Impacts of tropospheric ozone on photosynthesis & stomatal conductance of trees: A meta-analysis

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APRIL 9, 2007
Living with Cancer
The changing science
Beyond Baghdad: Where The Enemy Has Its Own Surge
The Sopranos' Last Song: What Exit Will Tony Take?
TIME
SPECIAL DOUBLE ISSUE
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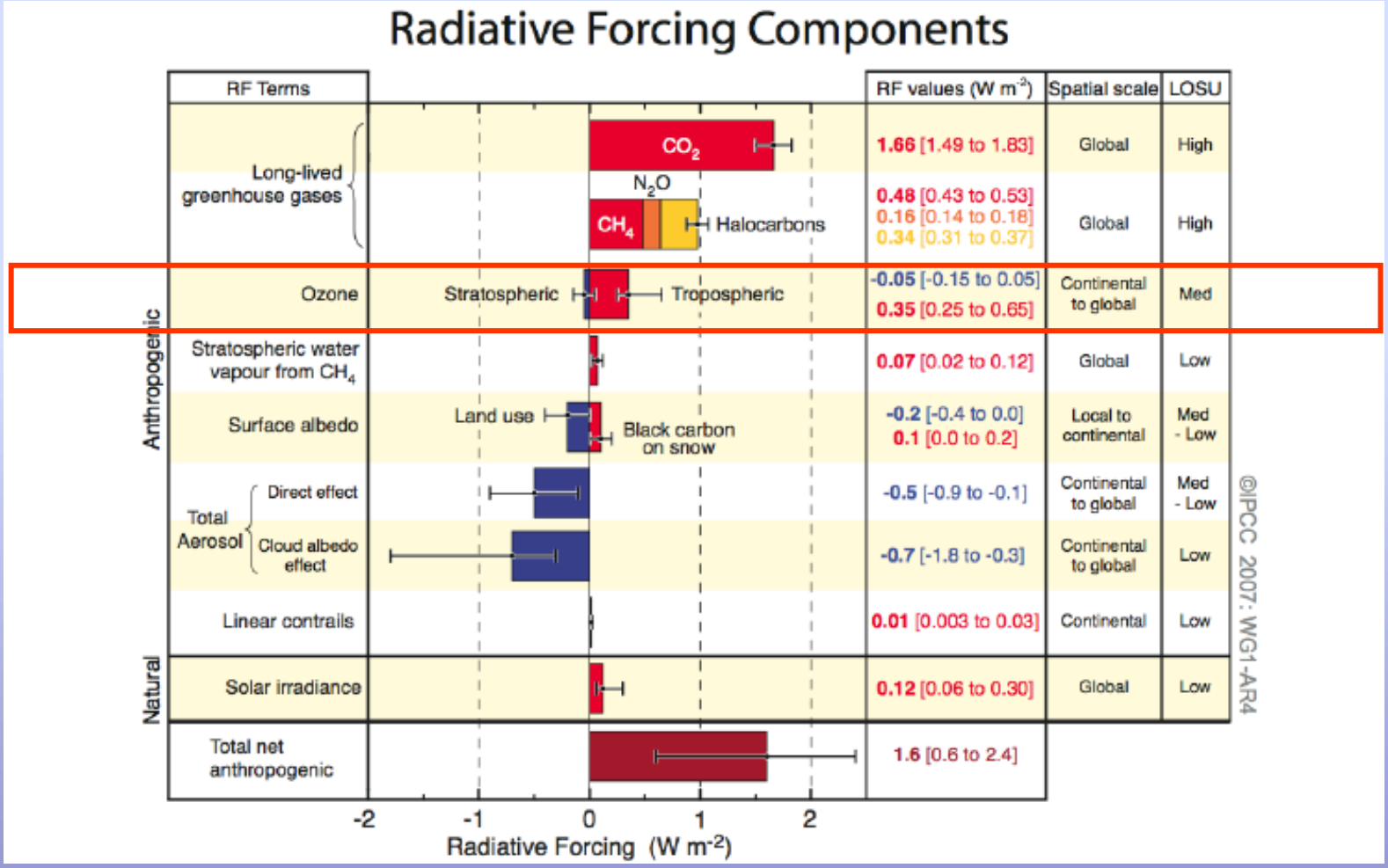
51 Things You Can Do to Make a Difference
www.time.com

Ozone is a Greenhouse Gas with the 3rd Largest Radiative Forcing

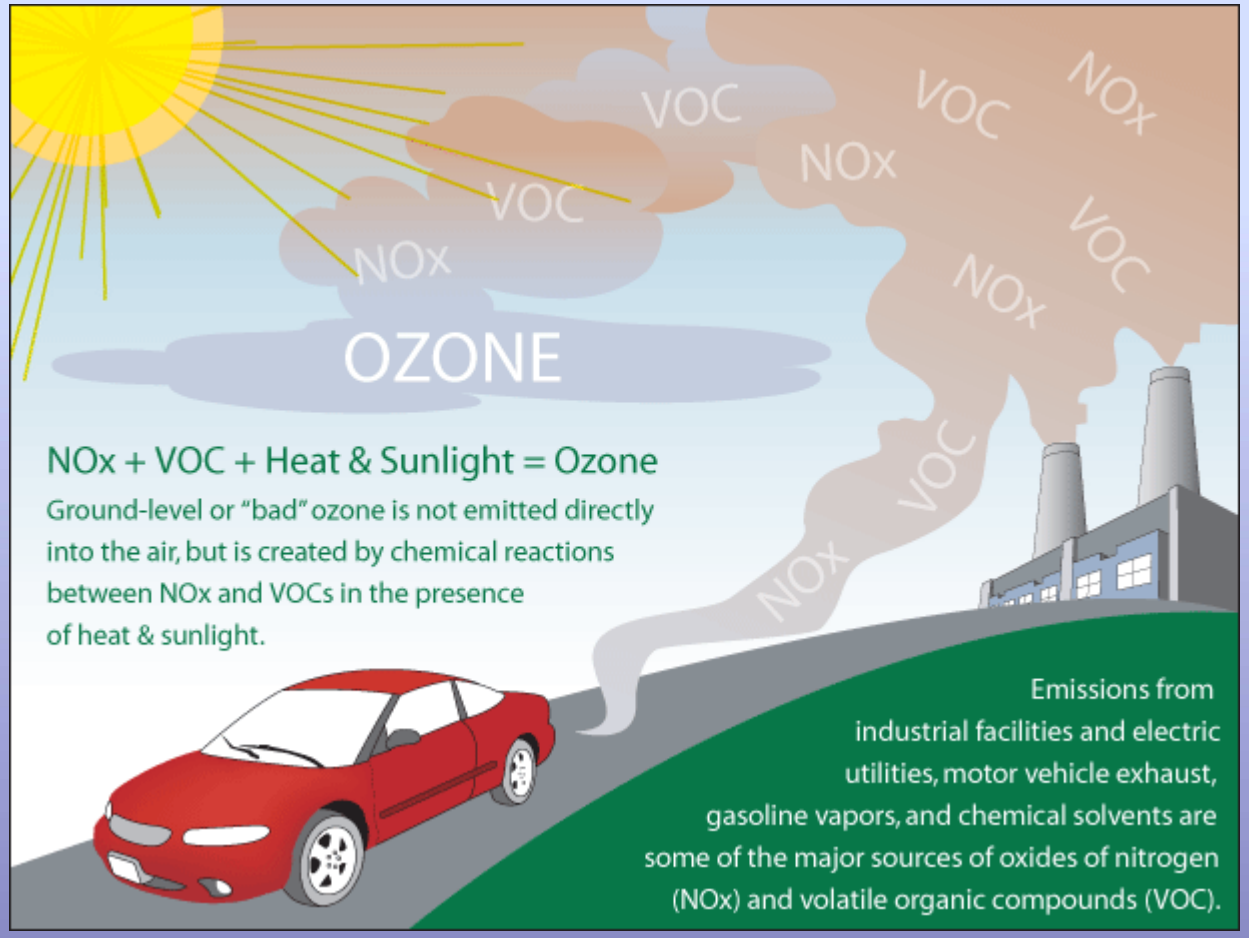


Intergovernmental Panel on Climate Change Assessment Report Four (IPCC AR4; 2007), *Summary for Policy Makers*. In:

Climate Change 2007: The Physical Science Basis

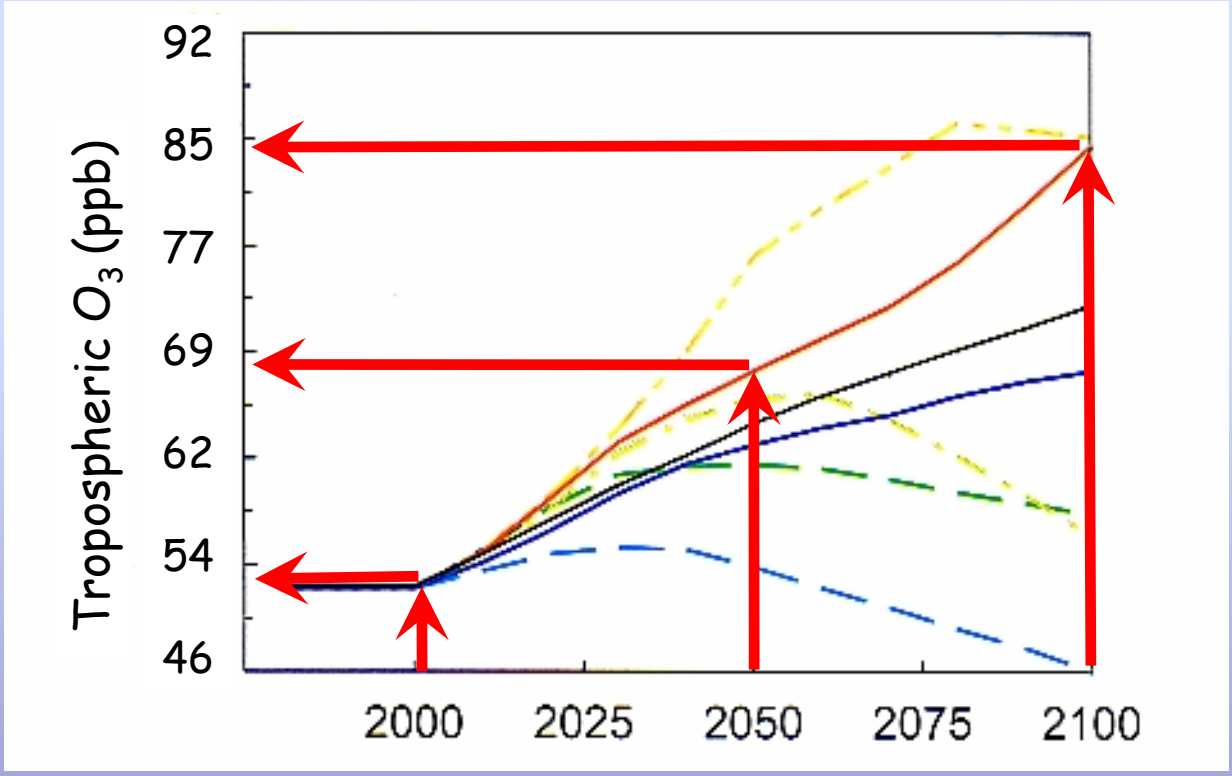
What is ozone?

