, transparent
- Fast
- Easily parameterized

Disadvantages

- Easy to leave out important relationships
- Underlying relationships could change in future



SIMFIRE (Knorr et al., 2016)

Fractional burned area per year (fire frequency) is computed as:

$$A(y) = a(B) F^{b} N_{\max}(y)^{c} \exp(-ep) \quad (1)$$

where y is the fire year[14], B is the biome type (based on vegetation type and height), F is the interannual average of annual maximum of monthly FAPAR (fraction of absorbed photosynthetically active radiation, a measure of vegetation continuity and leaf area), $N_{\max}$ is the annual maximum Nesterov index, and p is the population density (people km^{-2}). b, c and e are global parameters, and $a(B)$ denotes one parameter a for each of eight biome types. The particular form of equation (1) and the parameter values $a(B)$, b, c and e are taken from SIMFIRE optimized against global GFED3 burned area[36] for the complete range of population densities[14] (Supplementary Table 2). Annual fire frequency is redistributed to monthly values using the mean 2001–2010 GFED3 annual cycle of burned area within a varying

Process-based fire models

Advantages

- Capture *mechanisms* behind fire occurrence, spread, and suppression

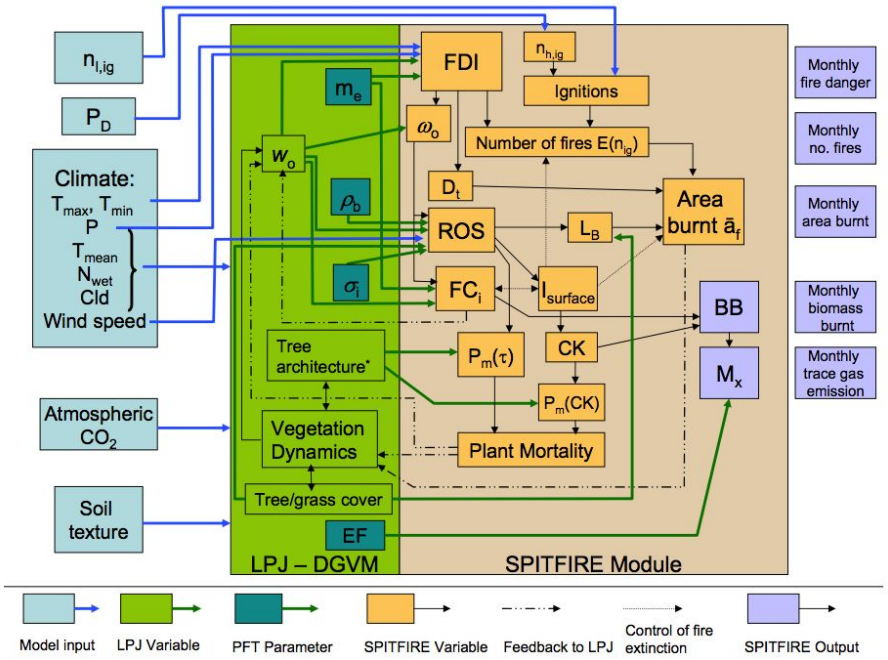
Disadvantages

- Lots of "moving parts"
- Hard to understand
- Hard to parameterize
- End up using empirical functions anyway!

CLM uses process- based (quasi-mechanistic) fire models

FATES actually uses SPITFIRE →

SPITFIRE (Thonicke et al., 2010)



Burned area in CLM: Two basic components*

*For non-peat fires outside cropland and tropical closed forests

Burned area in ***a*** gridcell = Number of fires x Area per fire

Well, okay, we also model **crop** burning. That's separate.

And **deforestation** fires.

And **peat** fires.

