Managing Biogenic VOC to reduce summertime ozone in China

YRD Clean Air Forum
Shanghai, China, August 28, 2025

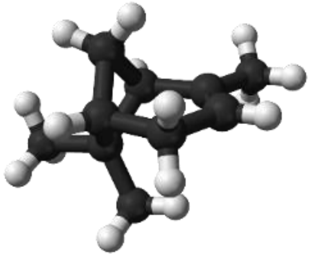
Alex Guenther
Distinguished Professor
Earth System Science Department
University of California, Irvine
alex.guenther@uci.edu

BVOC sampling site: YRD 2009

Photo: A. Guenther

What are Biogenic Volatile Organic Compounds (BVOCs)?

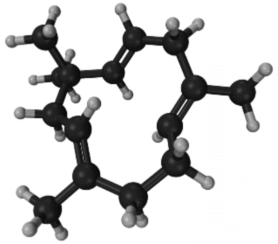
Biogenic: produced by living organisms (but can be modified by human activities)
Volatile: gas phase (but not all are completely in the gas phase)
Organic Compounds: contains C–H covalent bonds (but can include others: O, S, N, Cl …)



α-pinene

Pine

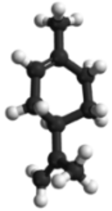
Anthropogenic

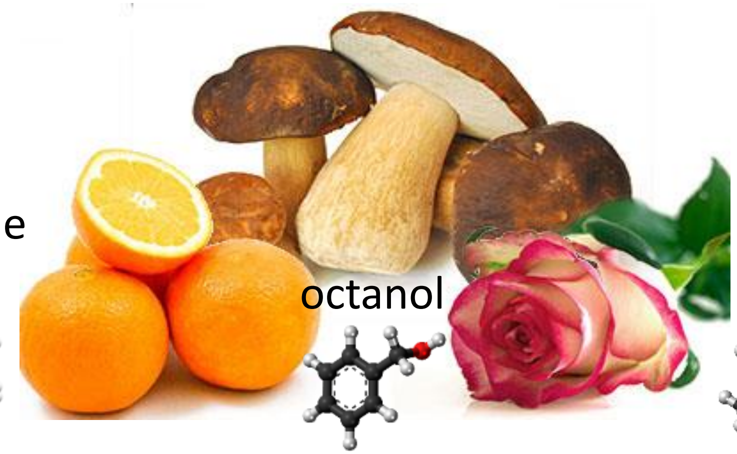


Humulene

Hops

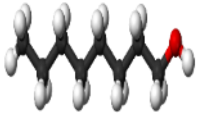
limonene



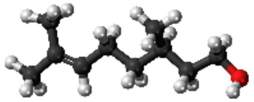


octanol

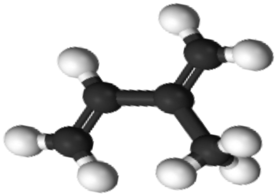
linalool



Citronellol



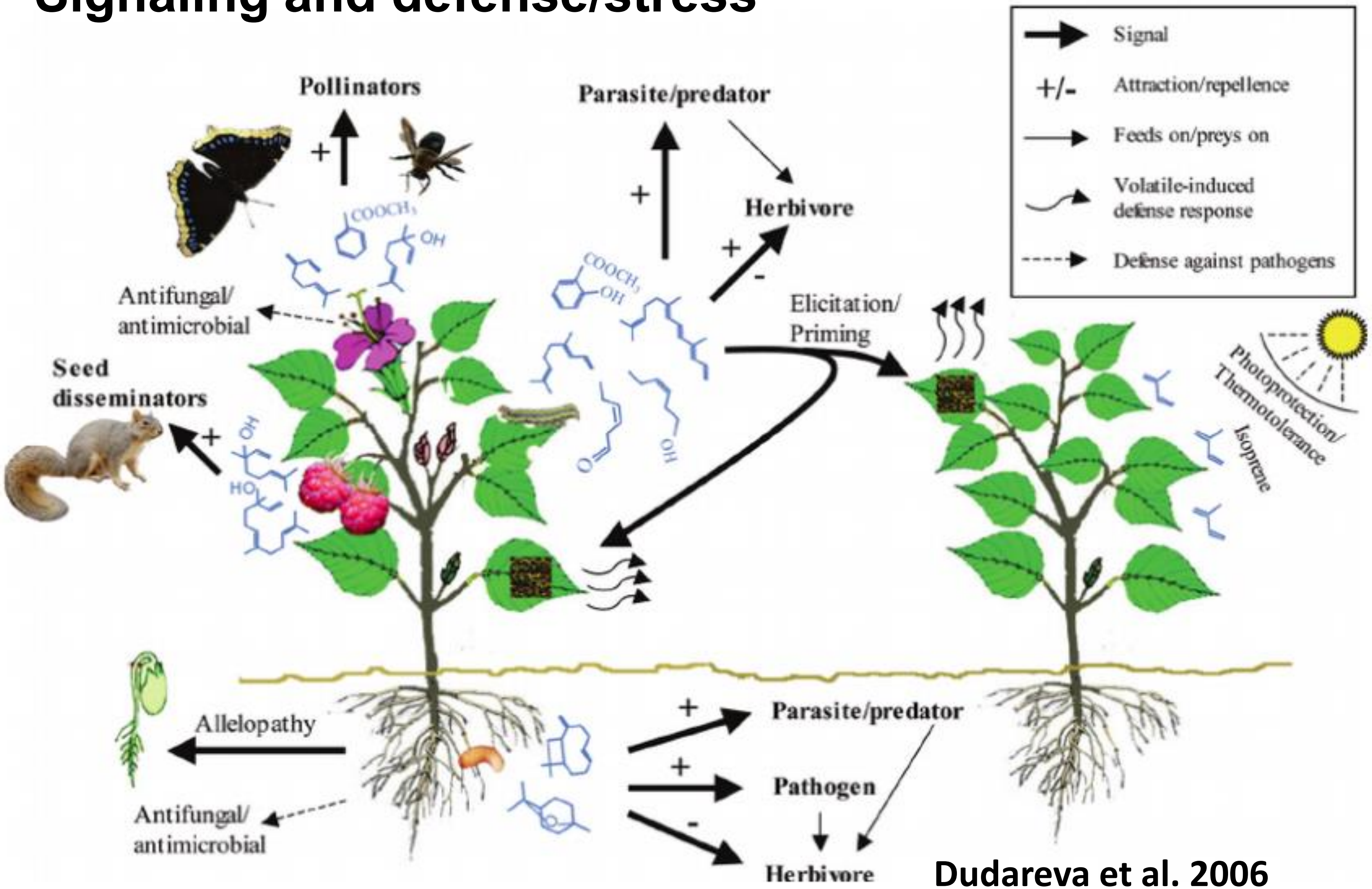
Oak



Isoprene: half of global total BVOC

Why do organisms emit these Biogenic Volatile Organic Compounds (BVOCs)?

Signaling and defense/stress

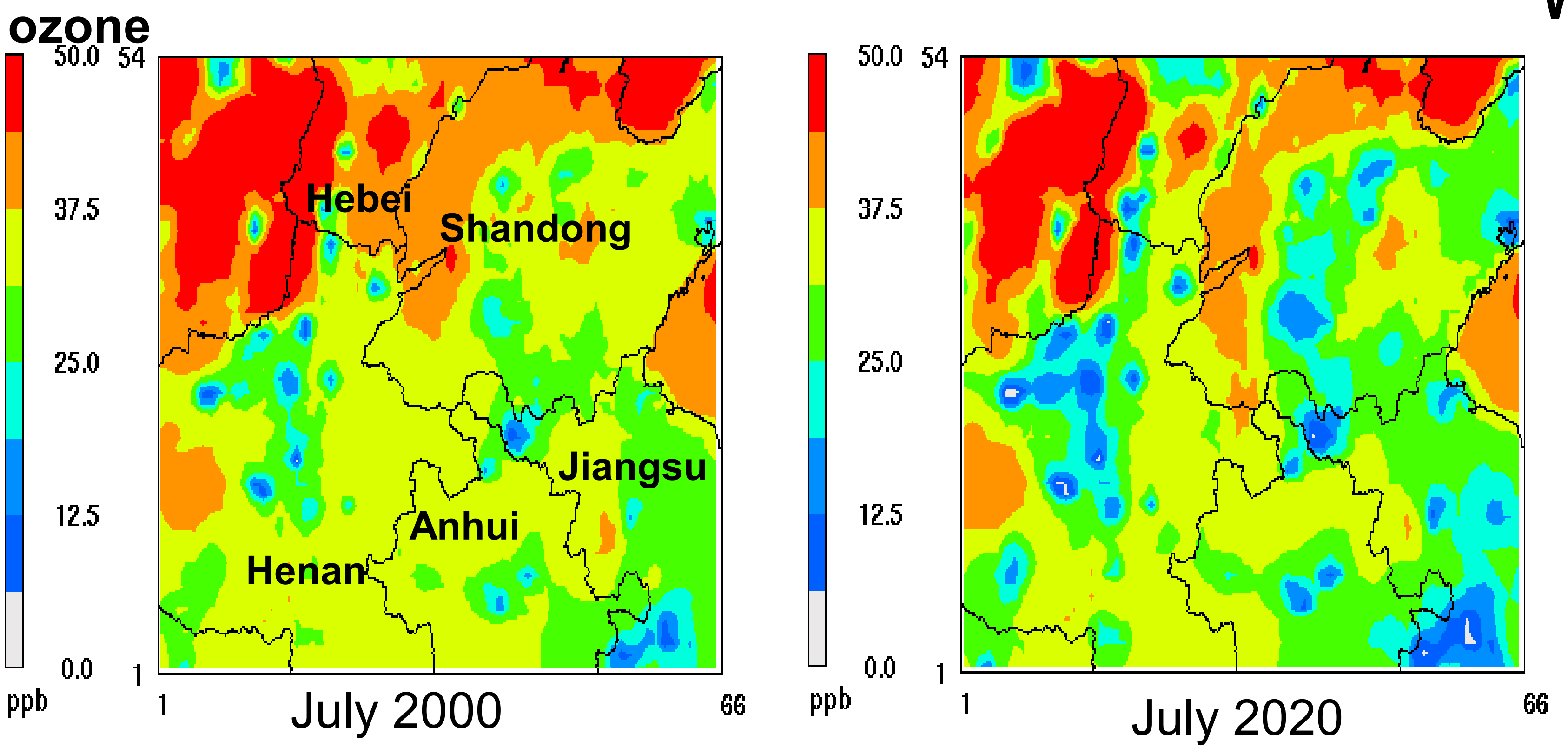


Dudareva et al. 2006

1. Beneficial roles
2. Stress can increase BVOC (but there is a limit)

"Future" predictions of 2020 ozone concentrations in Central Eastern China

Wang et al. 2005



Anthropogenic and biogenic VOC emissions were both ~4500 kTons

Anthropogenic VOC was assumed to increase by 50% and NOx by 150%

A slight decrease in ozone is predicted (associated with increases in NOx).

This assumes that biogenic VOC does not change but we noted that is likely that there will be substantial increases in biogenic VOC due to climate and landcover change.

BVOC emission increase in China during this time period: 1981 to 2018

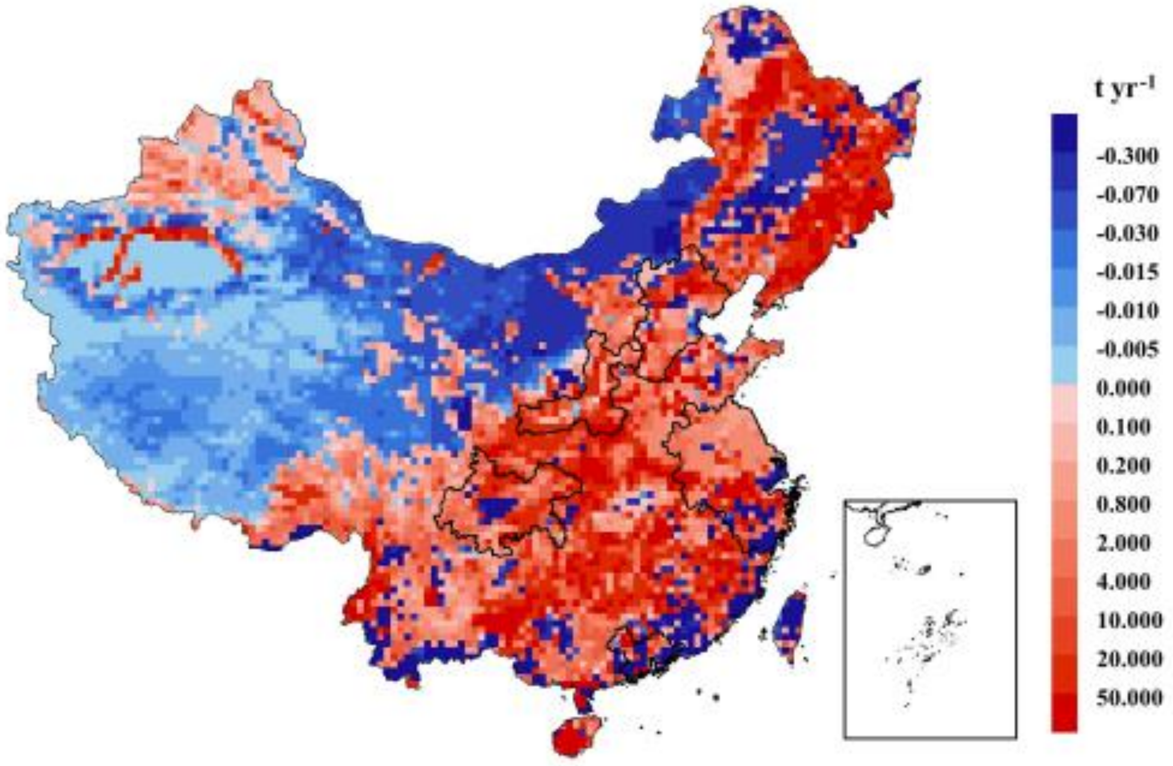


Figure 2. Spatial distribution of interannual variations in BVOC emissions caused by leaf biomass changes.

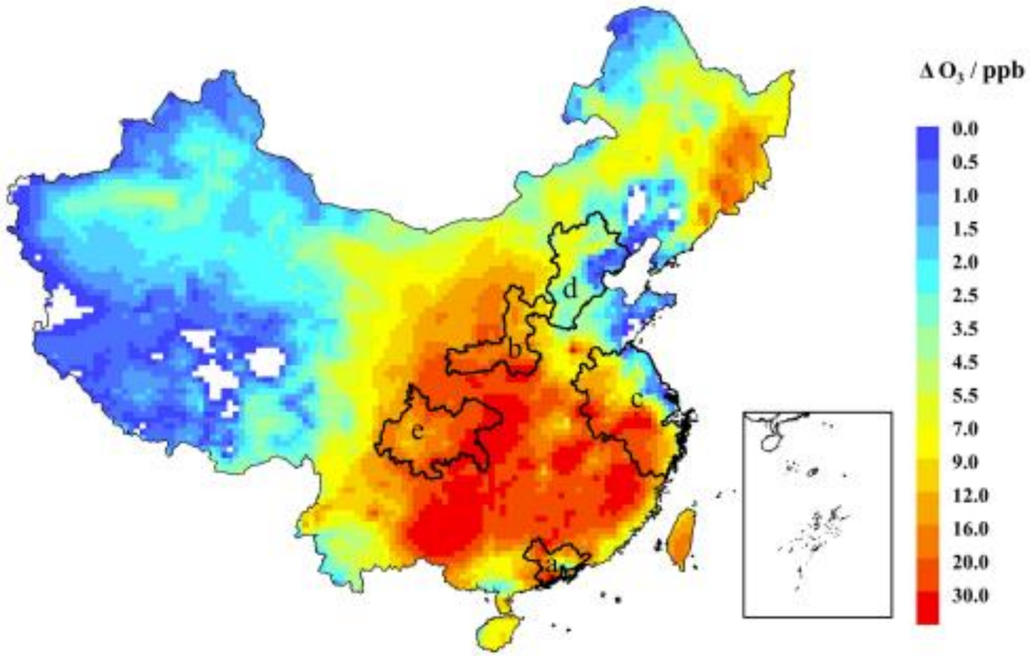
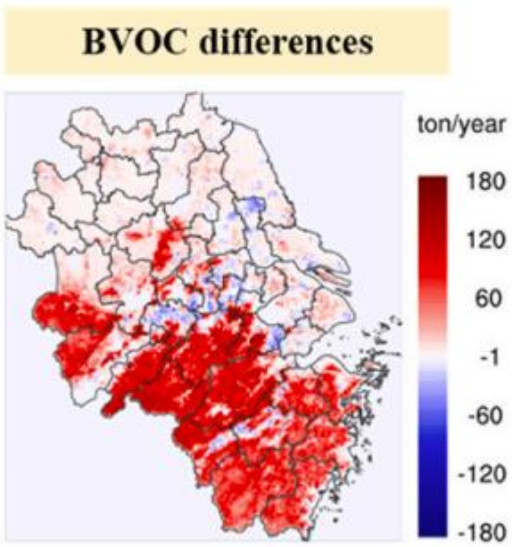


Figure 3. Spatial variations in impact of BVOC emission on MDA8 O_3 concentration. The key regions include the **(a)** Pearl River Delta (PRD), **(b)** Fenwei Plain (FWP), **(c)** Yangtze River Delta (YRD), **(d)** Beijing–Tianjin–Hebei (BTH), and **(e)** Chengdu–Chongqing (CC).