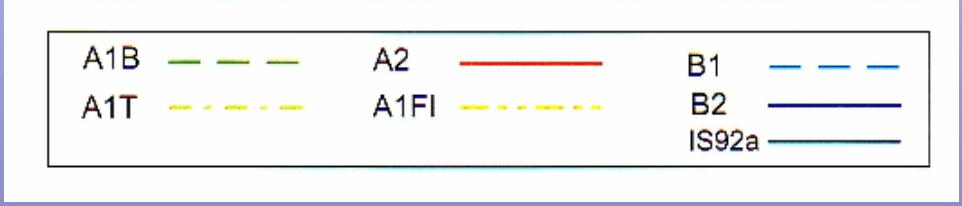
$$\text{Sunlight} + NO_x + \text{VOCs} \rightarrow O_3$$



www.epa.gov

Tropospheric O_3 Projections

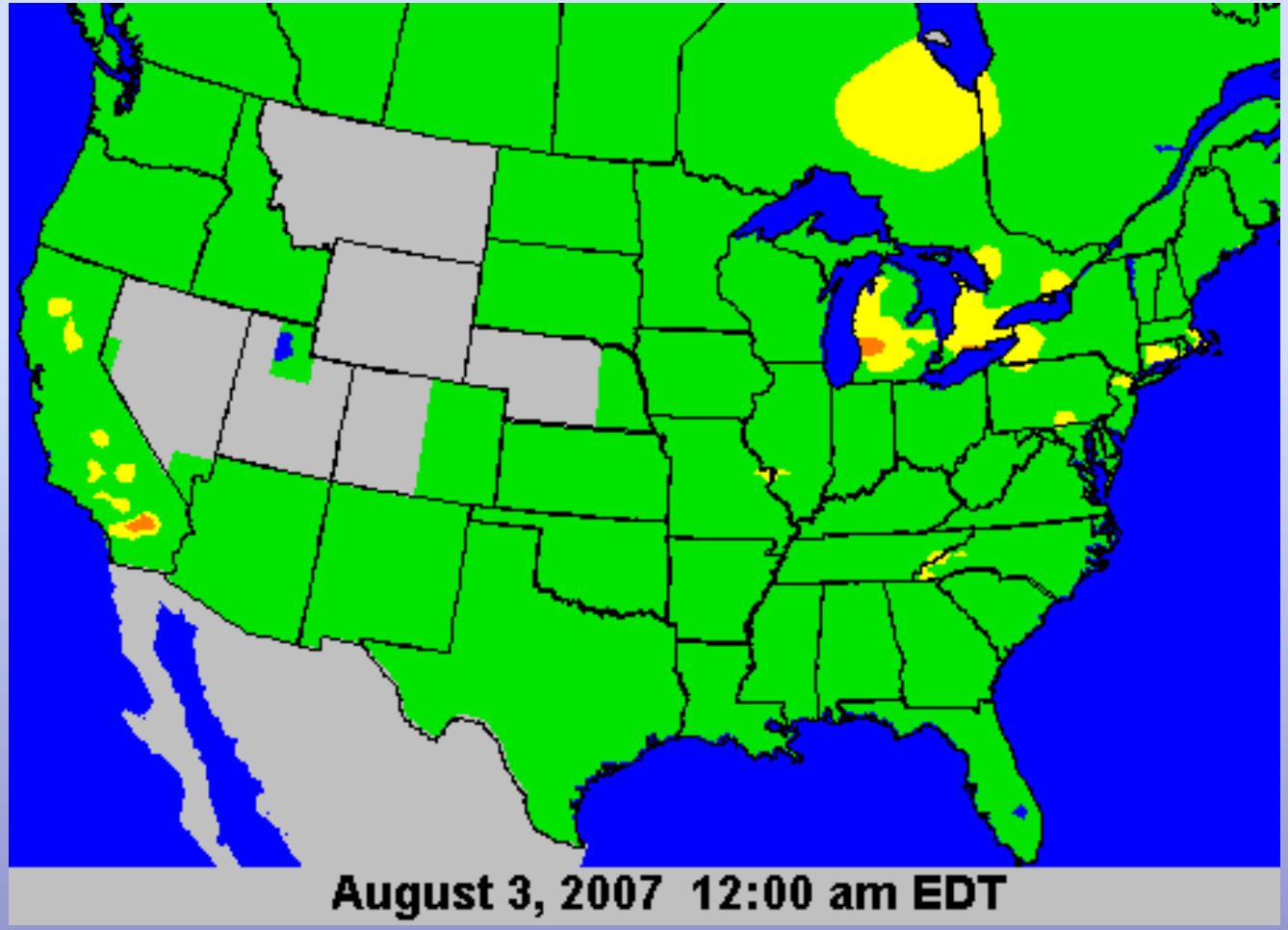




IPCC-TAR (2001), *Climate Change 2001: The Scientific Basis*

An Urban Problem?

Urban Myth-Busted: Not just a problem of big cities!