Fire in CLM big-leaf: The Li fire scheme:
Number of fires

Ignitions



$$N_i \times f_b \times f_{RH} \times f_{sm} \times f_d \times f_e \times f_{topo} = N_f$$



Fires



Num. ignitions | Natural ignitions | Anthro. ignitions | Gridcell area

$$N_i = (I_n + I_a) \times A_g$$

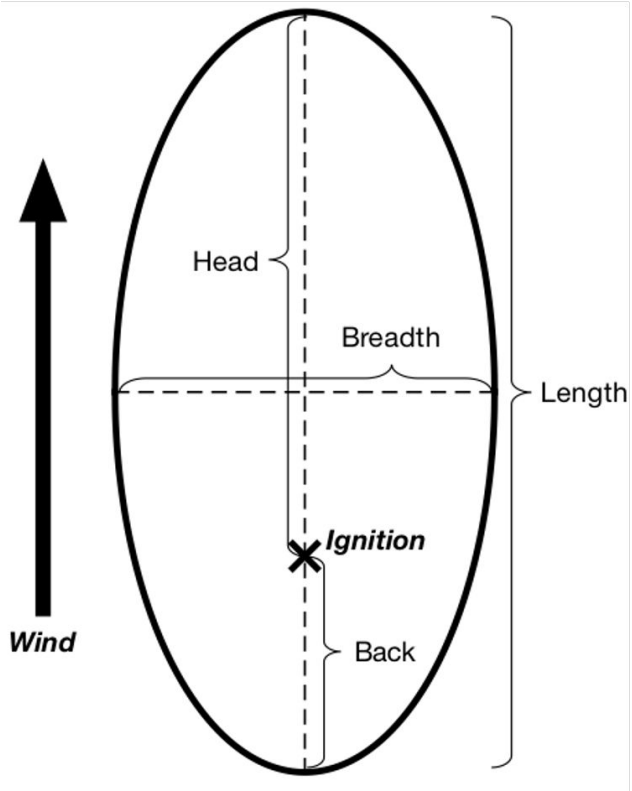
$$I_a = 0.01 D_p \times 6.8 D_p^{-0.6}$$

Population density

Functions [0–1] of:

- Topography (elevation > 2500 m?)
- Economy (GDP)
- Demography (pop. density again)
- Soil moisture
- Relative humidity
- Biomass (aboveground; live + dead)

Fire in CLM big-leaf: The Li fire scheme:
Burned area per fire



Assume every fire is an ellipse

- Ignition at one of the foci
- Area is a (complicated) function of:
  - Wind speed
  - Max. spread rate (per PFT)
  - Fuel moisture (RH, soil moisture)
  - Fire duration
- Fire duration is a function of:
  - Max. fire duration (5 days)
  - Population density
  - GDP
  - "Fuel continuity" (fractional area of the "natural vegetated" column)

Fire in CLM big-leaf: The Li fire scheme: Impacts on vegetation

PFT- and pool-specific factors

- Combustion completeness (CC)
- Mortality (M) of non-combusted veg
- The same for *every* fire in a given PFT

Emissions work similarly

- 51 emitted compounds
- Each PFT-specific
- Not tissue-specific

PFT	CC_{leaf}	CC_{stem}	CC_{root}	CC_{ts}	M_{leaf}	$M_{livestem,1}$	$M_{deadstem}$	M_{ro}
NET Temperate	0.80	0.30	0.00	0.50	0.80	0.15	0.15	0.1
NET Boreal	0.80	0.30	0.00	0.50	0.80	0.15	0.15	0.1
NDT Boreal	0.80	0.30	0.00	0.50	0.80	0.15	0.15	0.1
BET Tropical	0.80	0.27	0.00	0.45	0.80	0.13	0.13	0.1
BET Temperate	0.80	0.27	0.00	0.45	0.80	0.13	0.13	0.1
BDT Tropical	0.80	0.27	0.00	0.45	0.80	0.10	0.10	0.1
BDT Temperate	0.80	0.27	0.00	0.45	0.80	0.13	0.13	0.1
BDT Boreal	0.80	0.27	0.00	0.45	0.80	0.13	0.13	0.1
BES Temperate	0.80	0.35	0.00	0.55	0.80	0.17	0.17	0.1
BDS Temperate	0.80	0.35	0.00	0.55	0.80	0.17	0.17	0.1
BDS Boreal	0.80	0.35	0.00	0.55	0.80	0.17	0.17	0.1
C_3 Grass Arctic	0.80	0.80	0.00	0.80	0.80	0.20	0.20	0.2
C_3 Grass	0.80	0.80	0.00	0.80	0.80	0.20	0.20	0.2
C_4 Grass	0.80	0.80	0.00	0.80	0.80	0.20	0.20	0.2

Questions?