BVOC impact on MDA8 ozone is up to 20 to 30 ppb- including in eastern YRD

Cao et al. 2022

Sensitivity of YRD ozone mitigation strategies to BVOC emission estimates



Absolute ($\mu g/m^3$) and relative contribution (%) of MDA8 from different BVOC emissions for selected cities in the YRD region during June 2021.

City	ΔMDA8 ($\mu g/m^3$) due to BVOC emissions		Relative contribution (%)	
	MODIS	ESA	MODIS	ESA
Hefei	13.8	18.8	8.8%	11.5%
Nanjing	10.7	15.0	6.9%	9.5%
Hangzhou	11.1	14.0	8.0%	9.8%
Shanghai	3.1	4.7	2.7%	4.1%

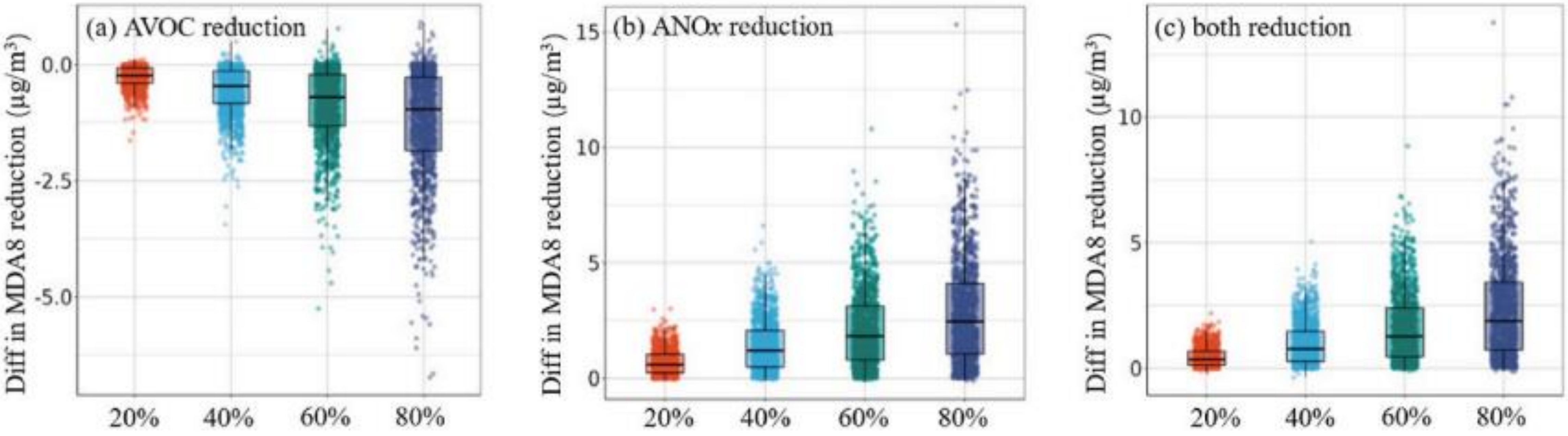
Huang et al. 2024

MDA8 ozone concentrations

Uncertainties in BVOC emission estimates impact ozone predictions

Sensitivity of YRD ozone mitigation strategies to BVOC emission estimates

Huang et al. 2024



Differences in the city-level daily MDA8 (ESA – MODIS, unit: μg/m3) in response to different emission reduction scenarios in the YRD. The x-axis represents different reduction ratios.

BVOC can influence ozone control strategies (NOx vs AVOC control)

Effect of forest isoprene emissions on ozone formation in Shanghai

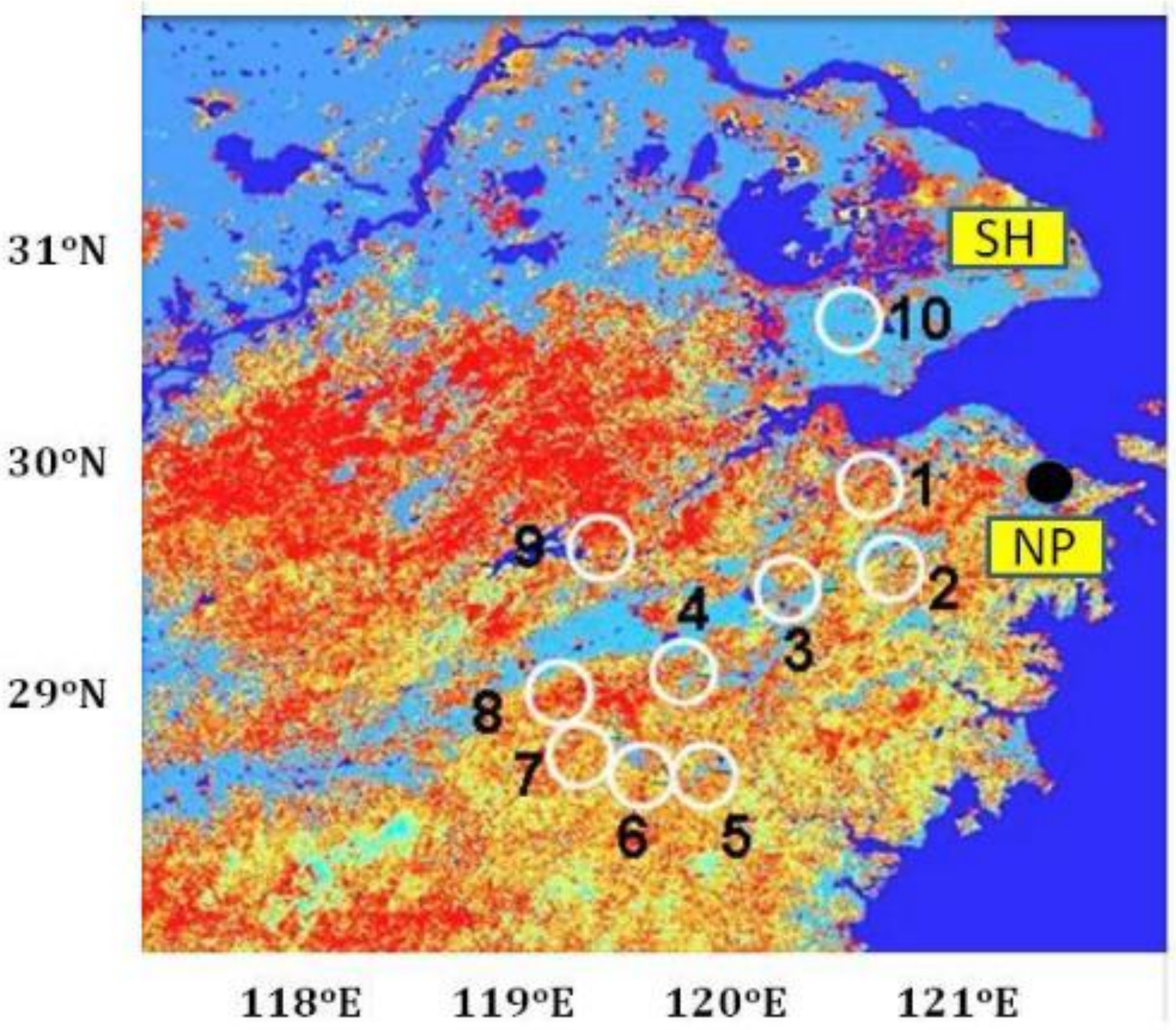


Fig. 1. MEGAN isoprene emission rates and measurement locations in the forests south of Shanghai.

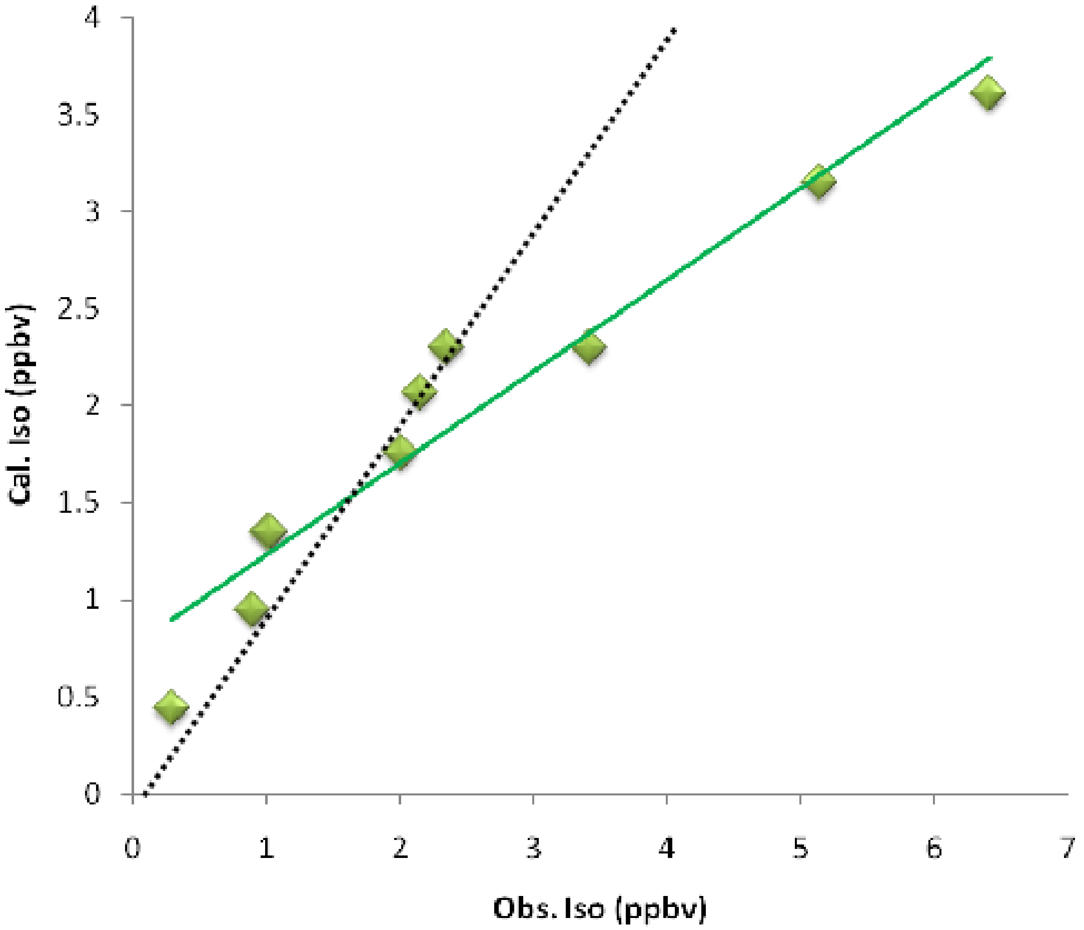
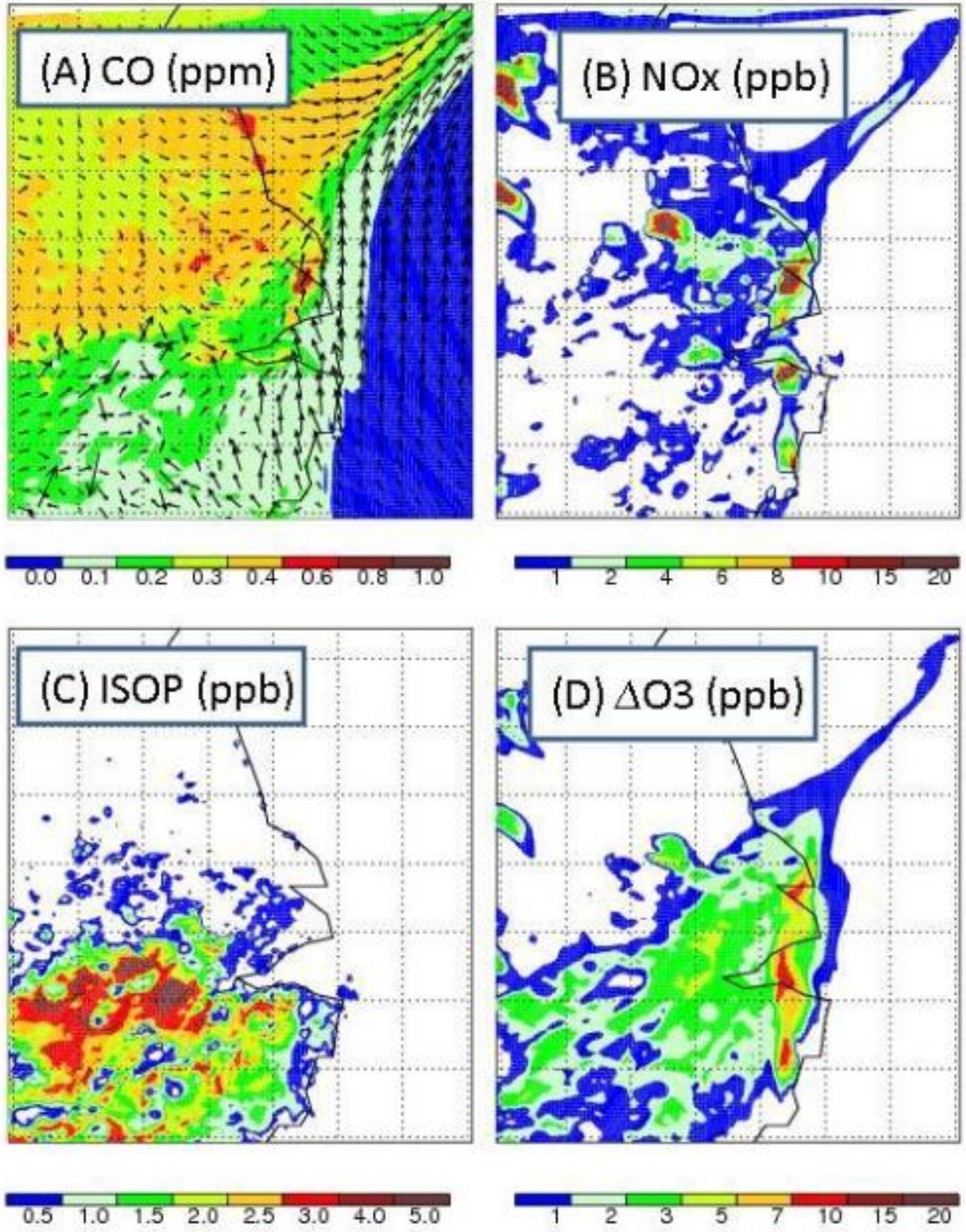


Fig. 3. One by one comparison of the calculated and measured isoprene concentrations. The green line is the fitting line of all the points, and the black dot line is the 1:1 line between the calculations and the measurements.