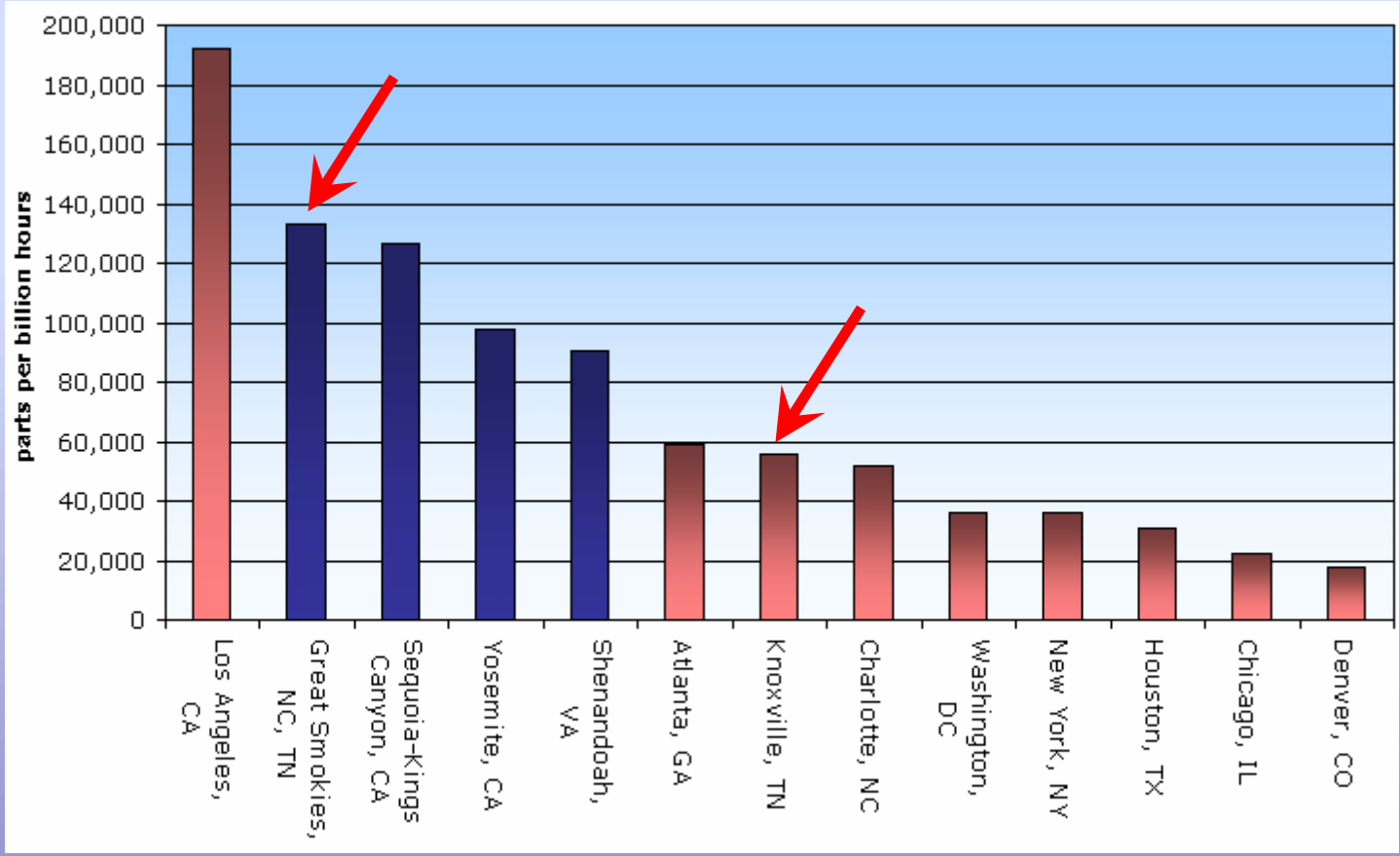


Ozone Concentration

- 0-40 ppb
- 41-80 ppb
- 81-120 ppb
- 121-160 ppb
- 161-240 ppb
- No data

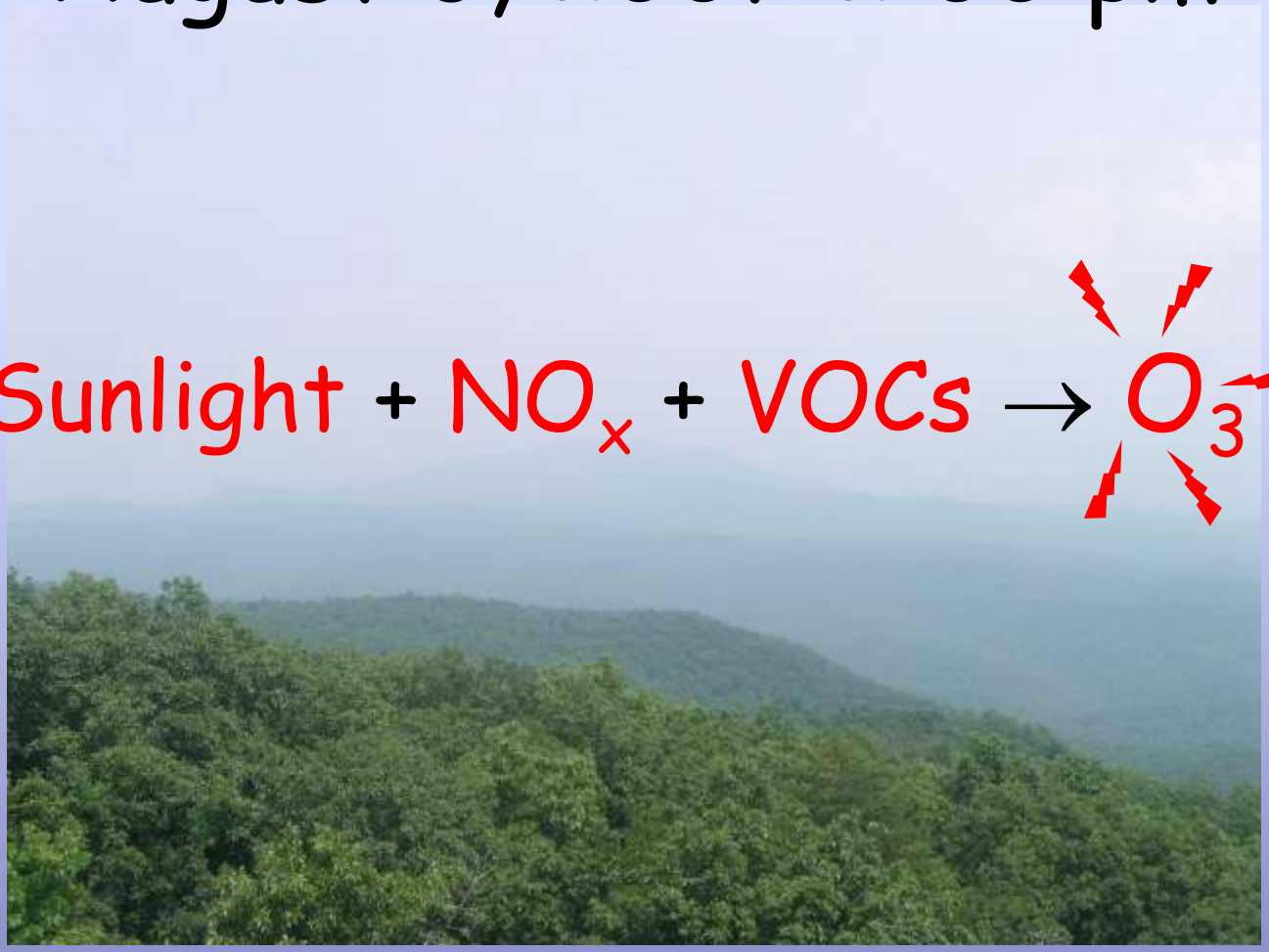
http://www.airnow.gov

Ozone doses between 1991-2001 in major cities and four major national parks



National Park Conservation Association: www.npca.org

Look Rock, Great Smoky Mountain National Park
August 3, 2007 2:00 pm

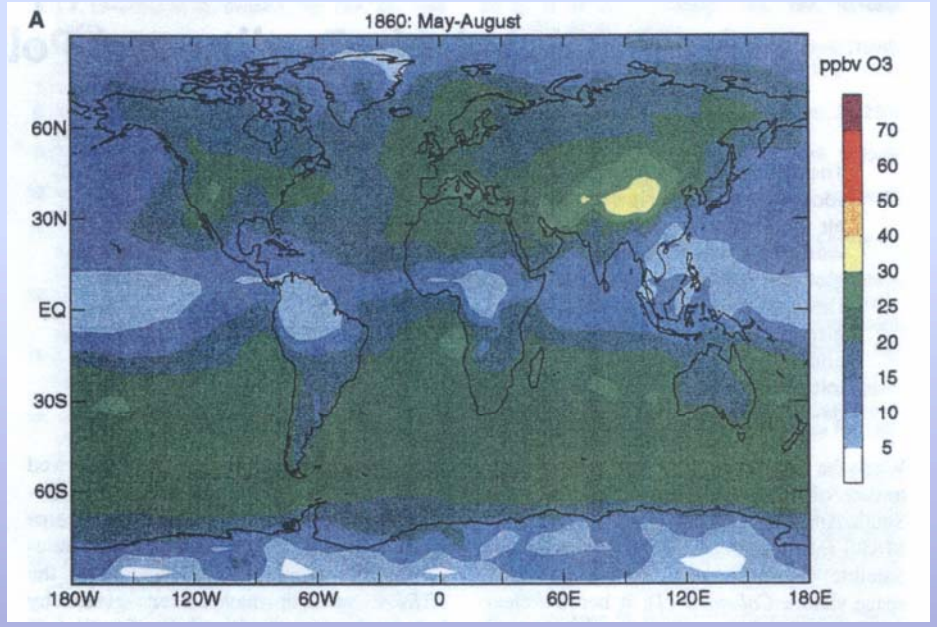


$$\text{Sunlight} + NO_x + \text{VOCs} \rightarrow O_3$$

http://www2.nature.nps.gov/air/webcams/parks/grsmcam/grsmcam.cfm

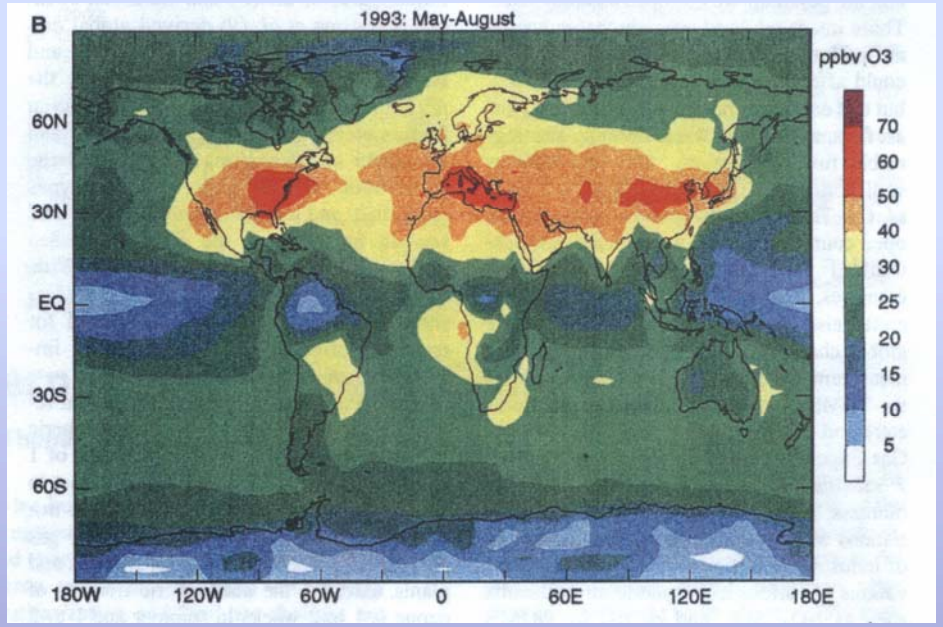
Pre-industrial & Recent Background [O_3]

1880s



15-25 ppb

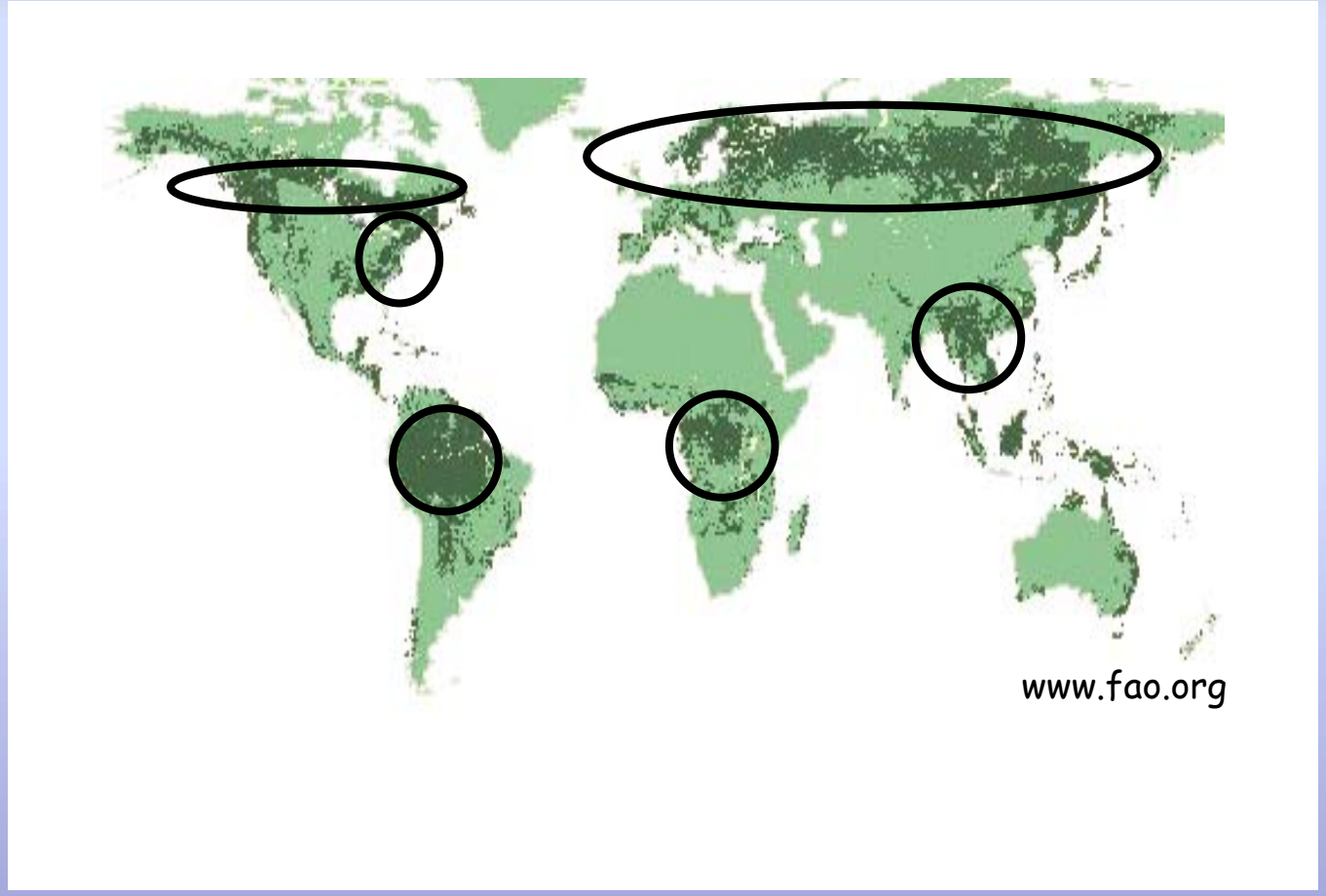
1993



40-50 ppb

Akimoto (2003) *Science*. 302: 1716-1719

Projected Ozone Concentration

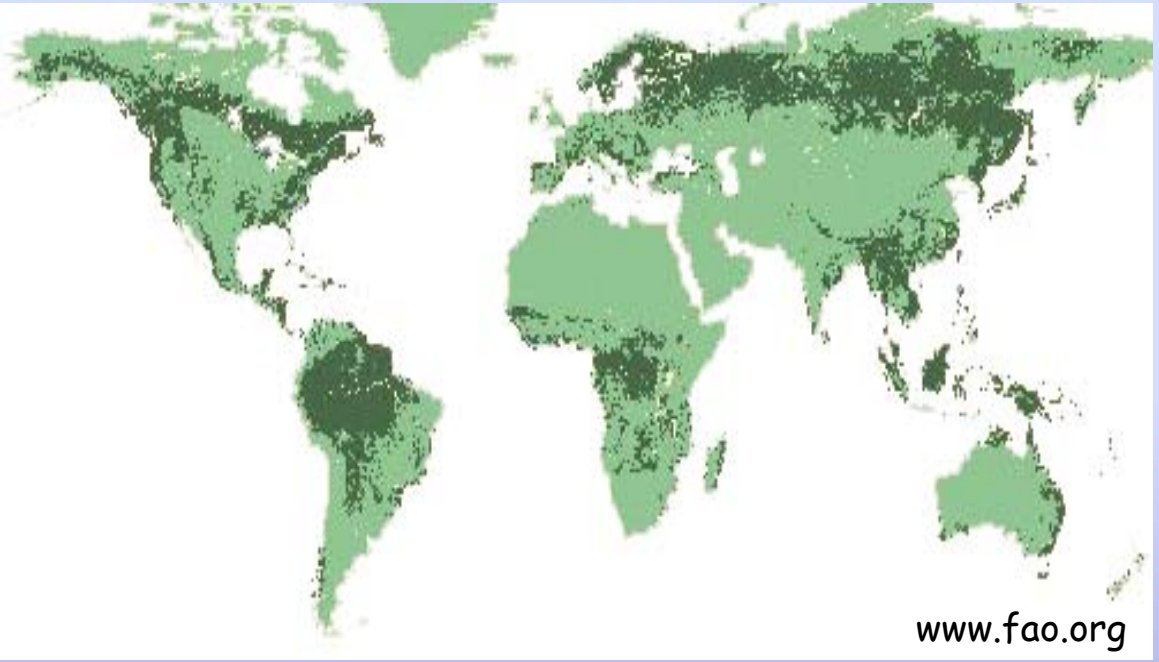


Global Forest Distribution

0 15 30 45 60

Increase in Tropospheric Ozone (ppb) for 2000-2100

30% Global Land Area



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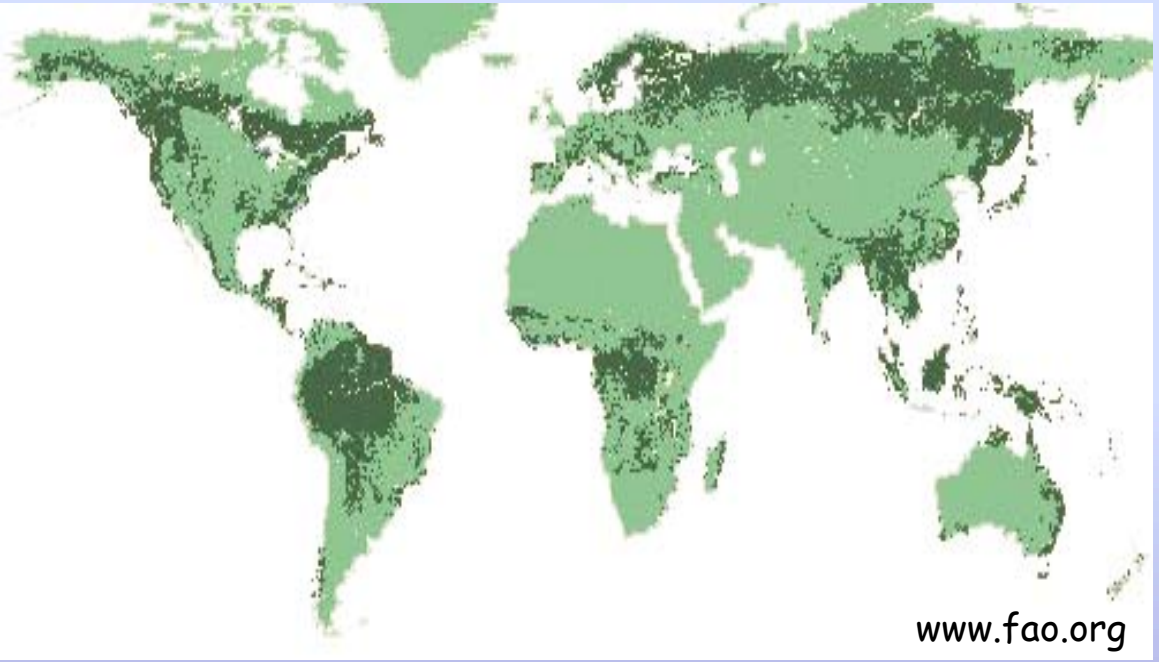
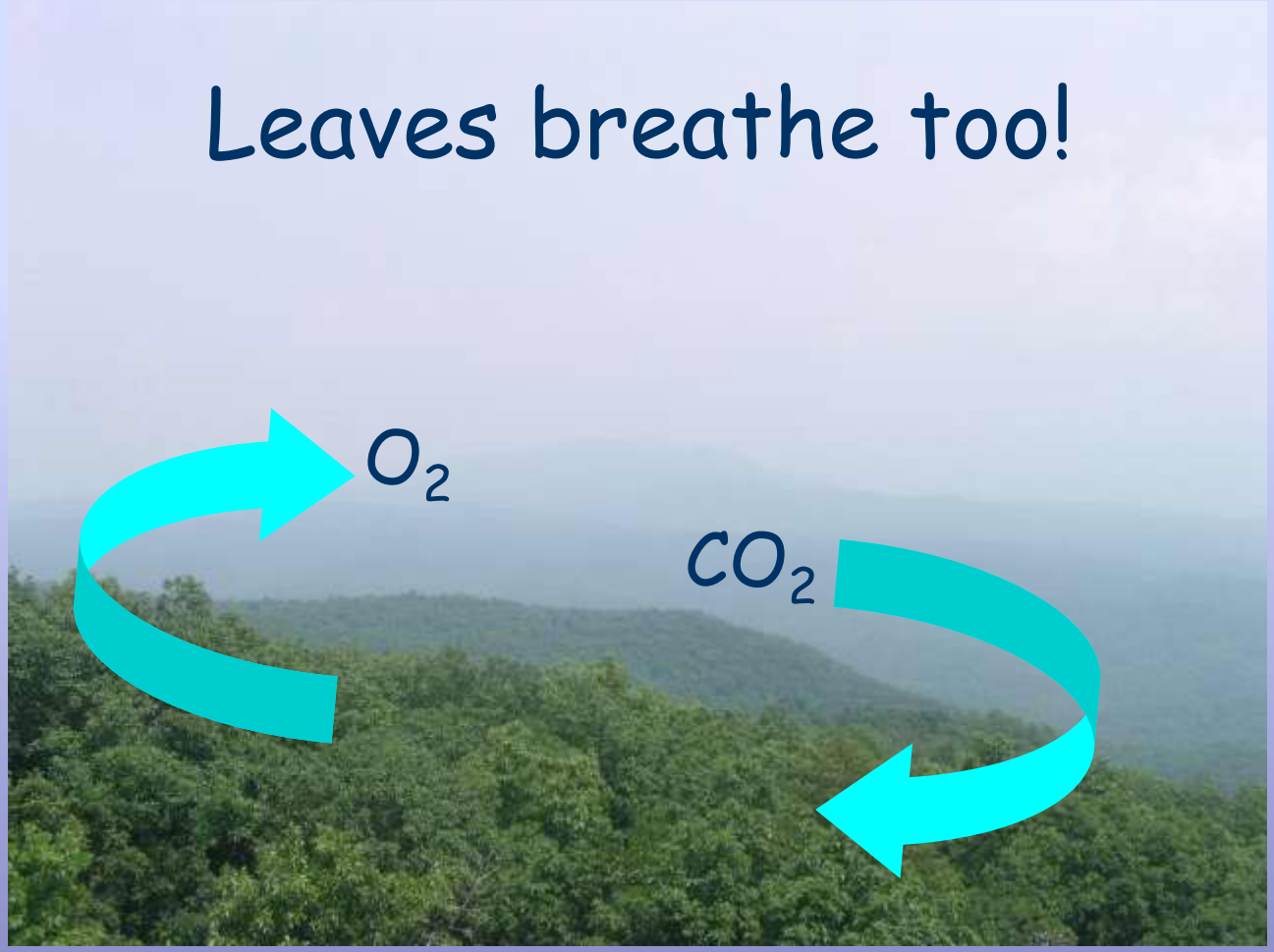