Geng et al. 2011

July 12 2009 case study

10 ppb increase in ozone when forest isoprene source is included in WRF-chem



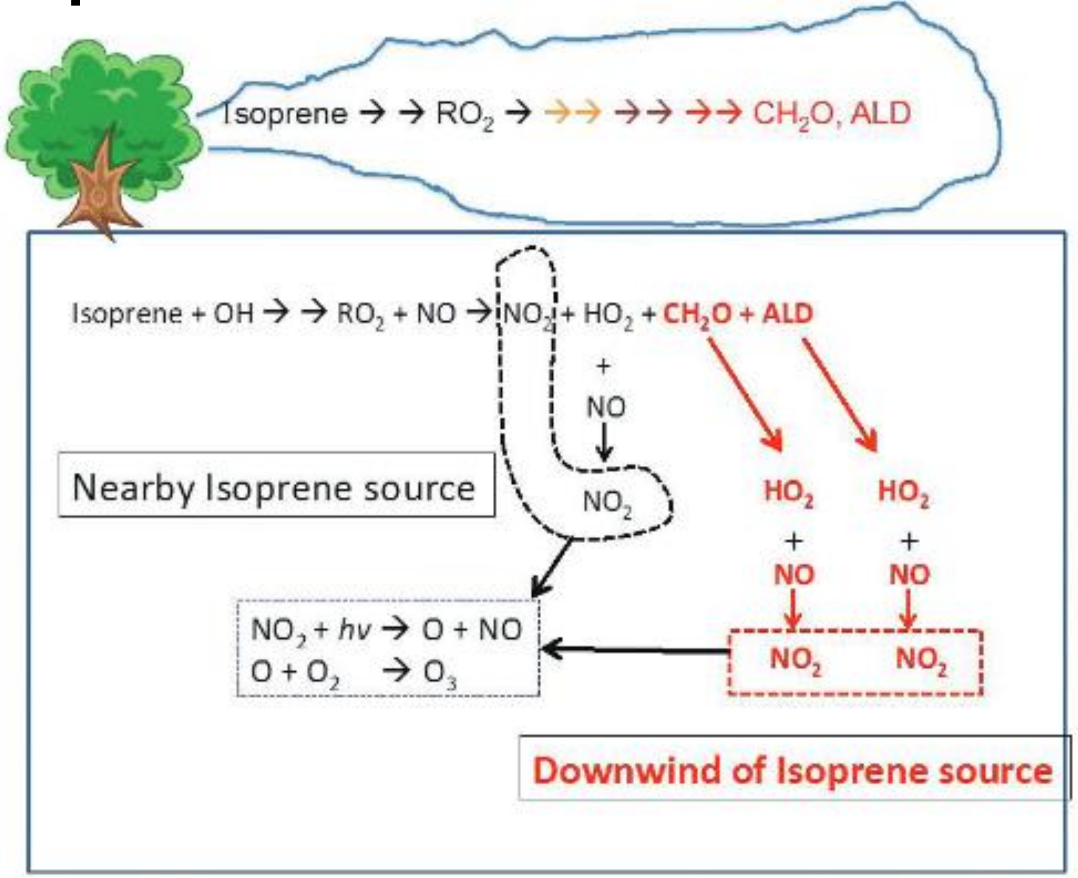
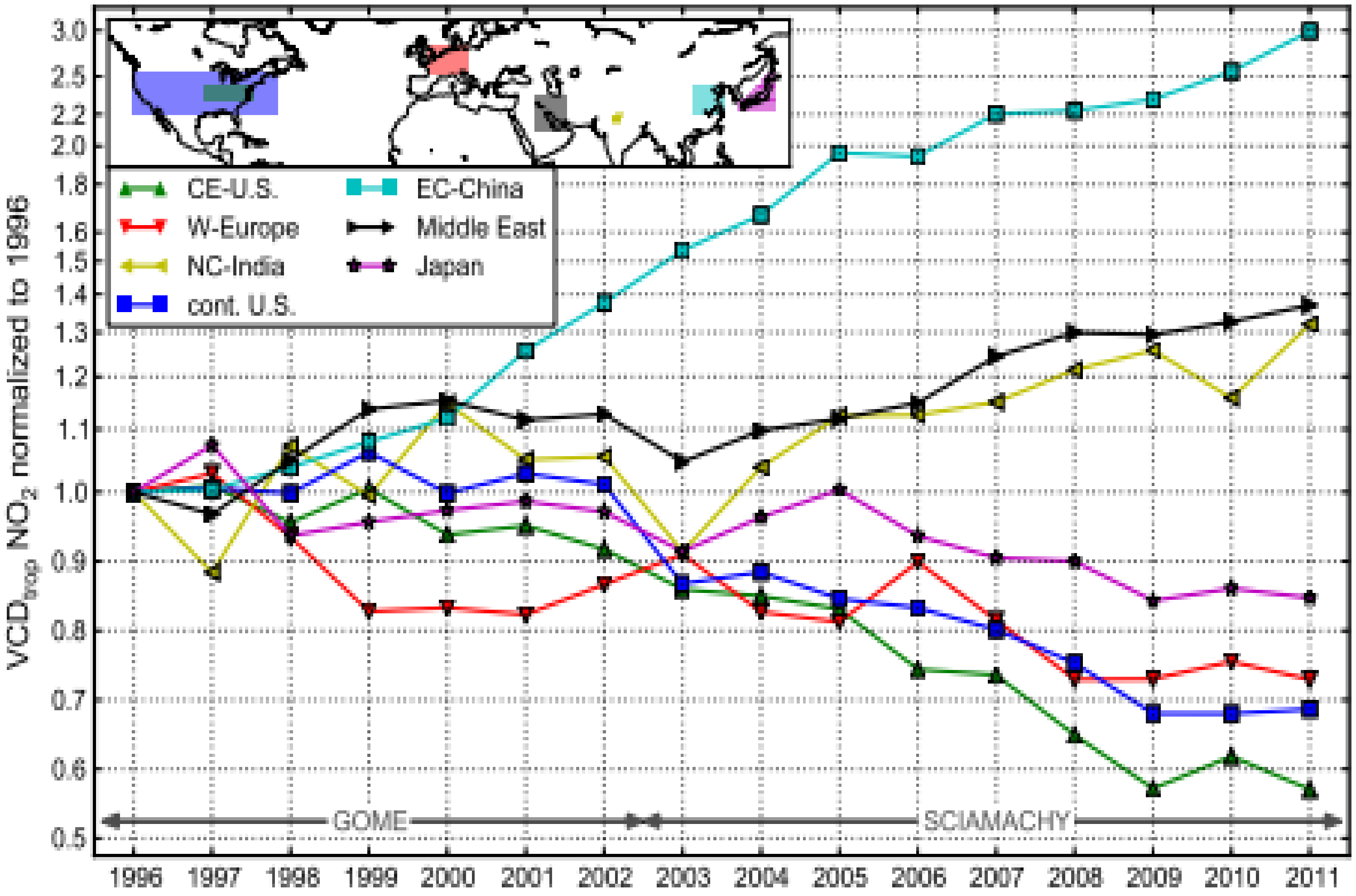


Fig. 7. Schematic picture illustrating the impact of biogenic emissions on the photochemical production of ozone in the forest source area and urban areas downwind of the forests.

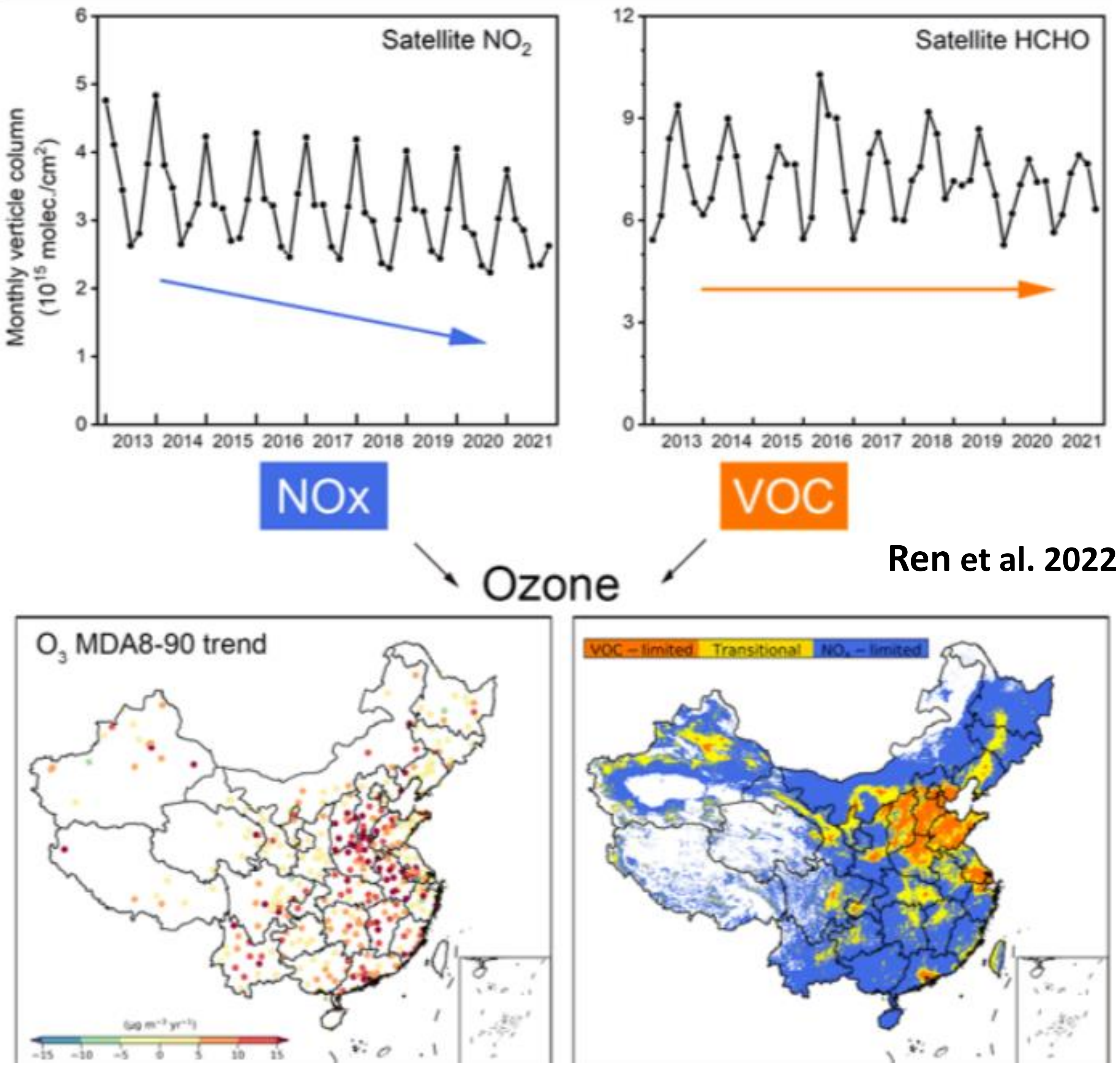
Geng et al. 2011

2000 to 2011: NO2 rapidly increased in China and decreased in US



Satellite estimates of NO2 trends

Hilboll et al. 2012



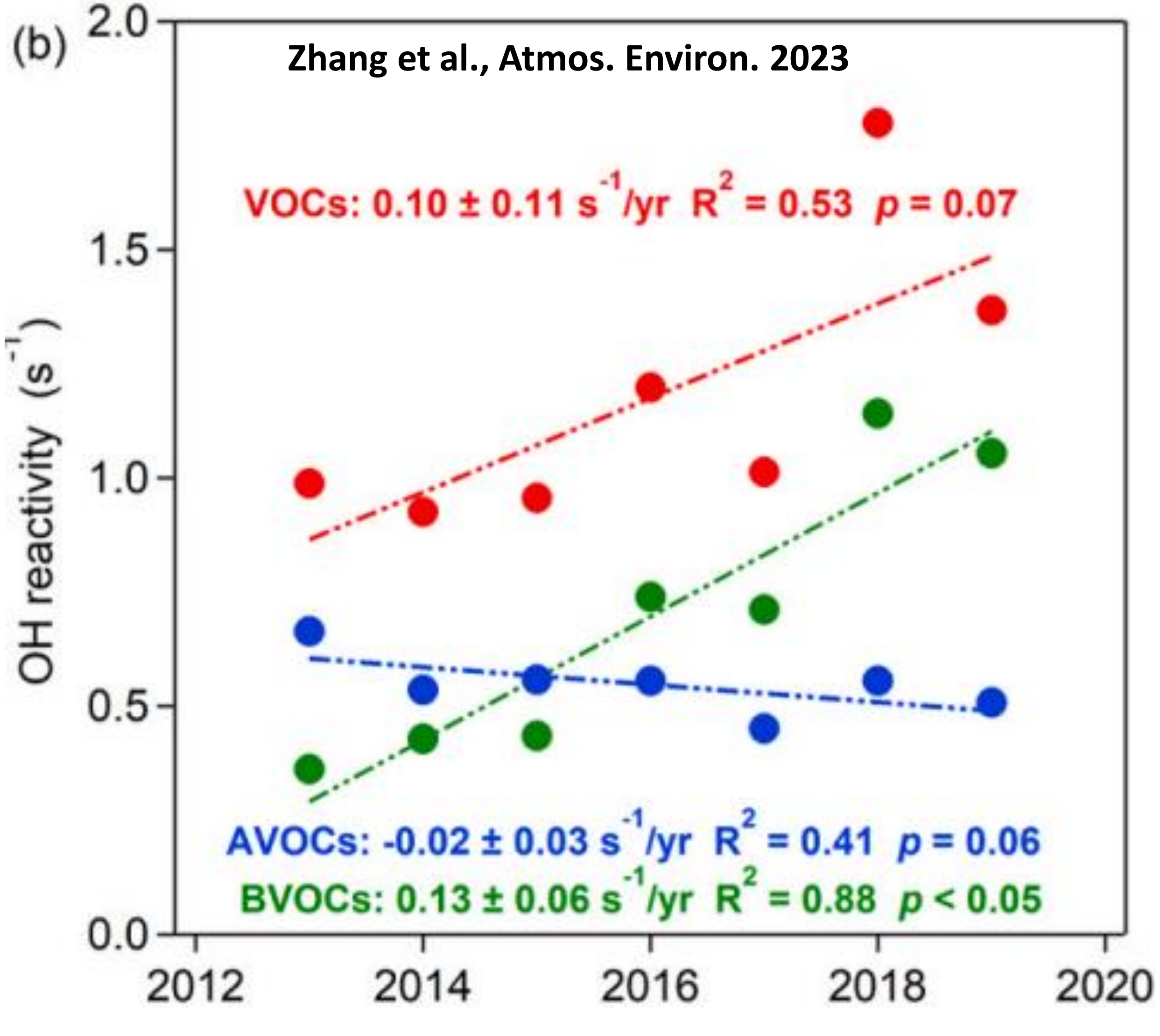
Ren et al. 2022

NO2 is starting to decrease in China but VOC is not

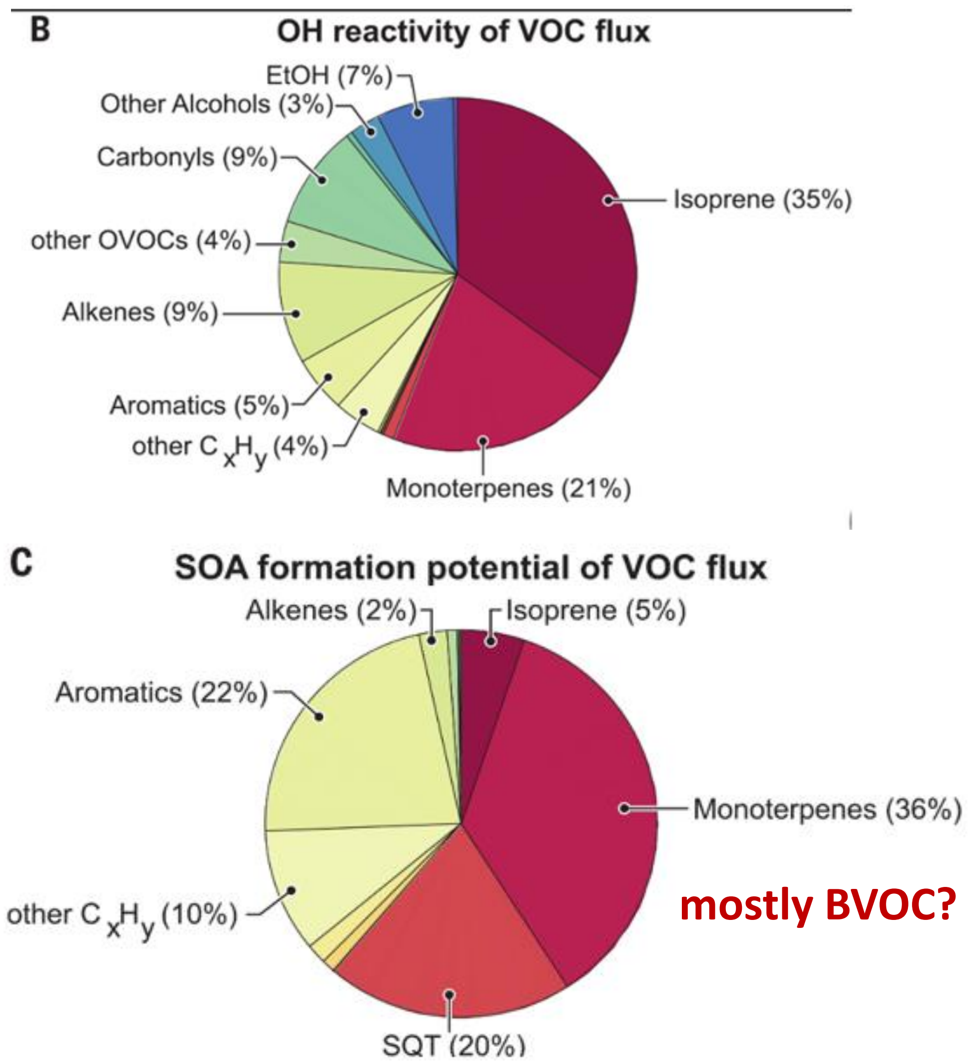
Anthropogenic VOC may be decreasing but is balanced by increasing biogenic VOC