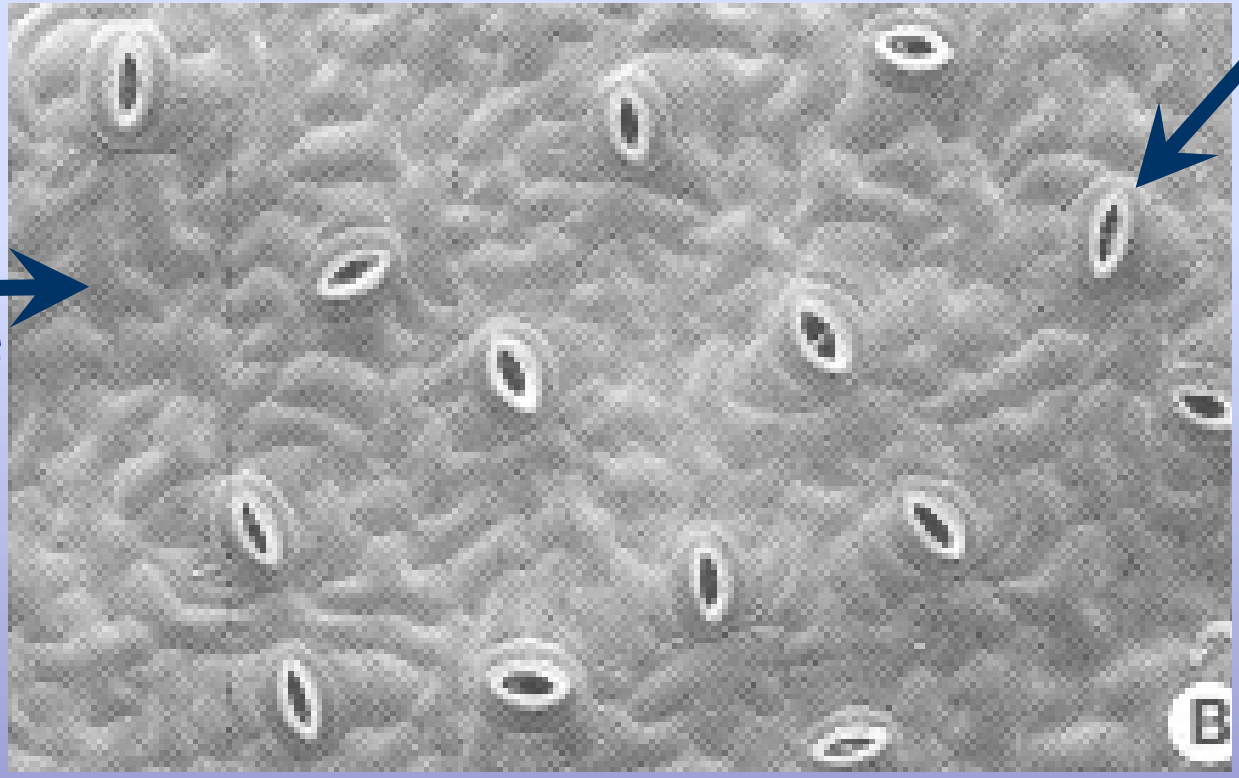
70% Terrestrial Net Photosynthesis

How does ozone impact plants?



http://www2.nature.nps.gov/air/webcams/parks/grsmcam/grsmcam.cfm

How? Through stomata: pores on the leaf surface (epidermis)

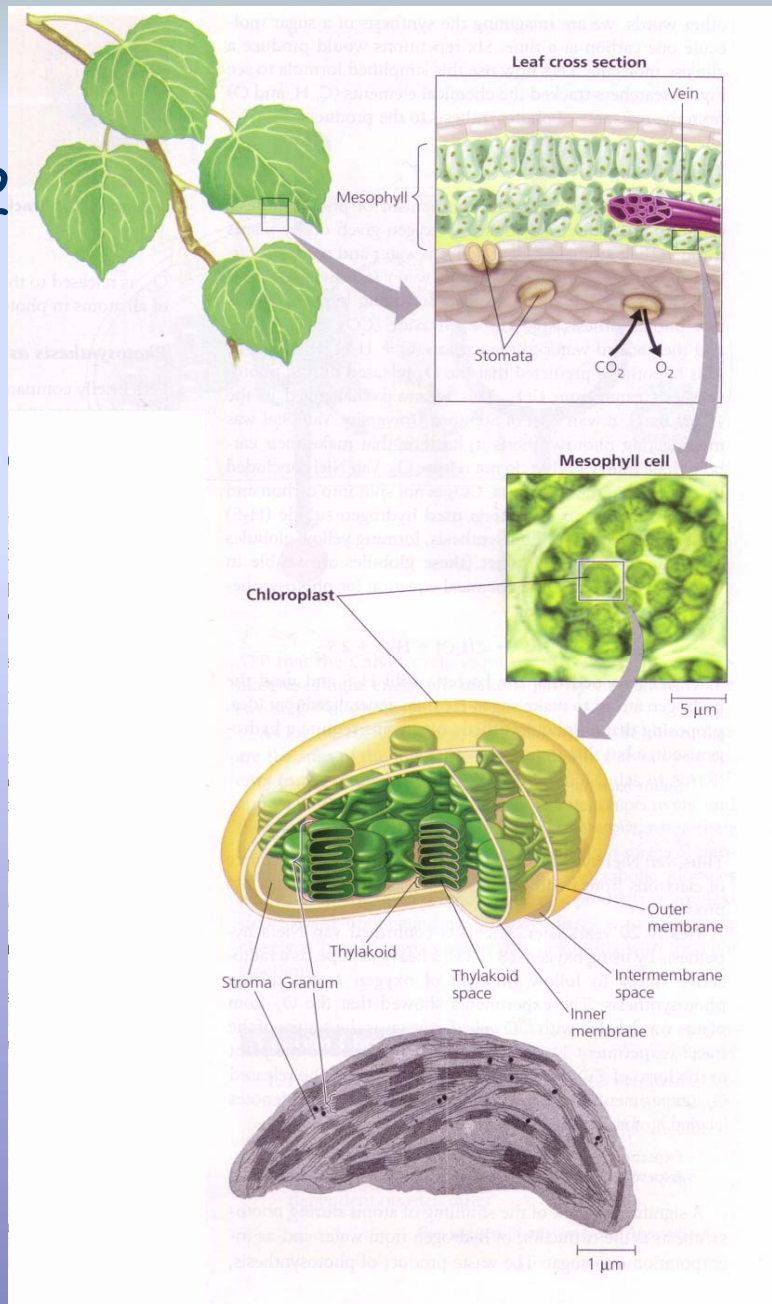


Matyssek et al. (1995) *Tree Physiology*. 15: 159-165

Photosynthesis

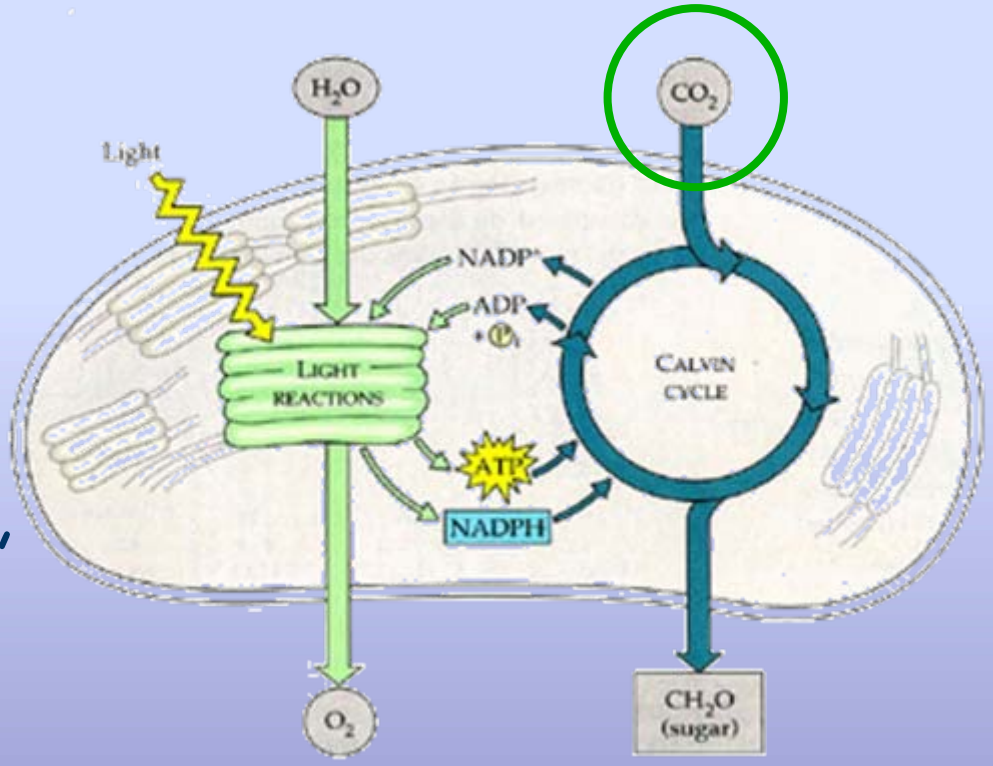
$$CO_2 + H_2O \rightarrow [CH_2O] + O_2$$