Biogenic VOC is dominating over anthropogenic VOC even in urban areas

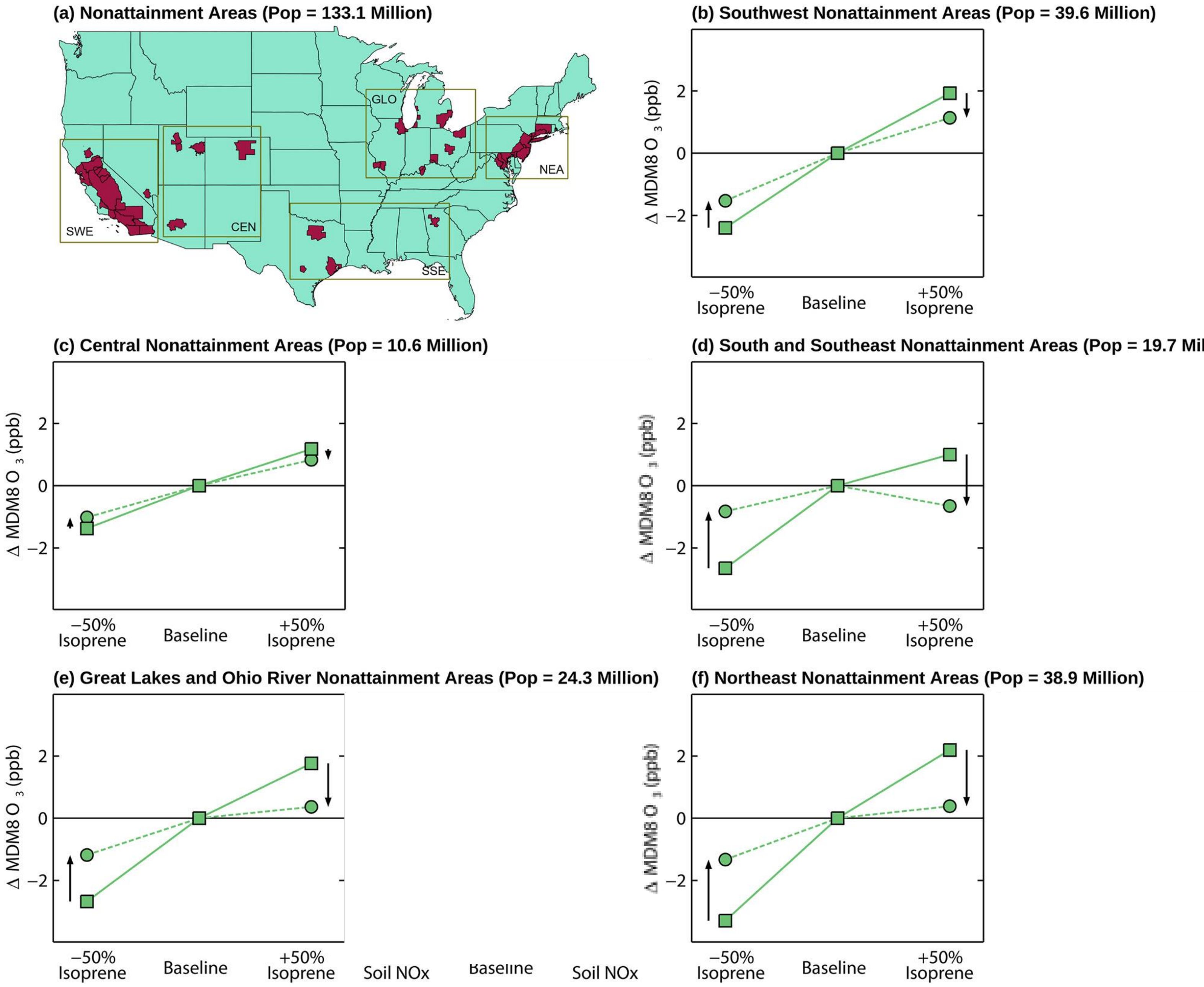
Hong Kong VOC OH reactivity dominated by BVOC



Los Angeles VOC OH reactivity and SOA formation potential dominated by BVOC



RECAP aircraft flux study (Pfannerstill et al. 2023, 2024)



Geddes et al. 2022

Following anthropogenic NOx reductions, O3 sensitivity to biogenic VOC decreased in many O3-nonattainment areas.

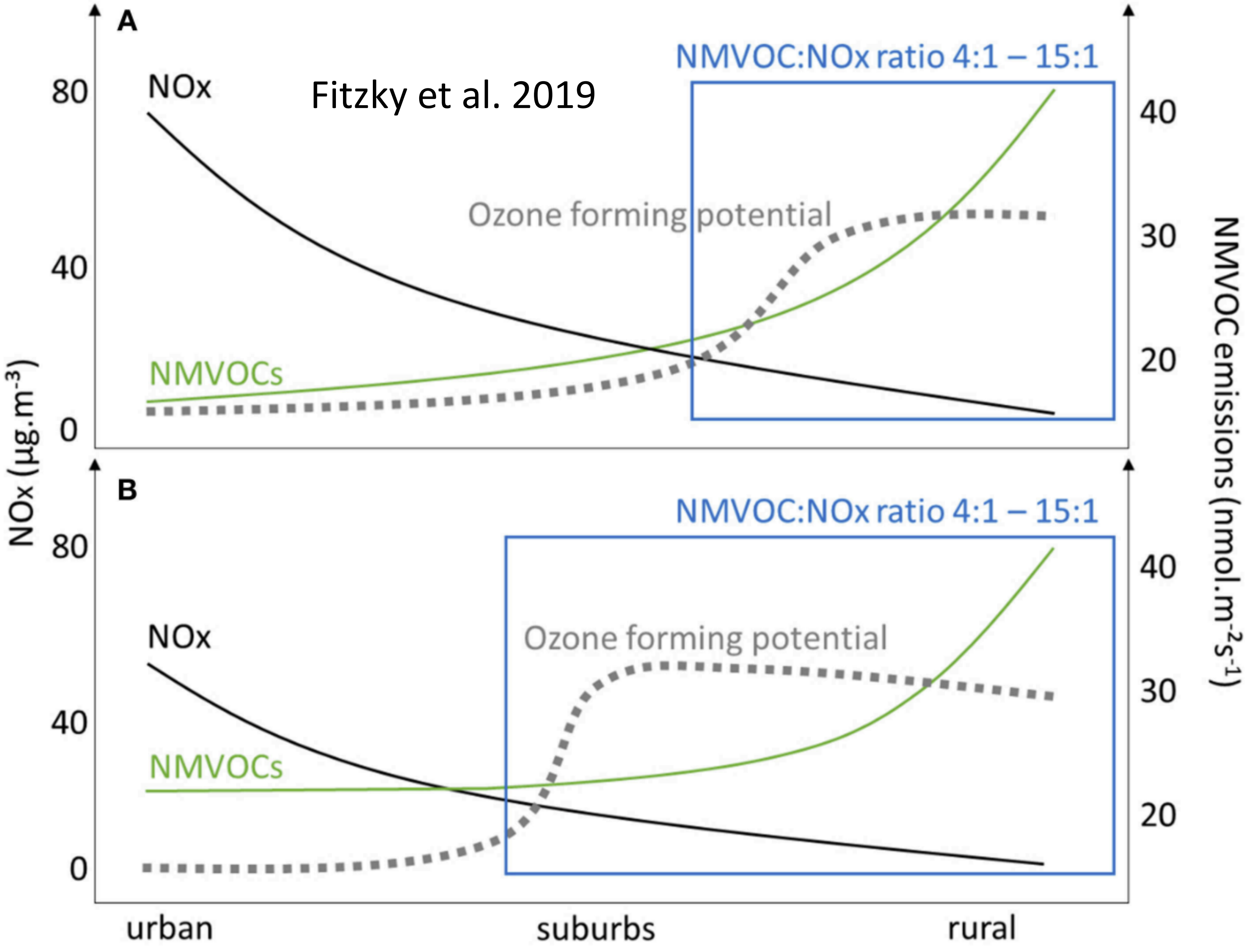
Soil NOx is becoming the most important biogenic emission in rural areas

Maximum daily 8-hour average ozone response to BVOC in 2006 compared to 2017

Solid lines (squares): sensitivity for 2006 anthropogenic NOx

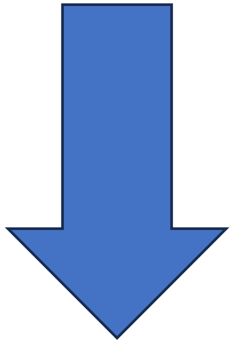
Dashed lines (circles): sensitivity for 2017 anthropogenic NOx

Main BVOC impacts are shifting from rural to urban



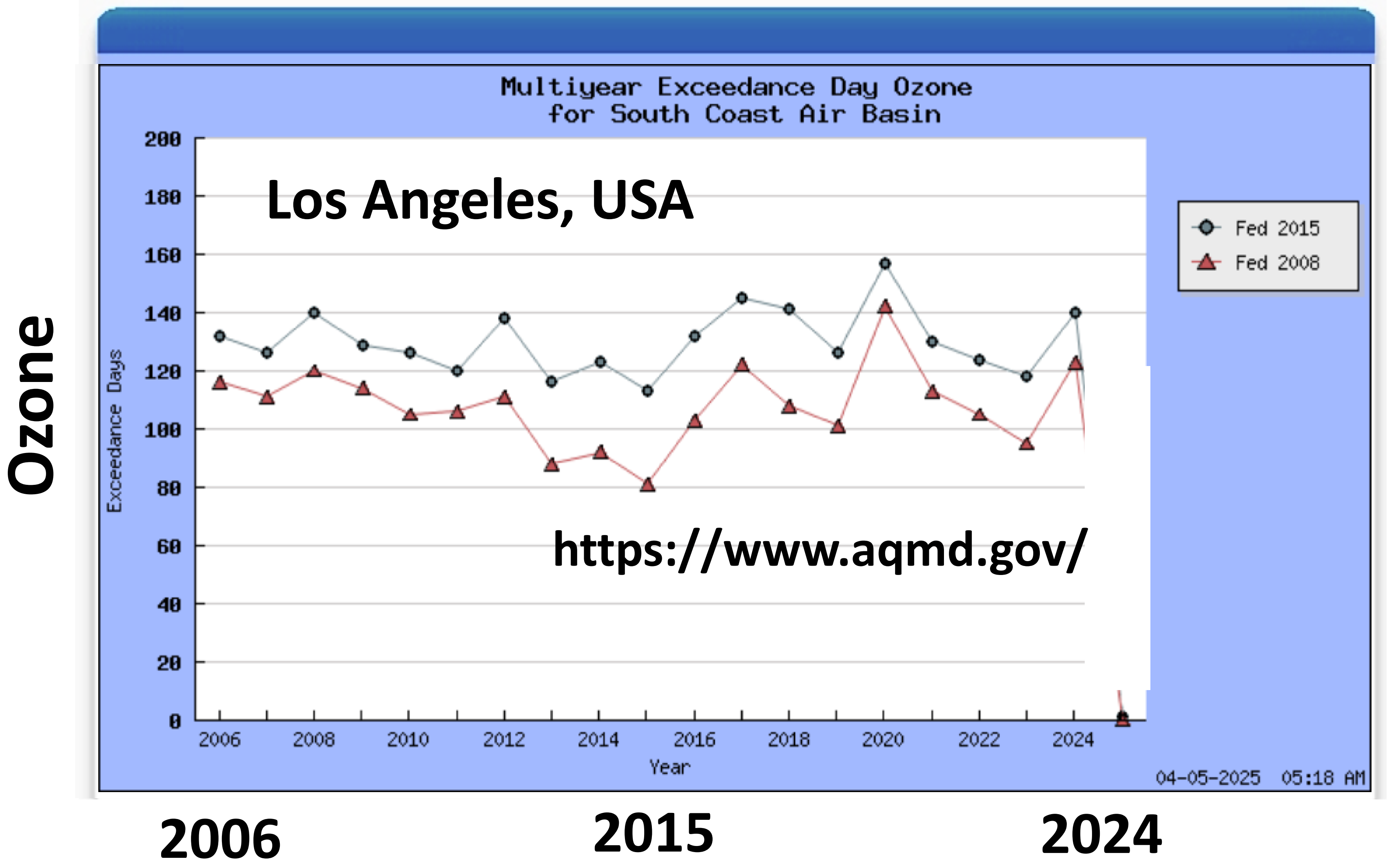
Suburban and even urban areas are changing from

High NOx
Low BVOC

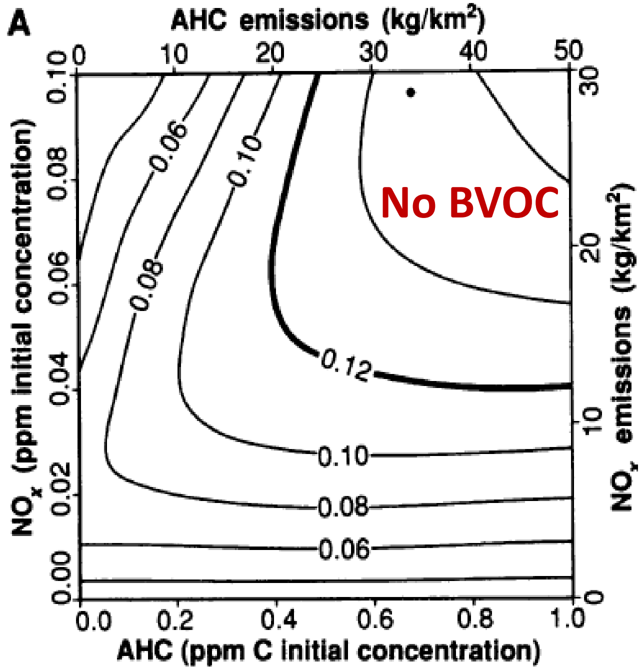


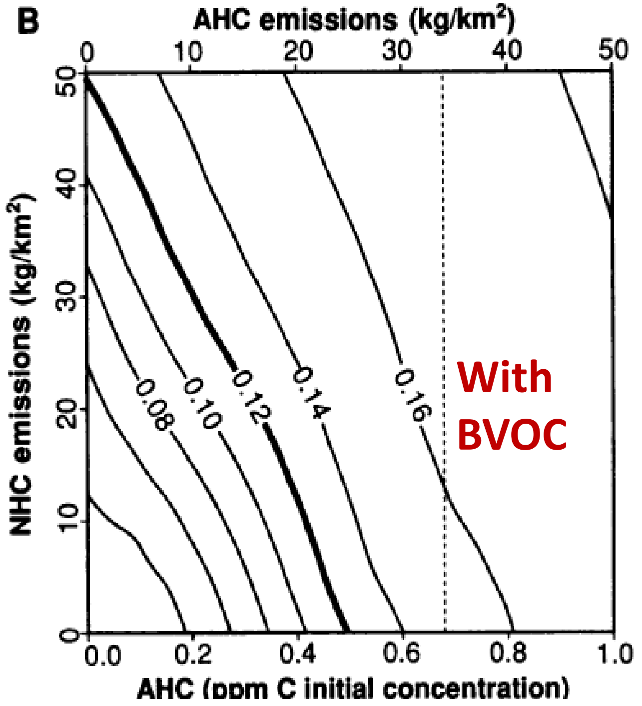
Decreased NOx
Increase BVOC

Persistent ozone concentrations in urban LA even with decreasing anthropogenic VOC and NOx



BVOC impacts on ozone

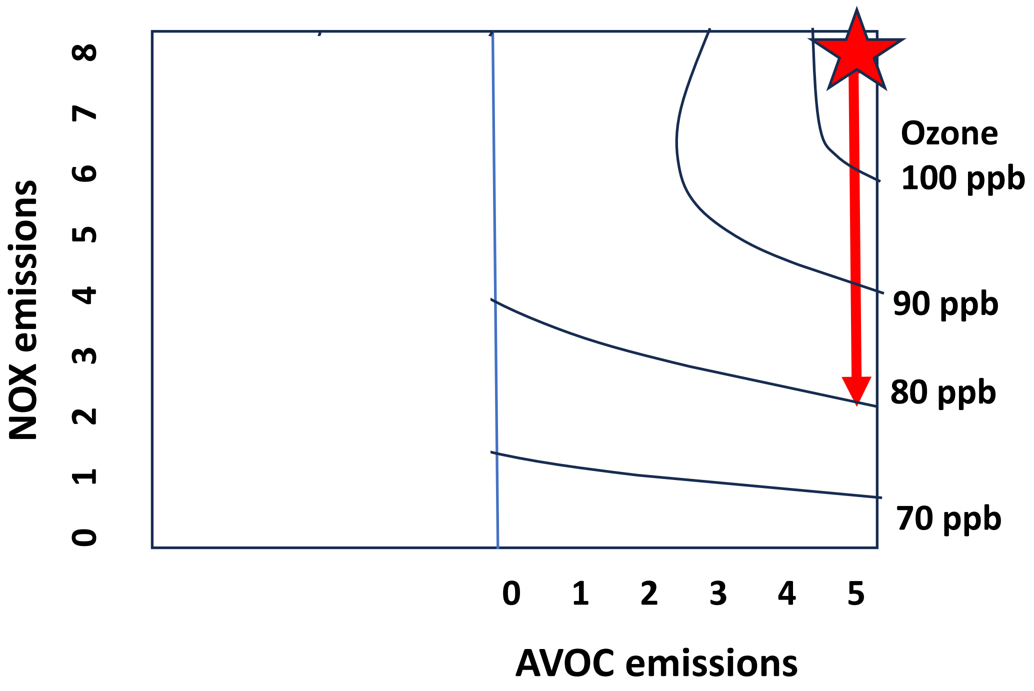


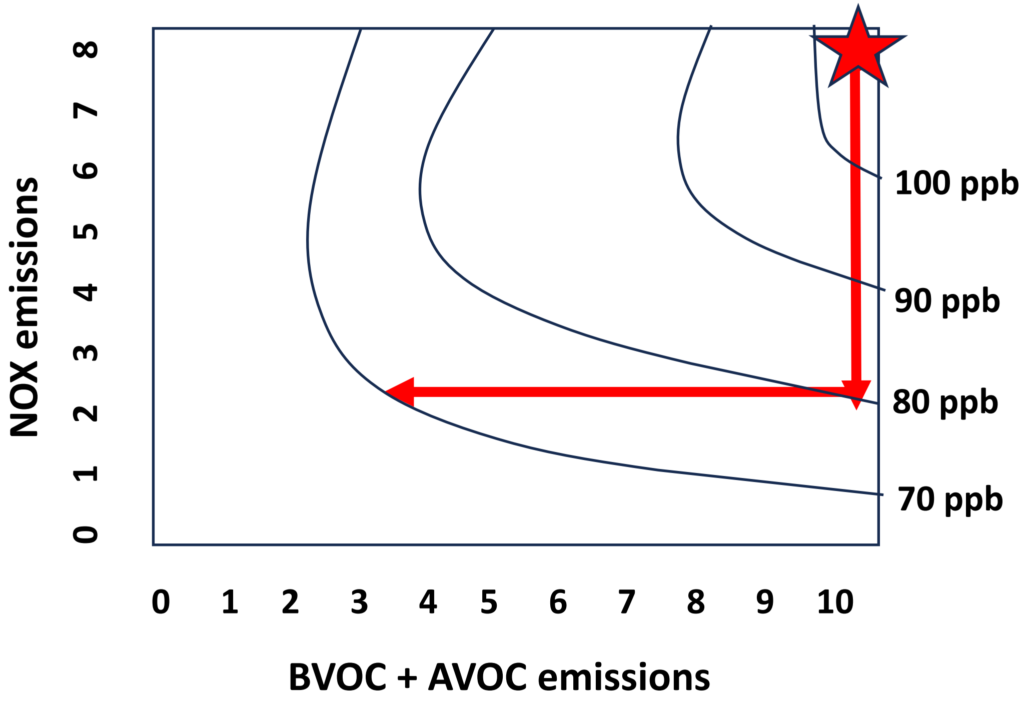


<u>Chameides et al 1988</u>

- BVOC can contribute to ozone production
- Reducing anthropogenic VOC looks like the best ozone abatement strategy but not when you include BVOC
- Conclusion: decrease NOx emissions to reduce ozone

How can we get Los Angeles ozone to the level recommended by WHO (and required by USEPA)?





NOx emission reductions may work only so far

May need to consider BVOC emissions to achieve lower ozone levels

MEGAN BVOC Emission Rate Estimates

Emission Rate = S x EF x EA

Guenther et al. 2012

Emission Rate: Emission to atmosphere

Source Density: Amount of source per land surface area

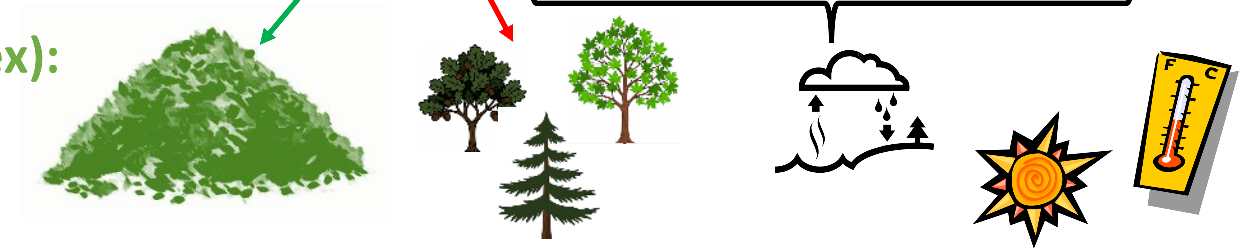
Emission Factor (EF): Emission rate at “standard” conditions. It is dependent on the amount and type of biogenic sources in a landscape.

Emission Activity (EA): Nondimensional factors that account for all emission variations (equal to unity at standard conditions). Dependent on environmental conditions including meteorology, atmospheric composition, landcover… (anything that causes emissions to vary)

$$Emission = LAI \cdot \varepsilon \cdot \gamma_{T} \cdot \gamma_P \cdot \gamma_A \cdot \gamma_{CO_2} \cdot \gamma_{SM}$$

LAI (Leaf Area Index): Source density

ε: Emission factor



Landscape capacity to emit BVOC

Activity dependent change in BVOC emission

- γ_{T} = Temperature
- γ_P = Psyn Active Radiation
- γ_A = Leaf age
- γ_{CO2} = CO_2 concentration
- γ_{SM} = Drought, other stress

How can urban BVOC emissions be controlled?

Do we know which plants are the low BVOC emitters?

Emission control strategies

- Manage stress: stressed plants emit more BVOC
- Manage maintenance: harvesting, pruning and mowing are a source of BVOC wound compounds
- Manage plant selection (high vs low emitters differ by more than 1000x)

Implementation approaches

- Increase awareness: Need a simple index
- Cost (Tax, fees, cap and trade)
- Bans (or limits) of targeted tree species

How do we know which trees to select?
Issue #1: Emissions data are unavailable or inaccurate

UFEI

RESOURCES ▾ DETAILS ▾ LOGIN

SelecTree

A TREE SELECTION GUIDE

Enter a tree name...

SEARCH PACIFIC ISLANDS | SEARCH CHARACTERISTICS | SEARCH TREE LISTS | APPRAISALS

SEARCH BY CHARACTERISTICS

selectree.calpoly.edu

MAIDENHAIR TREE

Ginkgo biloba

FAMILY Ginkgoaceae

See: all *Ginkgo* or *Champion*

1. Need an index that indicates the importance of this trait (e.g., Potential Air Pollution Index)
2. Need updated database. For example, Ginkgo is a very low emitter

CONSIDERATIONS

Branch strength: Strong

Root damage potential: Moderate

Potential health issues: Allergy, Irritant

Biogenic emissions: Moderate

Wildlife interactions: Attacts squirrels

Disease and pest susceptibility: Anthracnose

Disease and pest resistance: Armillaria, Root Rot

Utility friendly: No

WCISA Appraisal: Suggested LCANT 24" box, Suggested LCANT 24" box, Group Rating 2, Approx. cross sectional area 2.24 sq. in.

How do we know which trees to select?

Issue #2:
Light dependent (not stored) emissions (isoprene, MBO, monoterpenes) can be suppressed or elevated by past environmental conditions

Plant stress or environmental conditions (i.e. sufficient light growth environment?) unknown for most reported data

Assuming all broadleaf isoprene emitting trees have a similar isoprene emission may be reasonable for regional to global modeling but is not sufficient for tree selection

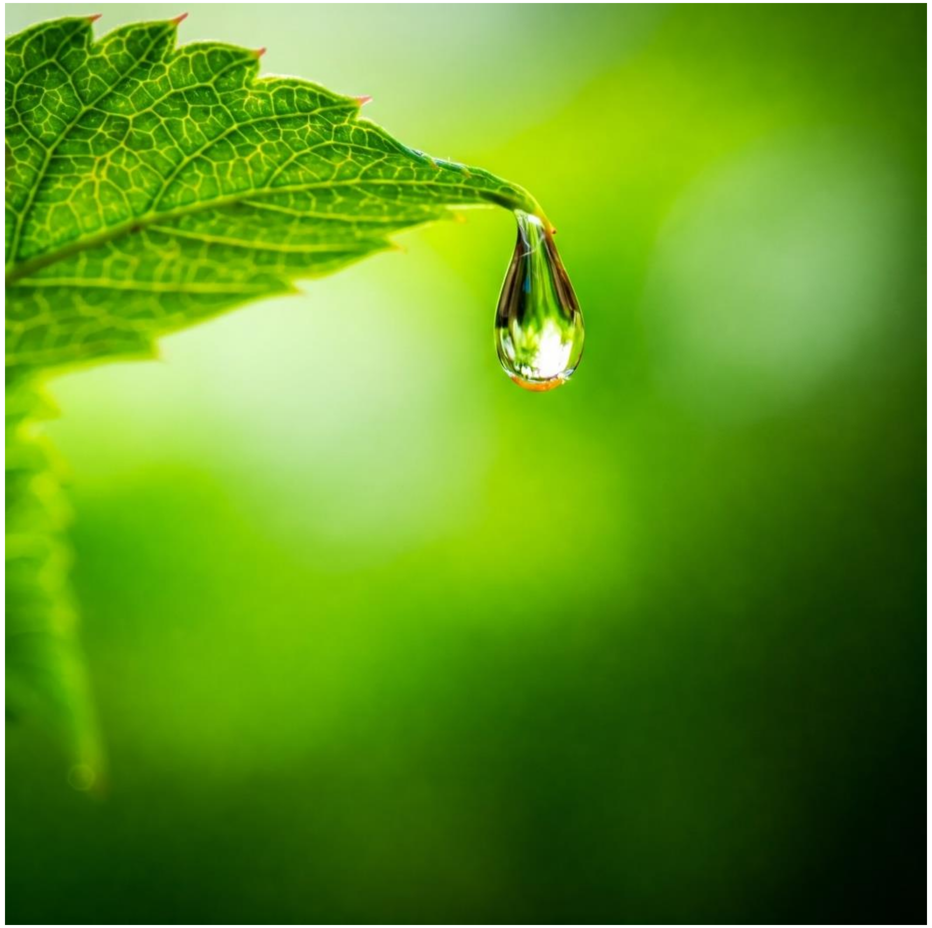
How do we know which trees to select?

Issue #3:
Plants with BVOC storage structures have high variability and can be disturbed by enclosure measurements

- Enclosure systems are known to damage storage structures causing artificially increased emission rates. This has led to omission of high "outliers".

- It appears that there are "super-emitters" in the real-world that significantly contribute to total BVOC emissions.

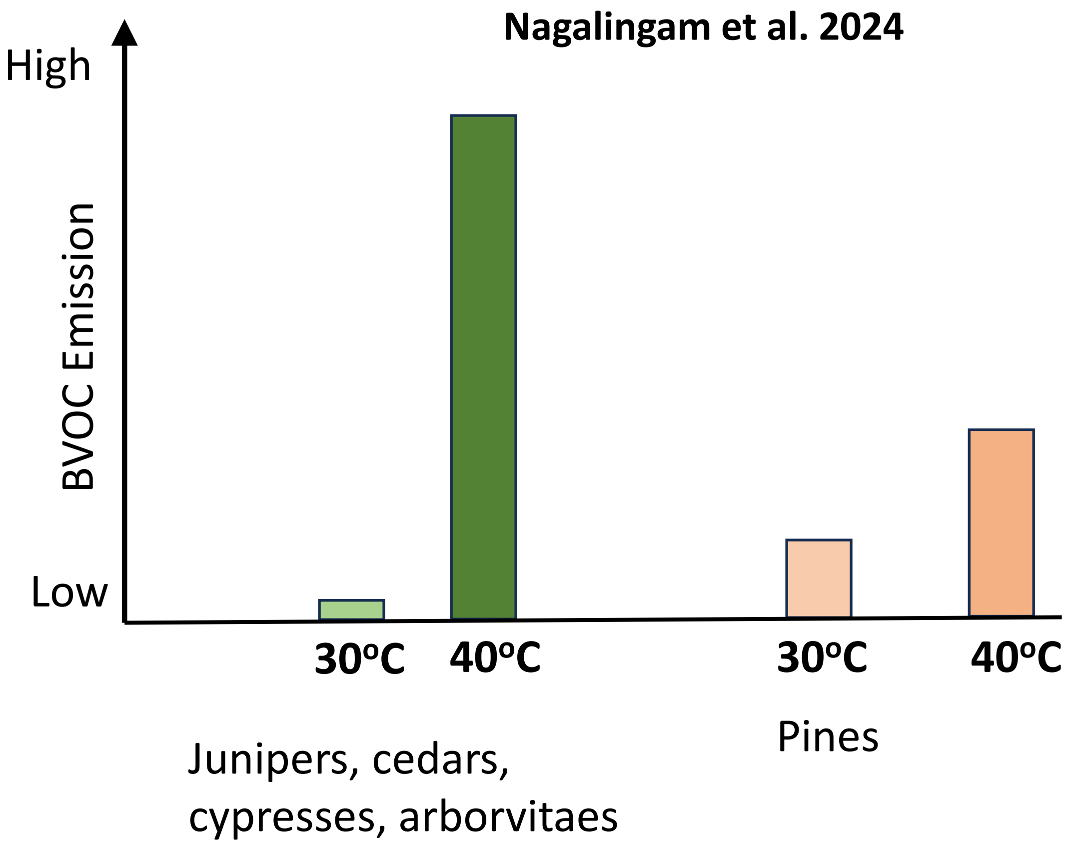
- Need new emission factors survey methods to characterize representative emissions (including super-emitters) for tree selection purposes