- Mesophyll cells packed with chloroplasts
- Chloroplasts packed with chlorophyll, a pigment that absorbs light



Photosynthesis: CO_2 entryway into biosphere

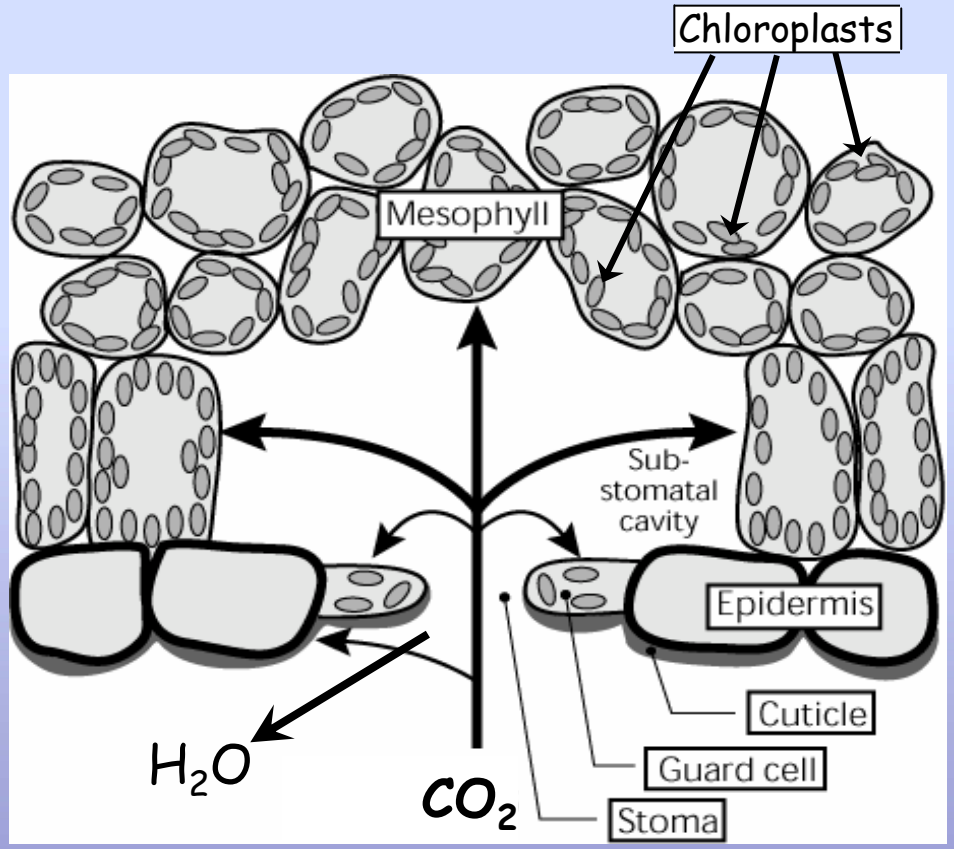
- Energy from light used to drive Calvin Cycle
- CO_2 binds to Rubisco, enters Calvin cycle and leaves as sugar!



Chloroplast

Stomatal Conductance

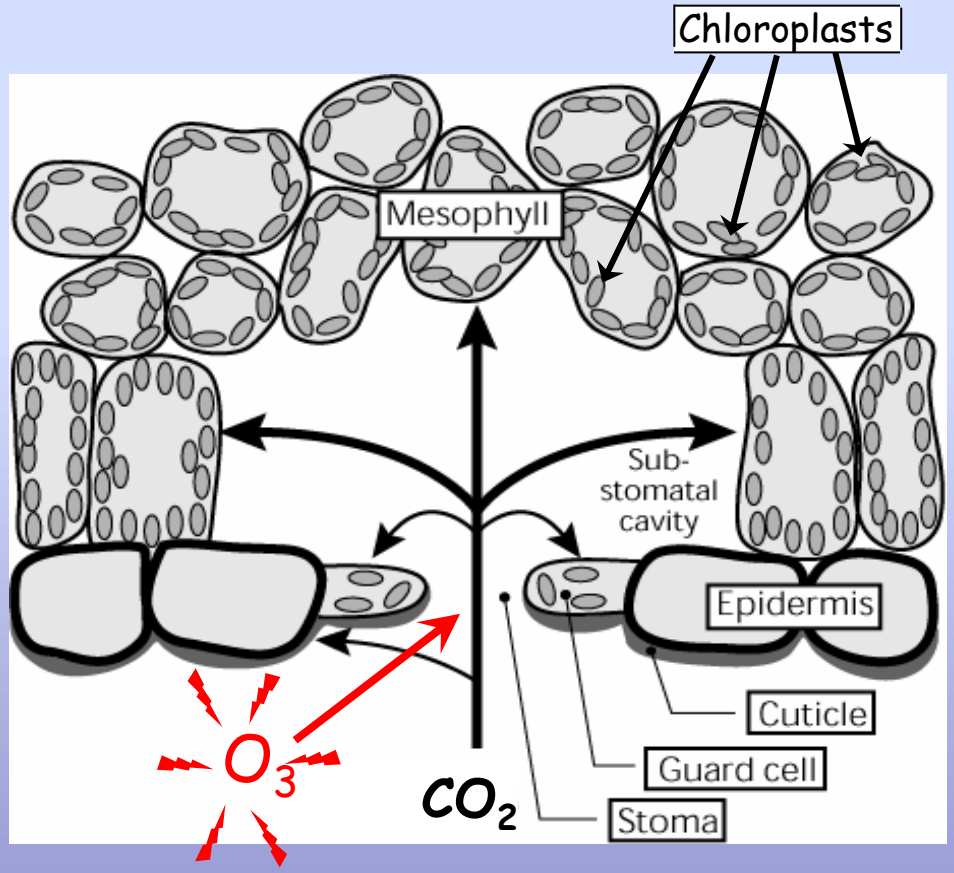
- The amount of gas that can pass through the stomatal pore over time
- CO_2, H_2O, ...



Adapted from Long, S.P. and S.L. Naidu (2002), In: Air Pollution and Plant Life

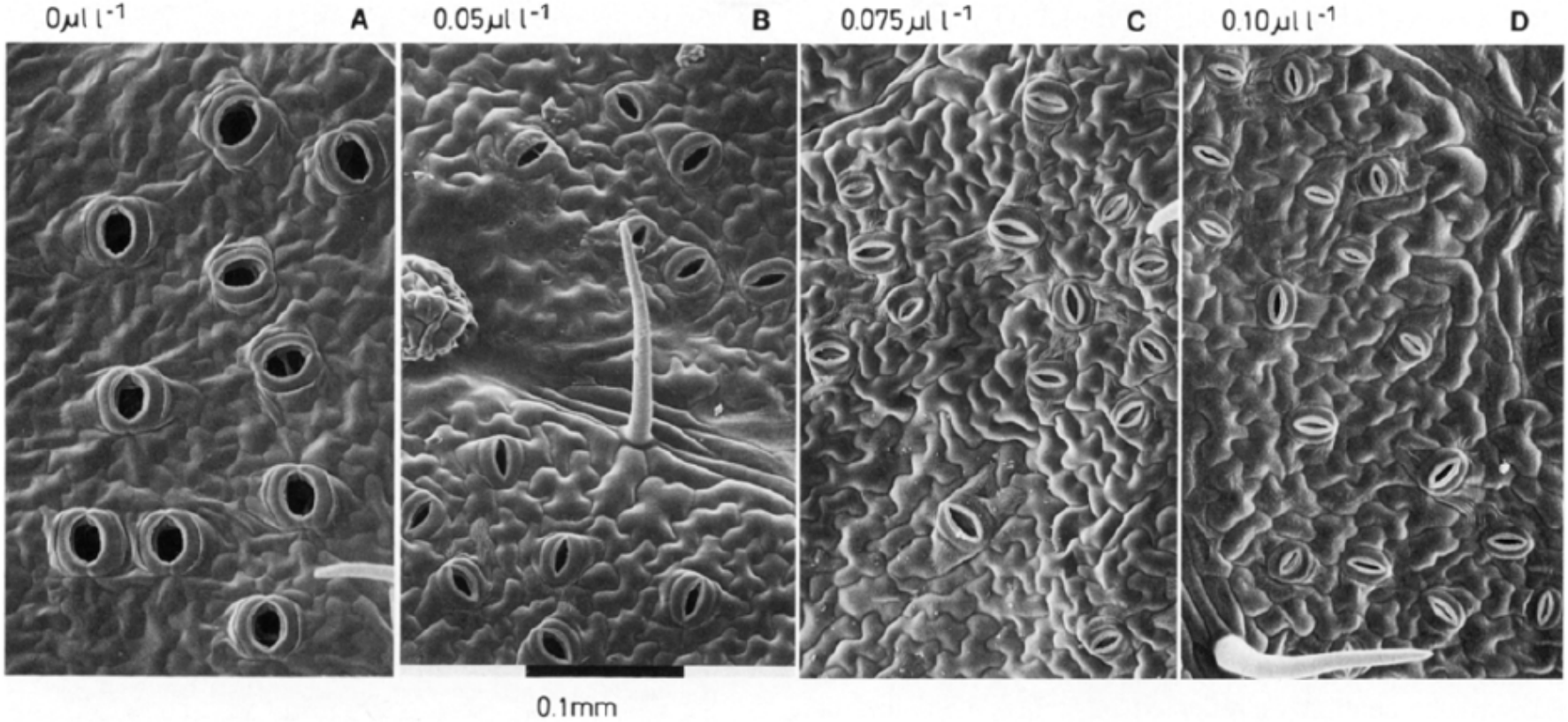
Ozone must gain entry inside the leaf before damage can occur