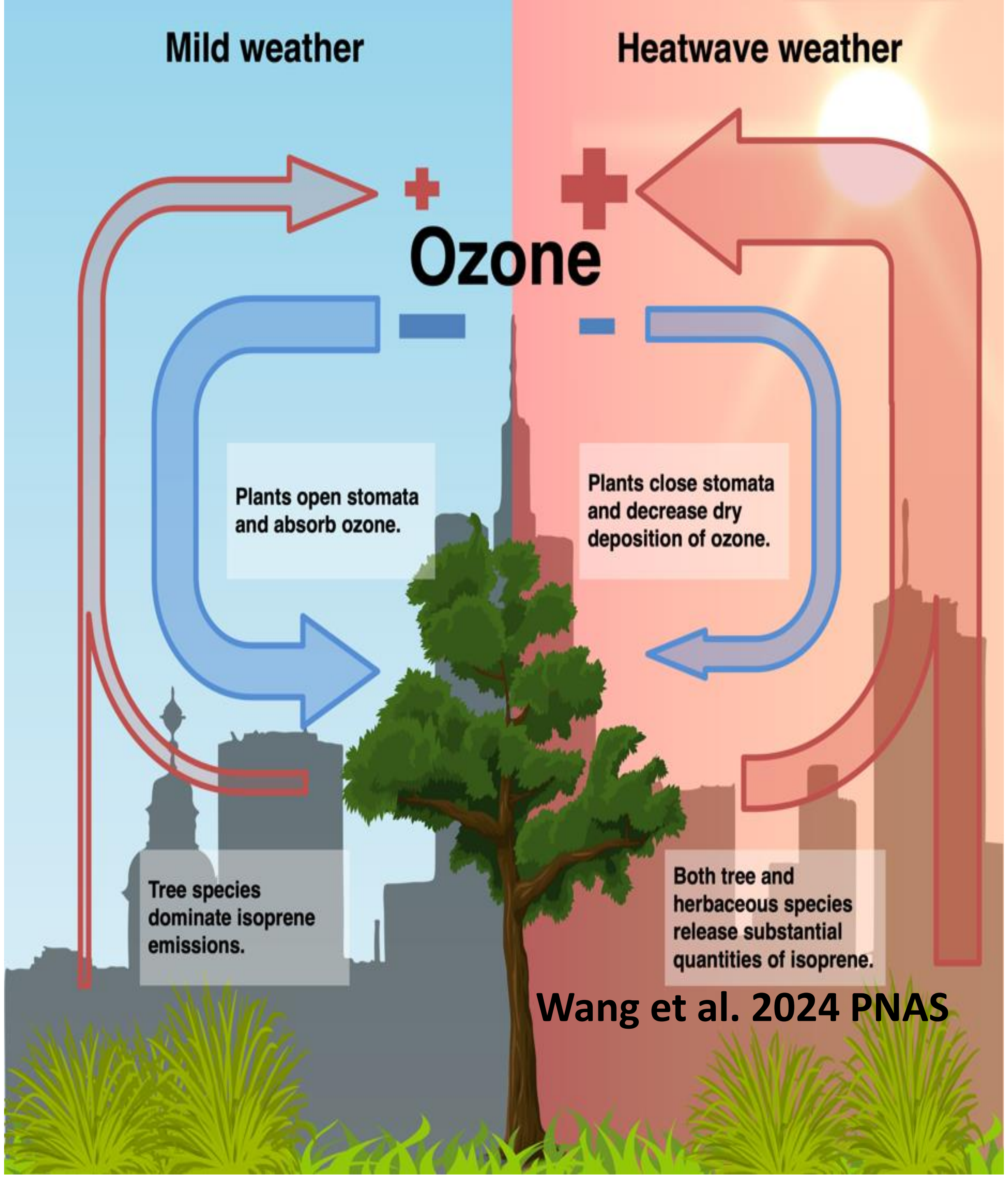


How do we know which trees to select?

Issue #4:
Stress induced emission potential

- Some plants are low emitters under optimal conditions but high emitters under stress conditions
- Stress conditions (e.g., heat waves) can be associated with poor air quality events
- Need new emission factor survey methods are to identify stress-sensitive species for tree selection purposes

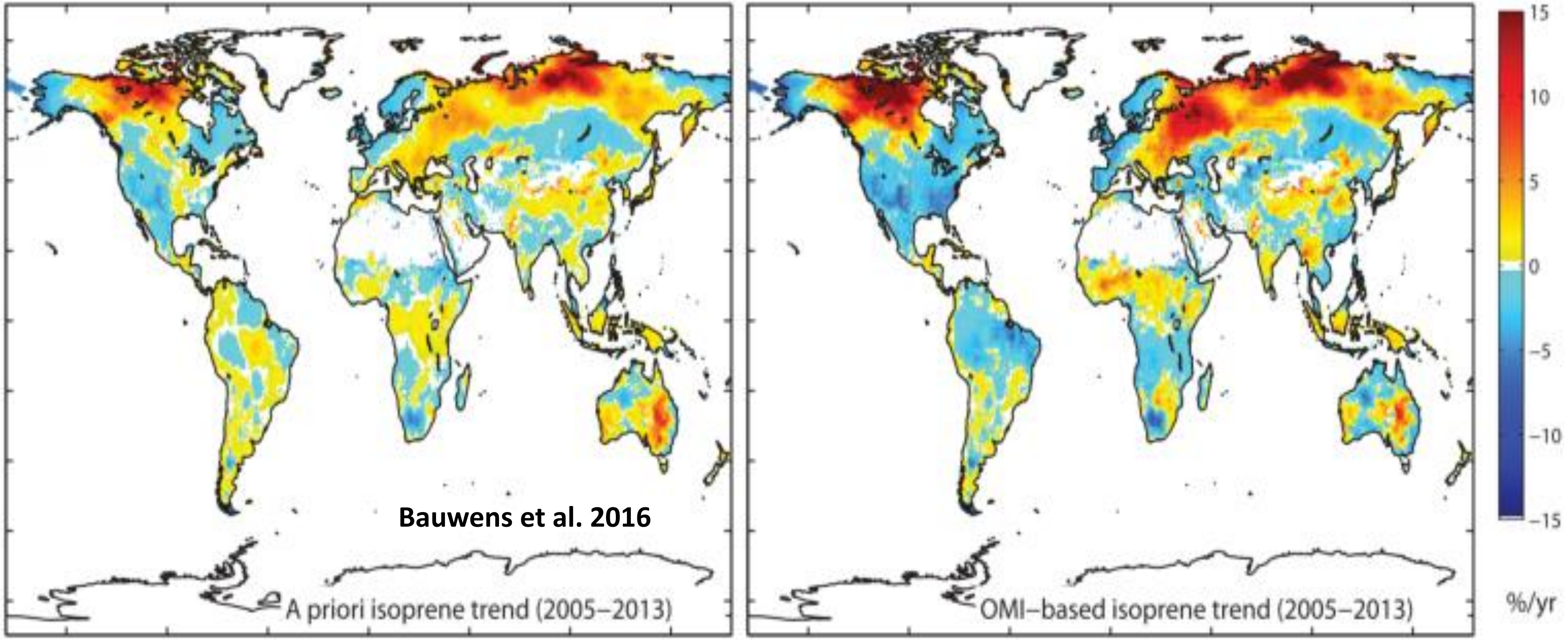




We may be missing some important plant species altogether

Sedges (grass-like plants) are not included in BVOC emission inventories but may be a major source of isoprene during heatwaves

How can we assess/monitor/validate BVOC emission estimates?



Bottom up (MEGAN2.1)

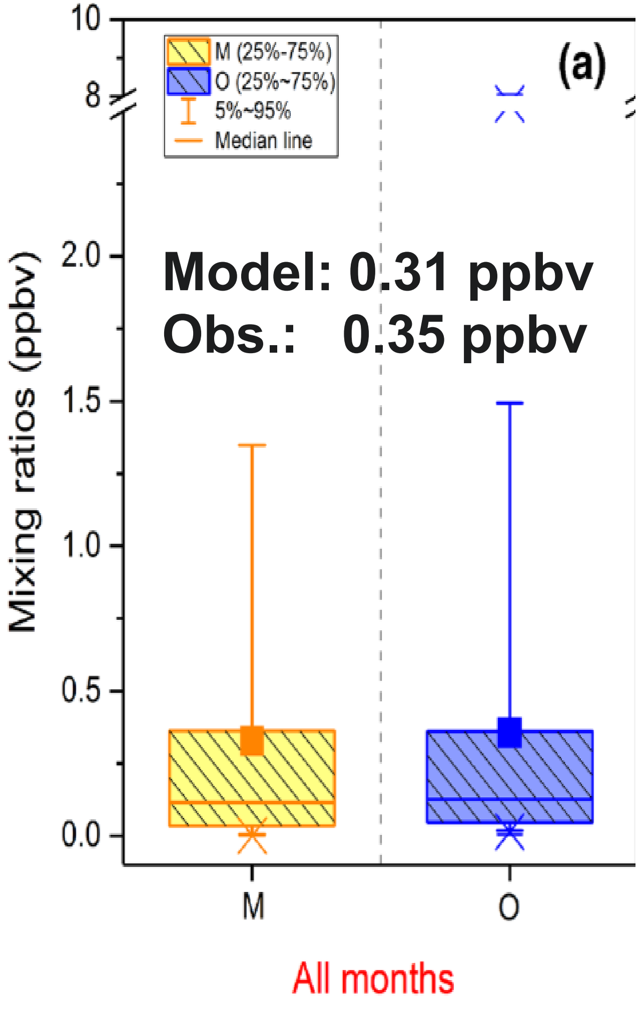
Top down (OMI)

Isoprene trend (%/yr)

New satellites (geostationary, multi-compound, high spatial resolution) and calibration efforts may improve these data

How can we assess/monitor BVOC emission estimates?

1731 surface layer isoprene measurements at 20 sites in China



North
Model: 0.14 ppbv
Obs.: 0.37 ppbv

South
Model: 0.53 ppbv
Obs.: 0.35 ppbv

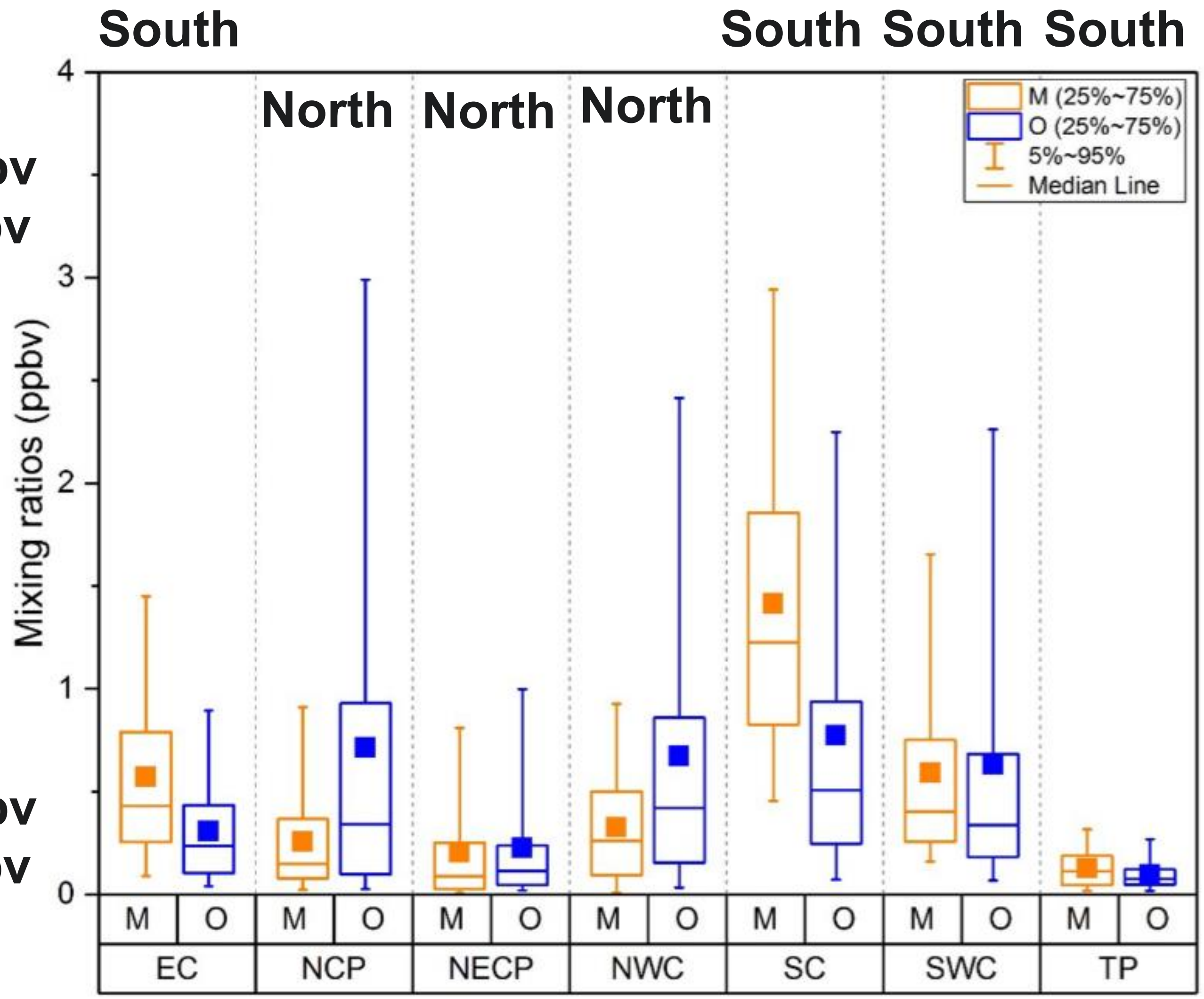
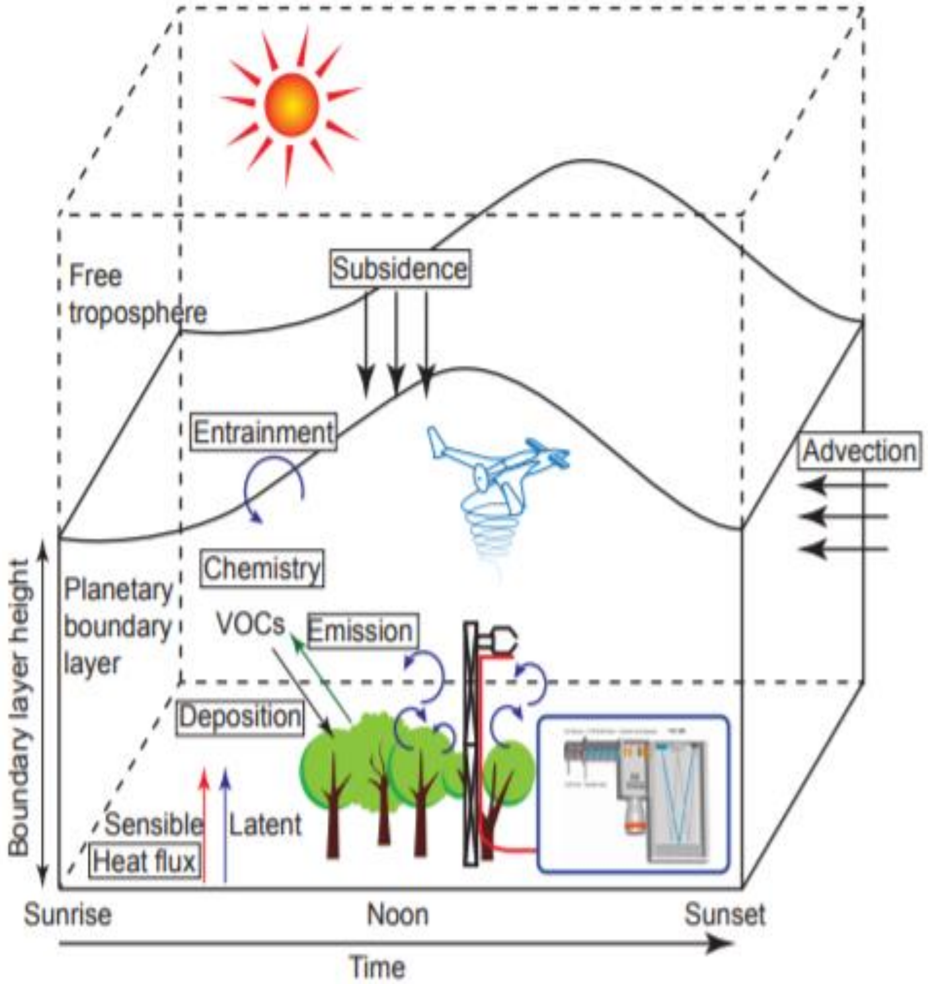


Figure 4. Comparison of isoprene mixing ratios between model simulation and ambient observation in different regions during growing season (May–October).

Zhang et al. 2020

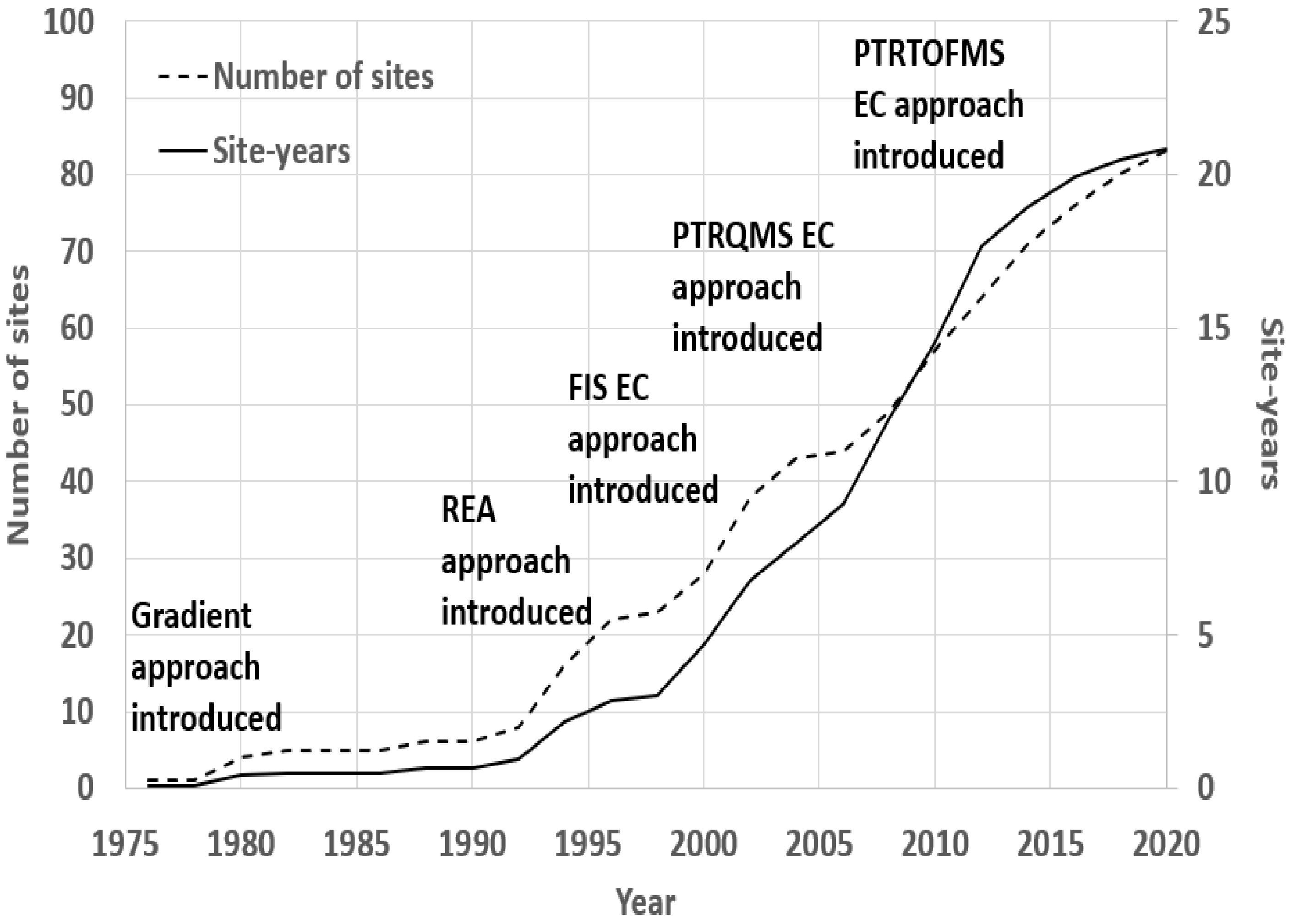
Atmospheric Boundary layer BVOC measurements



Estimate landscape scale fluxes (~2 to 15 km footprint) using

- **Mixed layer vertical gradient**
- **Mixed layer mass balance**

Direct approach: Long-term, above-canopy BVOC eddy flux data



In 2015:
FLUXNET CO2/H2O/energy fluxes: 1500 site years of data from 212 sites (average of 7 years)

BVOC fluxes: 20 site years from 65 sites (average of < 4 months).

Compared to CO2, BVOC has 30% of the sites but 1.3% of the site years.

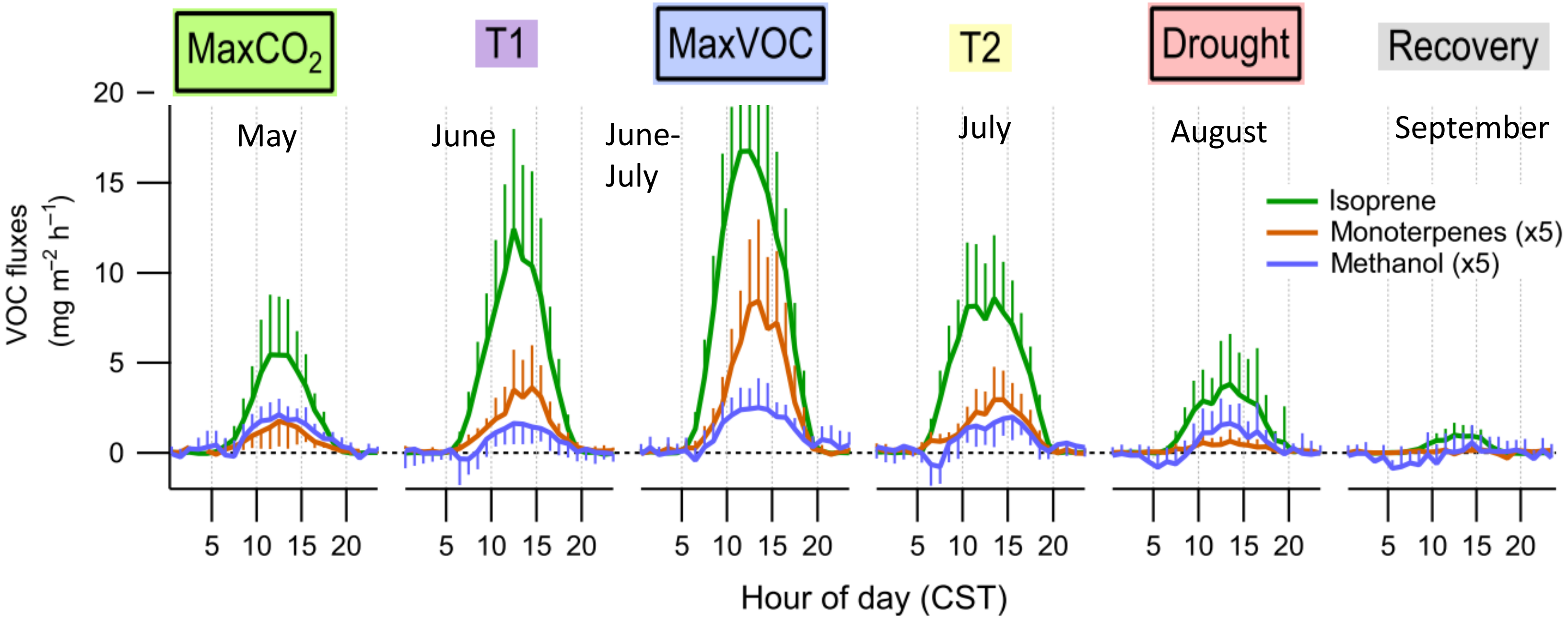
We need networks of low cost, low power BVOC flux systems (e.g., relaxed eddy accumulation with online GC) deployed on existing carbon/water/energy flux towers to provide these observations

A long-term measurement network can capture a wide range of conditions including extreme events

Missouri USA
2011-2012

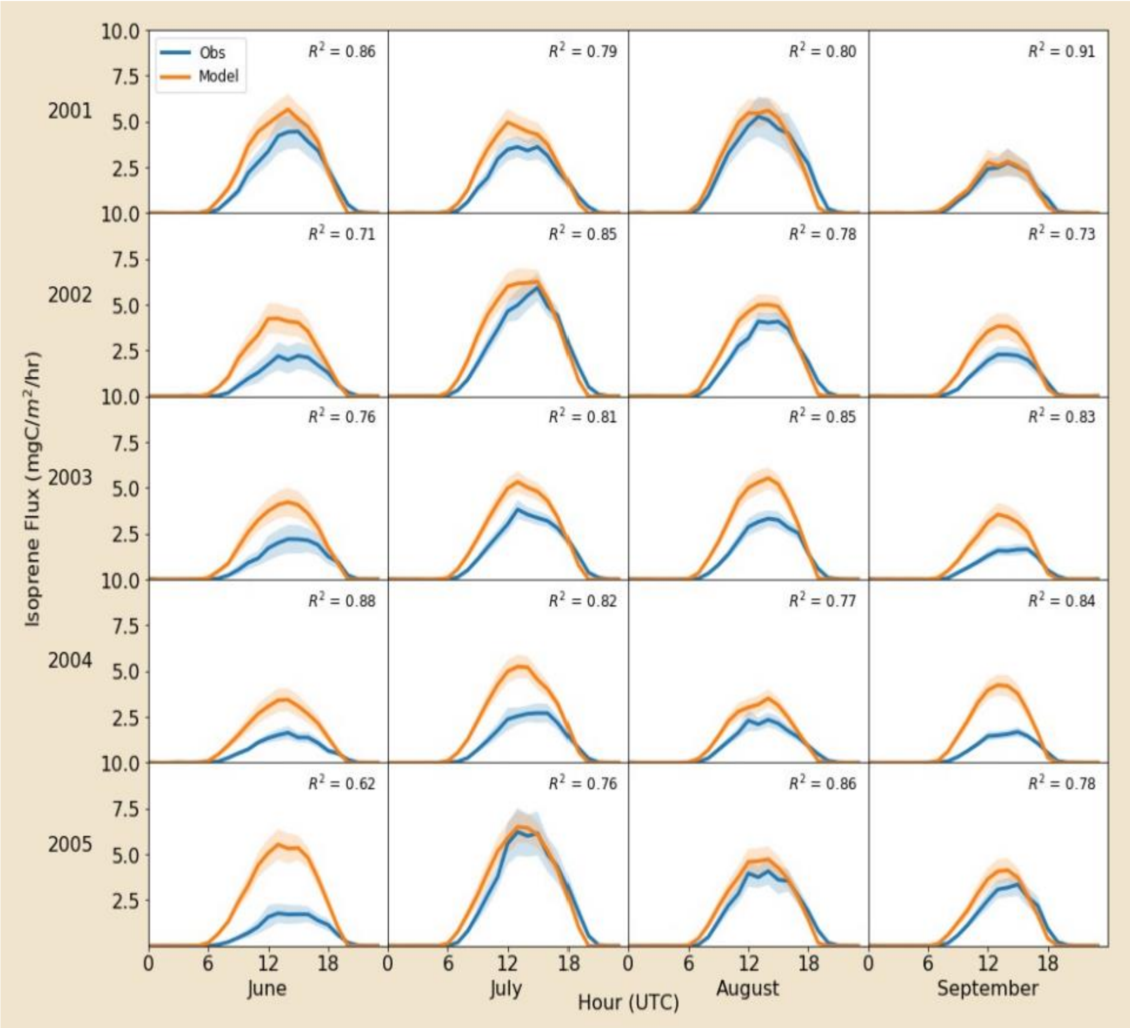
BVOC response to temperature and drought stress

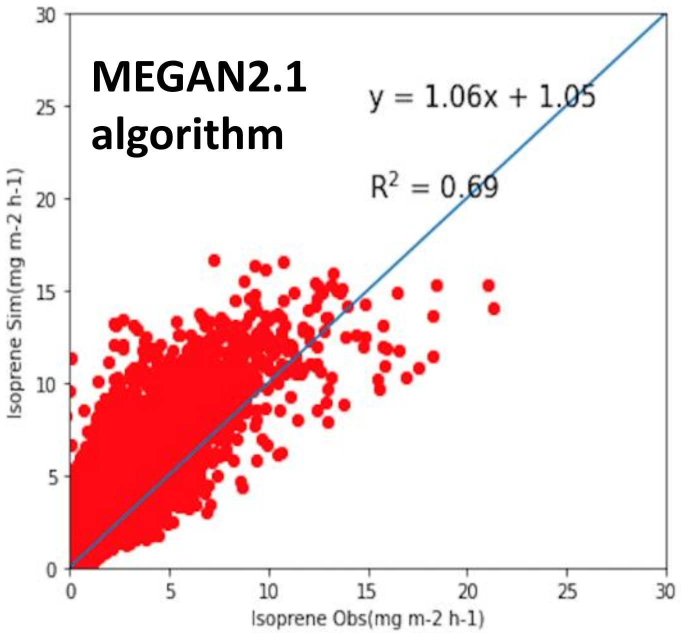
No Drought, ~25°C **Mild Drought, ~35°C** **Severe Drought, ~30°C**

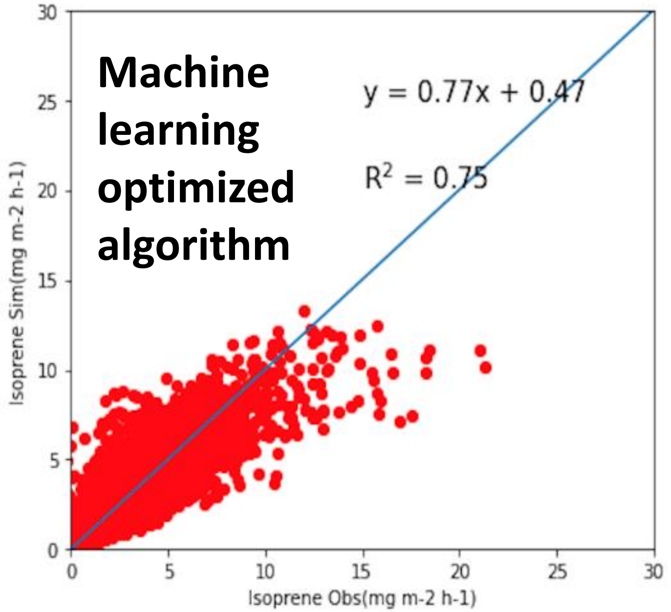


Above-canopy eddy covariance PTRMS flux measurements
Seco et al. 2015

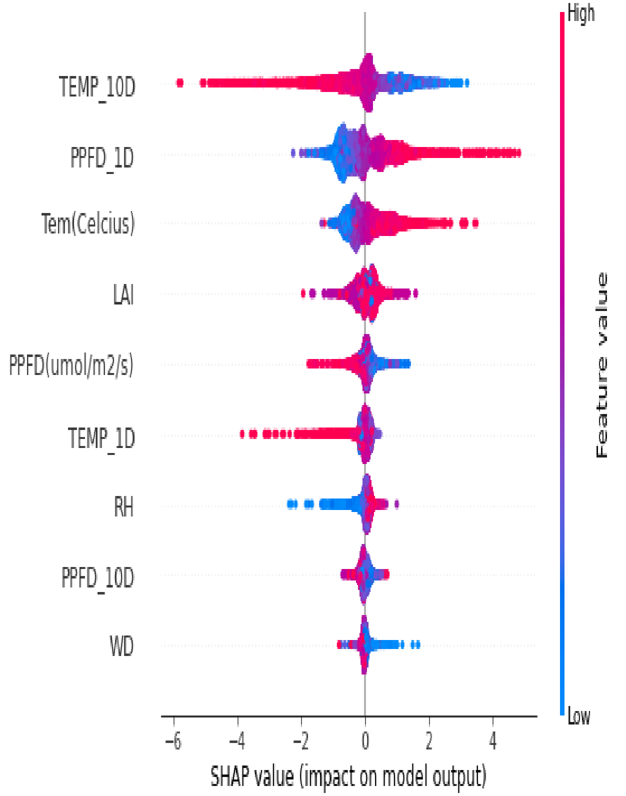
Long-term above-canopy flux data: seasonal and interannual BVOC variations







SHAP value identifies the most important driving variables



This is the only >2 year BVOC flux dataset.