- Readily reacts with aqueous surfaces
  - forms Reactive Oxygen Species (ROS)
- Up-regulation of defenses
  - anti-oxidants to detoxify
- Reduction in photosynthesis
  - Reduction in Rubisco activity/content



Adapted from Long, S.P. and S.L. Naidu (2002), In: Air Pollution and Plant Life

Ozone reduces stomatal conductance

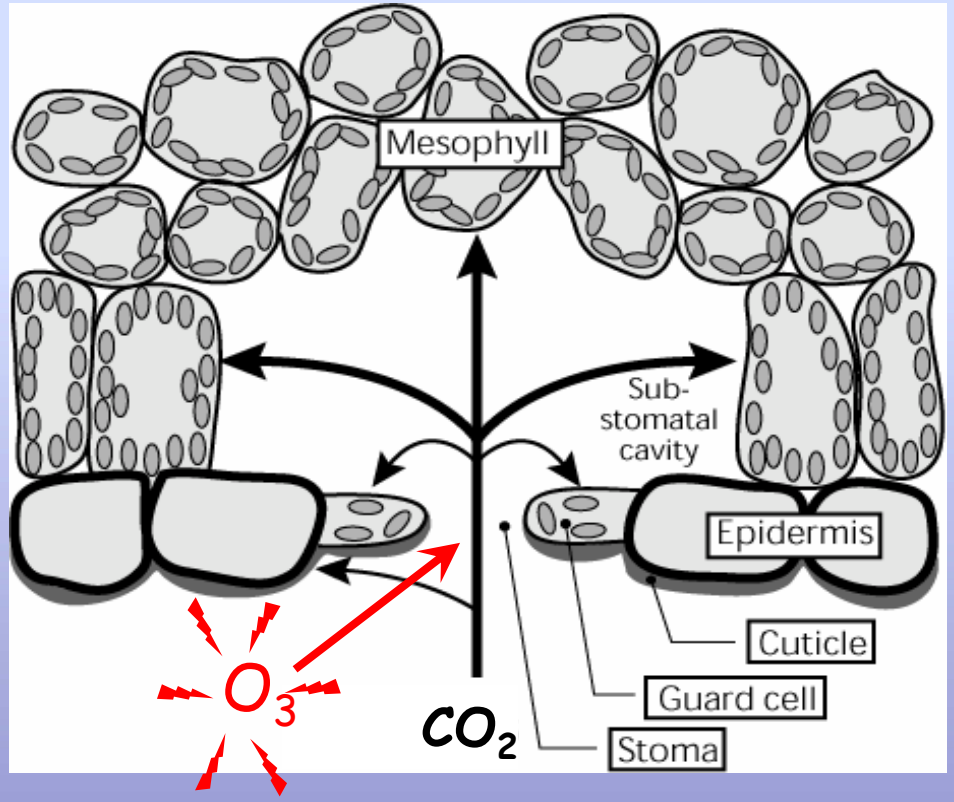


Increasing $[O_3]$

Matyssek et al. (1991) *Trees.* 5: 5-13

To cause damage, O_3 must gain entry…

- Any environmental condition that reduces stomatal conductance should reduce O_3 damage
  - Drought
  - Elevated CO_2



Adapted from Long, S.P. and S.L. Naidu (2002), In: *Air Pollution and Plant Life*

Ozone only harms plants when taken up through open stomata

Can we quantify impacts of ozone on the rate of photosynthetic CO_2 uptake?

Can we quantify the impact of ozone on the rate stomatal conductance ?

Photo Courtesy of Mihai Aldea

Has the impact been recorded in the literature?

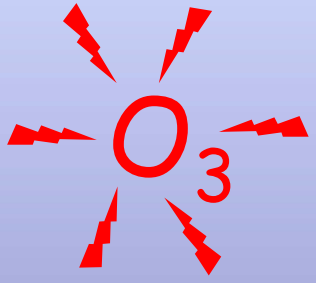
Has the impact been observed? Literature Survey

- Hundreds of observations of the impact of ozone on light-saturated photosynthesis (Asat) and stomatal conductance (gs)
- Impact relative to pre-industrial, current and potential future ozone concentrations
- No quantitative consensus in reviews
- High variability between primary experiments

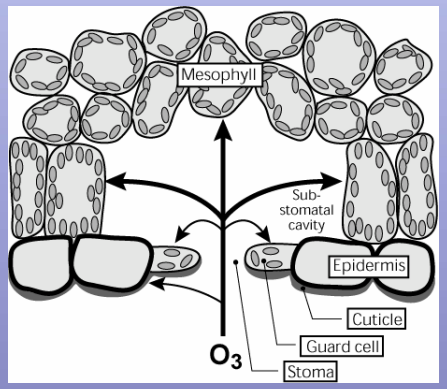
Why so much variability?

- Angiosperm vs. gymnosperm

- Genus
  - Pinus, Picea, etc.
  - Quercus, Betula, etc.



- $[O_3]$



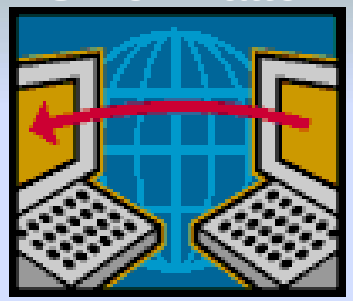
- Additional treatment
  - Drought
  - Elevated CO_2

With hundreds of available observations, can the impact be quantified?

Meta-analysis

- Quantitative summary of primary research
- Statistically determines a mean relative response from different experiments investigating the effect of the same treatment
- Increasingly used in environmental and ecological sciences
  - Wittig et al. (2007) *Plant, Cell & Environment*
  - Ainsworth & Long (2005) *New Phytologist*

Web of Science
Silver Platter



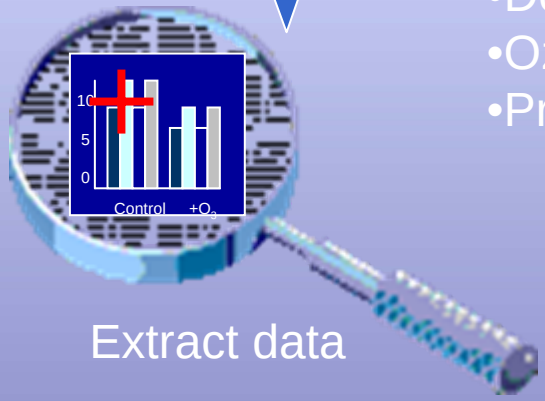
Search:
Ozone, trees
production,

1867 ™

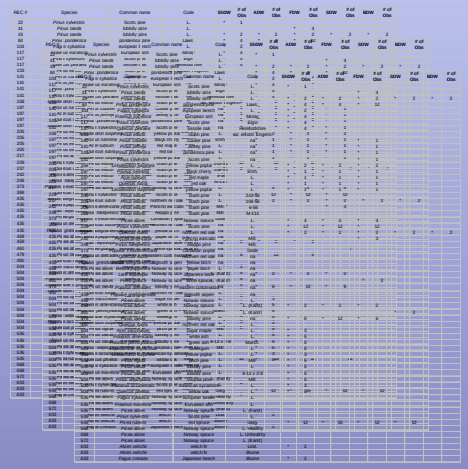
Collect articles from
Univ. Illinois Library

Filter studies for
adequate detail of
- Replication
- Design
- Ozone concentration
- Production data

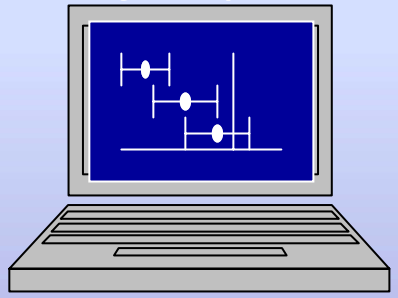
Extract data



Database



Summarize statistical meta-
analysis (MetaWin™)



Statistical Tool: Meta-analysis

- Observation of mean effect:

  $\overline{X}_T$ = Mean effect in Treatment [O_3]

  $\overline{X}_C$ = Mean effect in Control [O_3]

- Estimate mean treatment Effect Size (E)

$$E = \ln r = \ln\left(\frac{\overline{X}_T}{\overline{X}_C}\right)$$

- % Change From Control = $[(r-1)\cdot 100]$

Meta-analysis: Three point perspective

- How bad have things gotten since pre-industrial times?
  - Current [O_3] / Pre-industrial [O_3]
- How bad might things get under elevated concentrations projected for later this century relative to pre-industrial times
  - Future [O_3] / Pre-industrial [O_3]
- How bad will things get tomorrow relative to today?
  - Future [O_3] / Current [O_3]