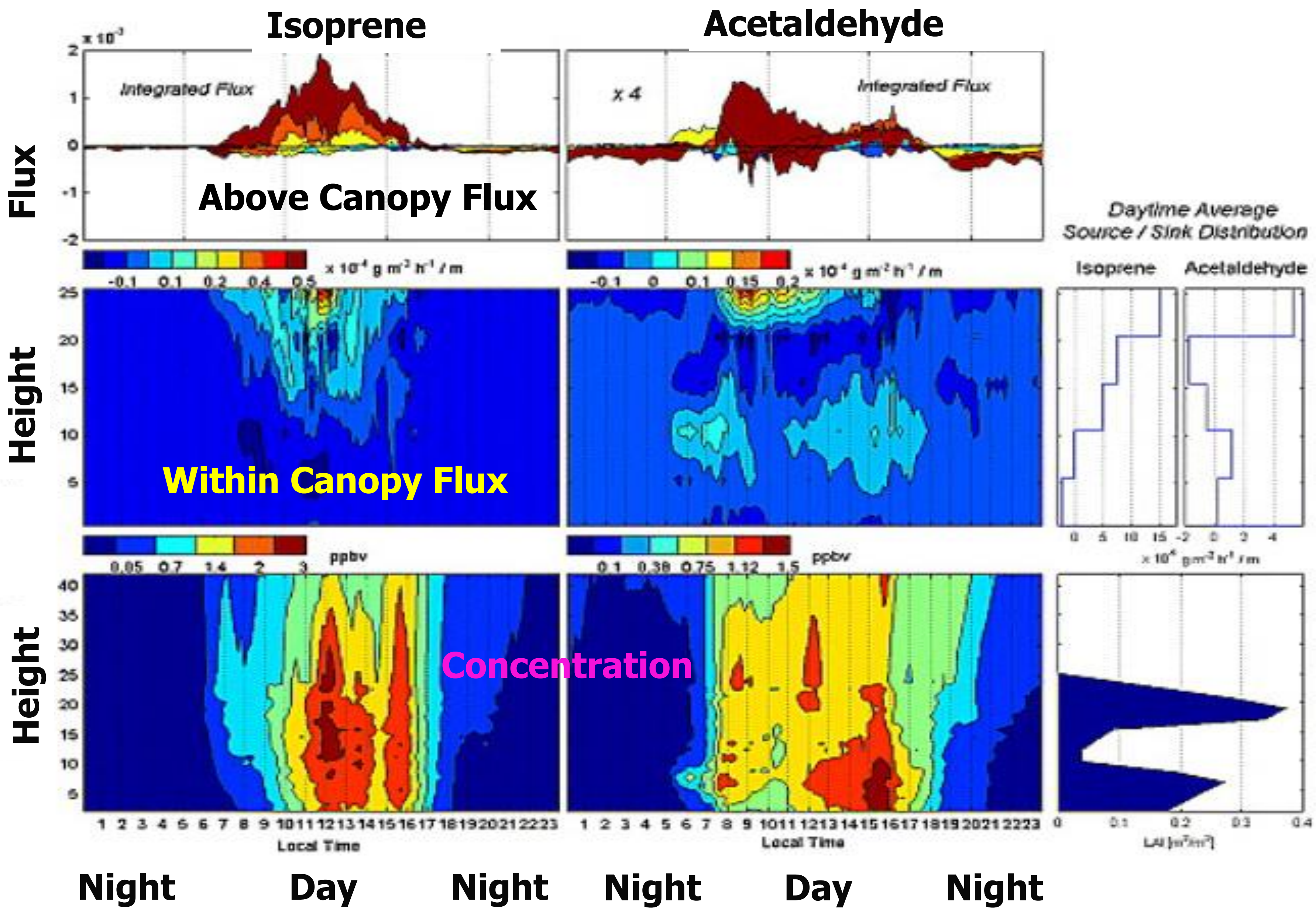
Measurements made with relatively low-cost fast isoprene sensor observations

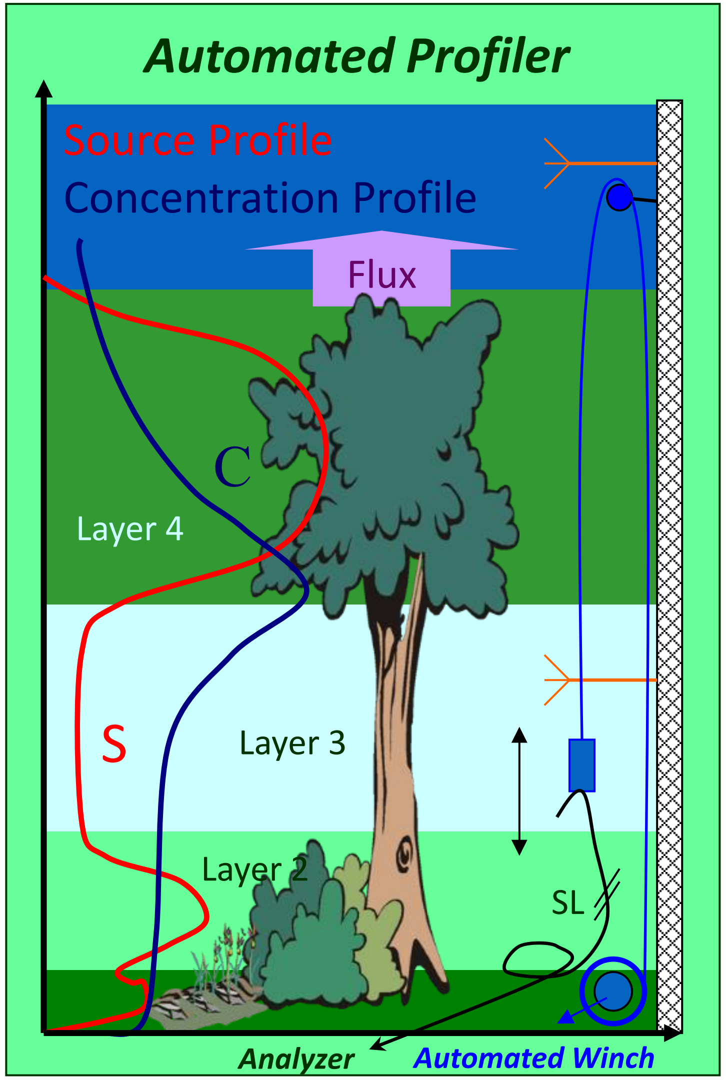
Pressley et al. 2005

Kittitananuvong et al.

Hui Wang

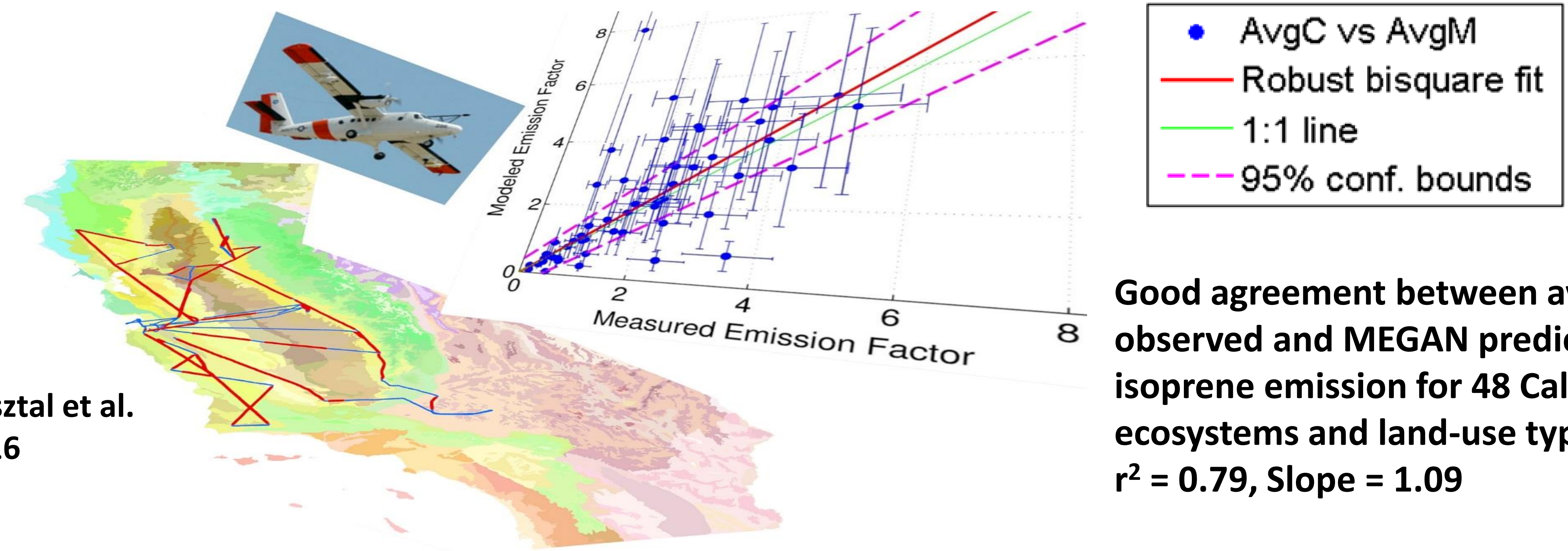
Canopy scale flux measurements: Within canopy microclimate, chemistry, transport and uptake determine what gets into the atmosphere





Costa Rica tropical forest
Karl et al. 2004

Direct approach: Aircraft flux (EC-PTRMS) measurements to investigate BVOC differences due to landcover change/management

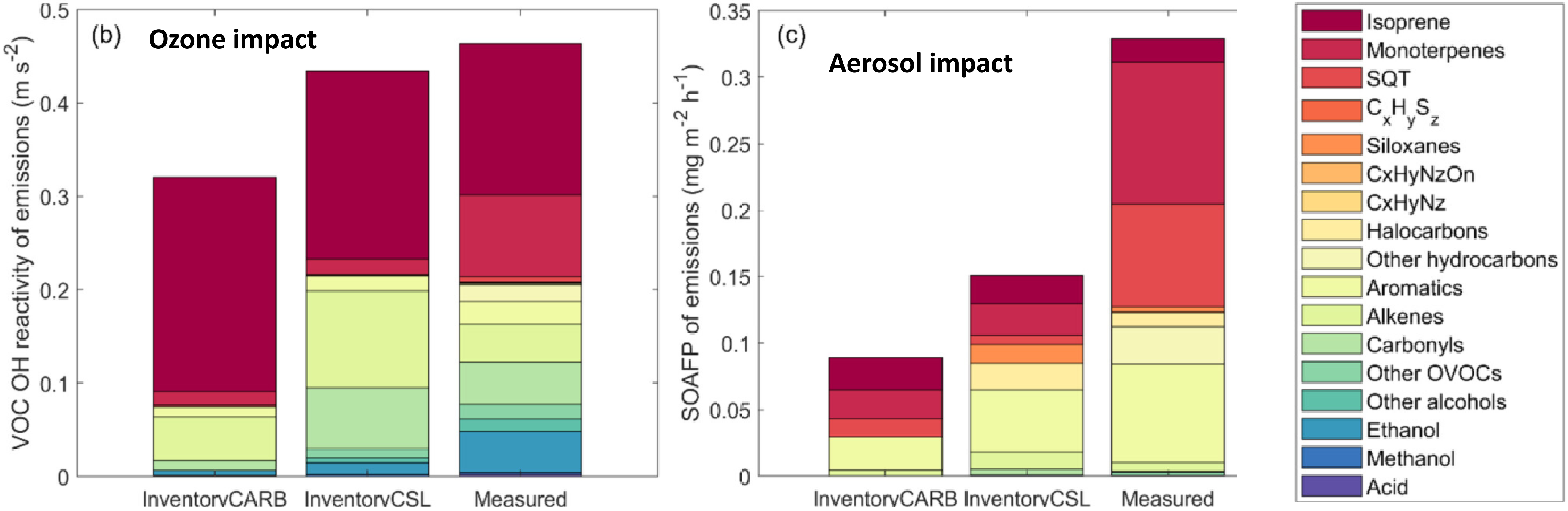


Misztal et al. 2016

Good agreement between average observed and MEGAN predicted isoprene emission for 48 California ecosystems and land-use types
r^2 = 0.79, Slope = 1.09

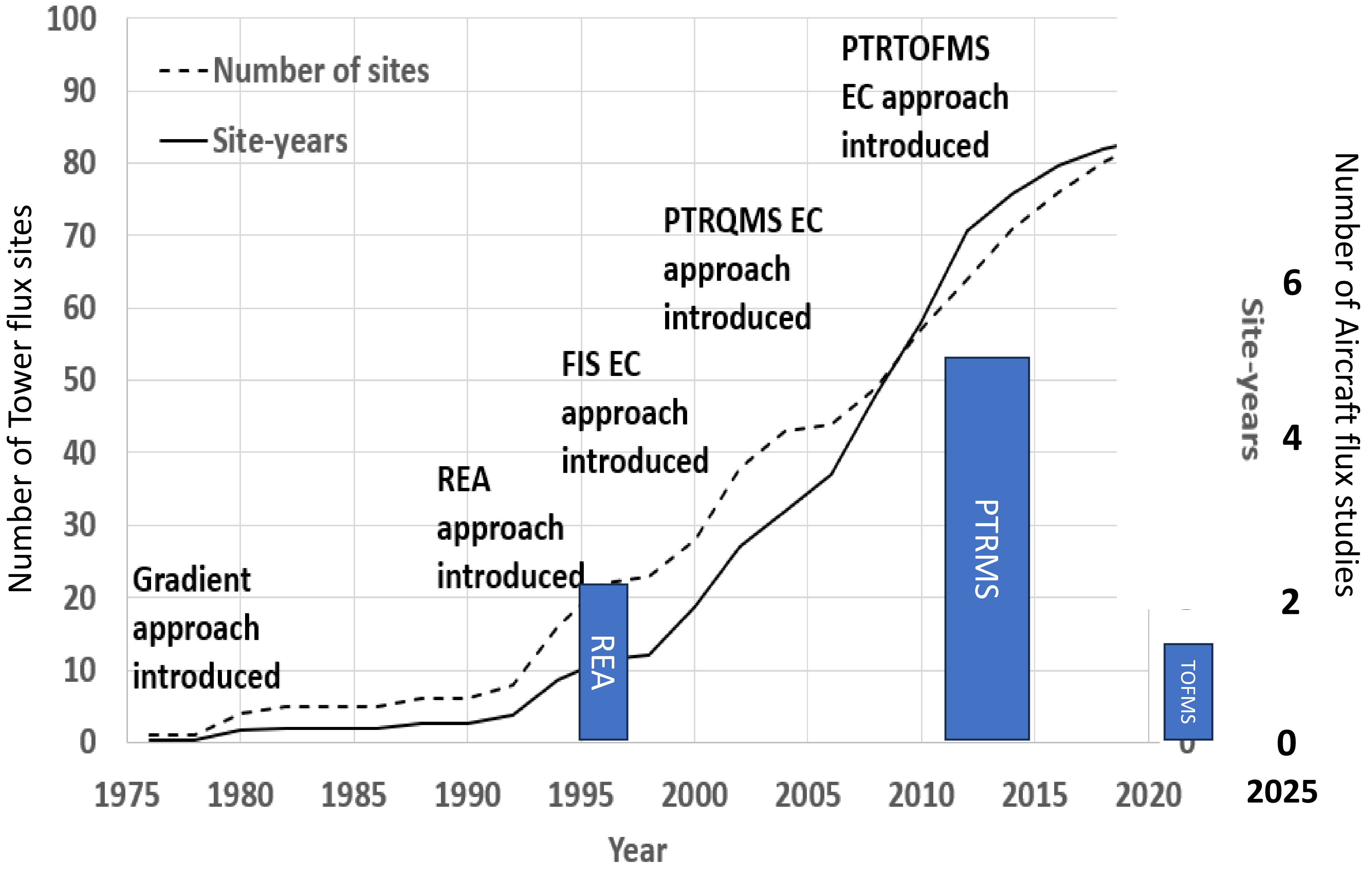
There have been only eight airborne BVOC flux studies:
5 N. America, 1 Africa, 1 Europe, 1 S. America
These 8 studies used 7 different aircraft.

Eddy covariance with PTRTOFMS can measure a wide range of biogenic and anthropogenic VOC fluxes



Los Angeles urban biogenic and anthropogenic VOC fluxes
Pfannerstill et al. 2023

Above-canopy BVOC eddy flux data: Tower and Aircraft
Each aircraft study covers an area larger than all tower measurements combined



Key Points

1. Reducing ozone below ~100 ppb can be challenging.
2. BVOC emissions from managed (urban, plantations) landscapes can be controlled
3. BVOC emission knowledge gaps (emission factors, assess/monitor) need to be addressed

Acknowledgements: This research was supported by NSF, NASA, DOE, EPA

BVOC sampling site: YRD 2009

Photo: A. Guenther