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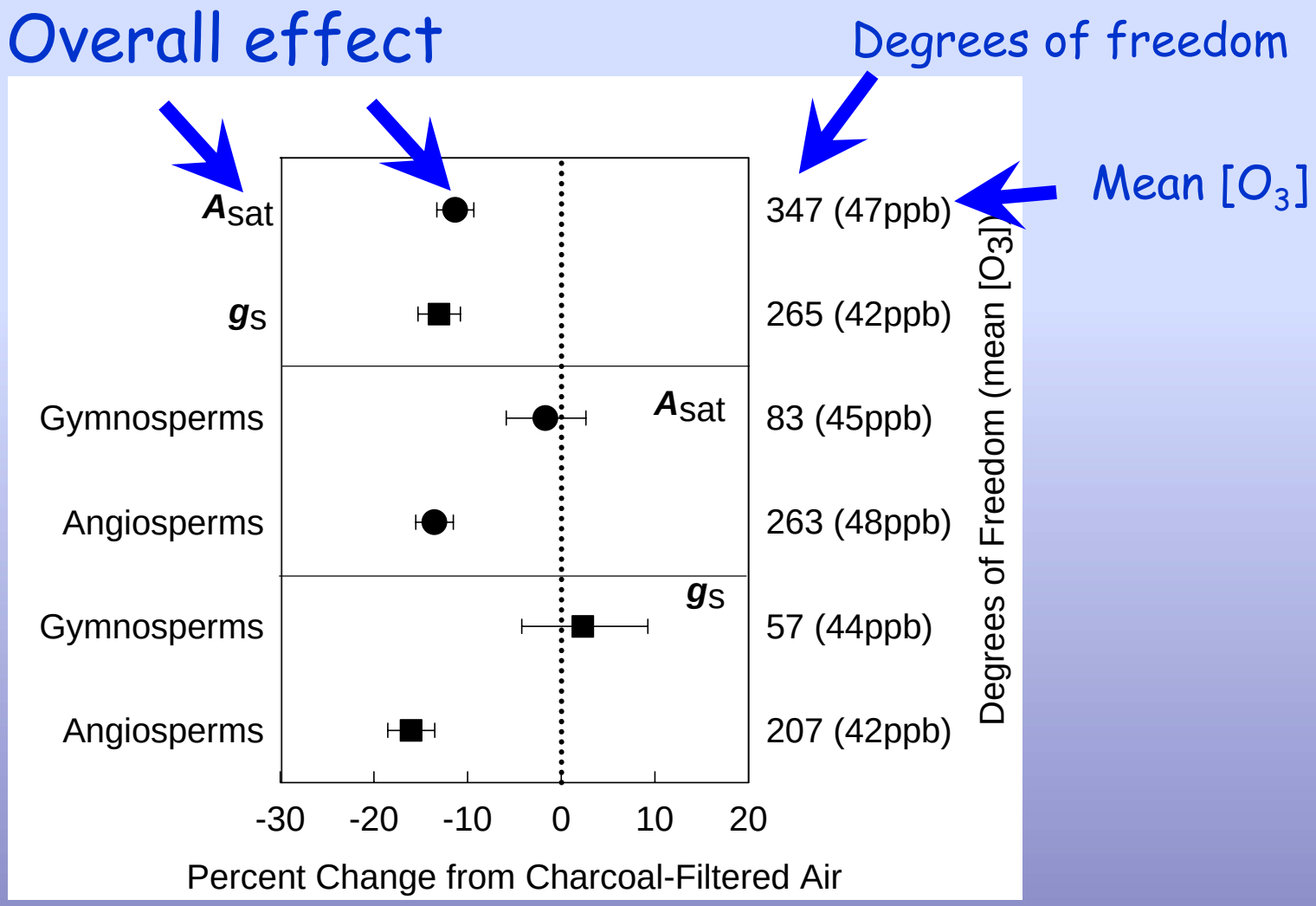
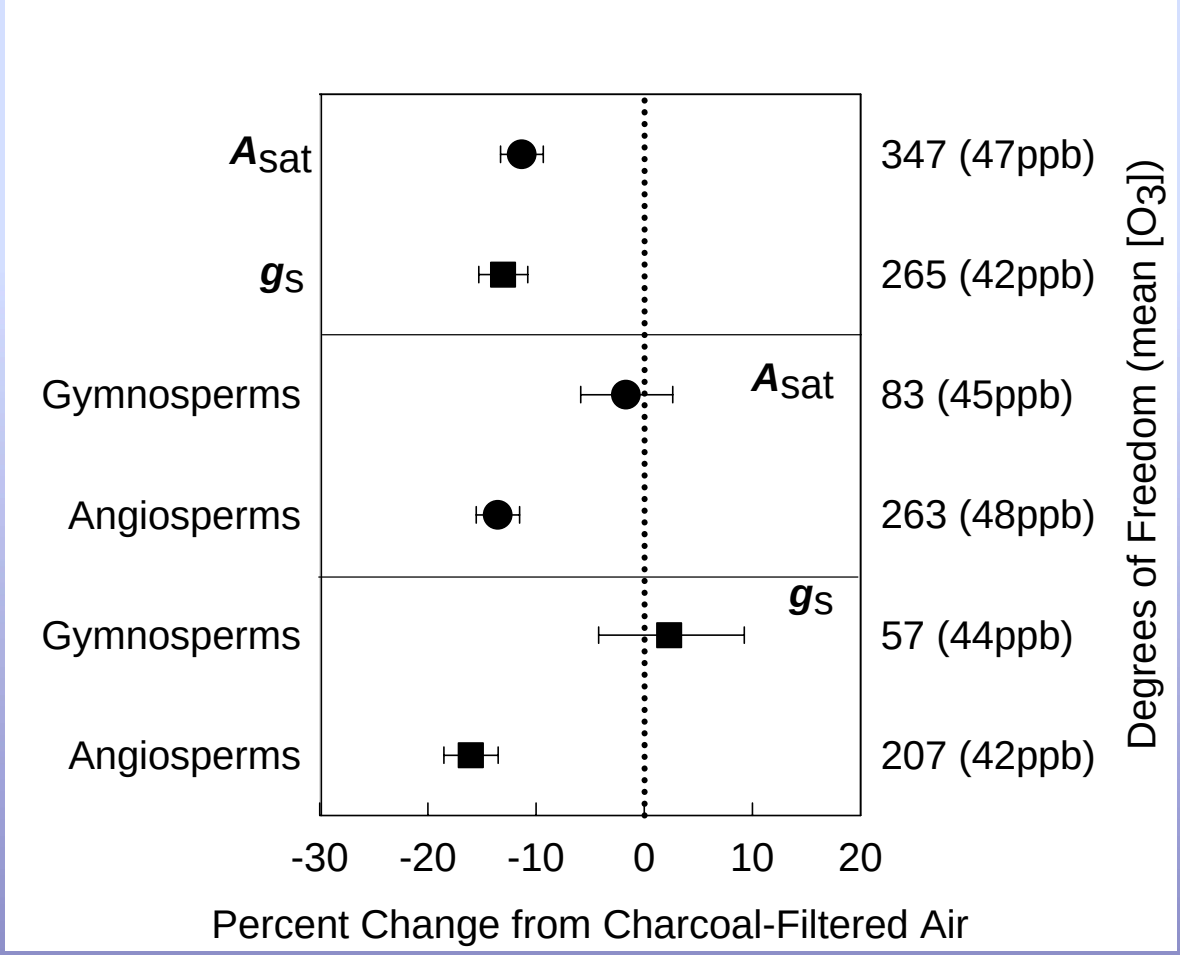
Current [O_3] /Pre-industrial [O_3]

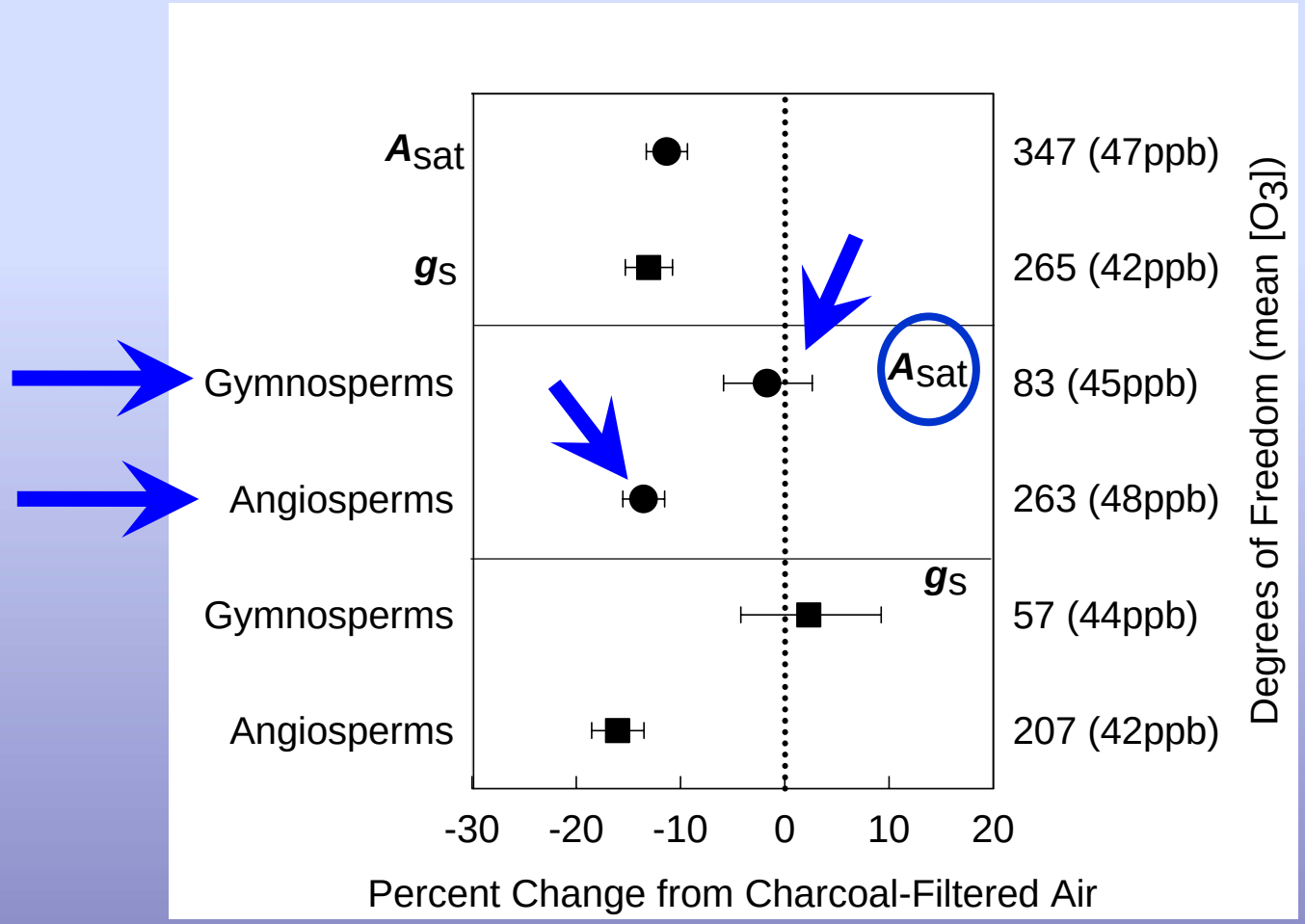


Current [O_3] /Pre-industrial [O_3]



Current [O_3] /Pre-industrial [O_3]

Effect on different groups: Gymnosperms vs. Angiosperms



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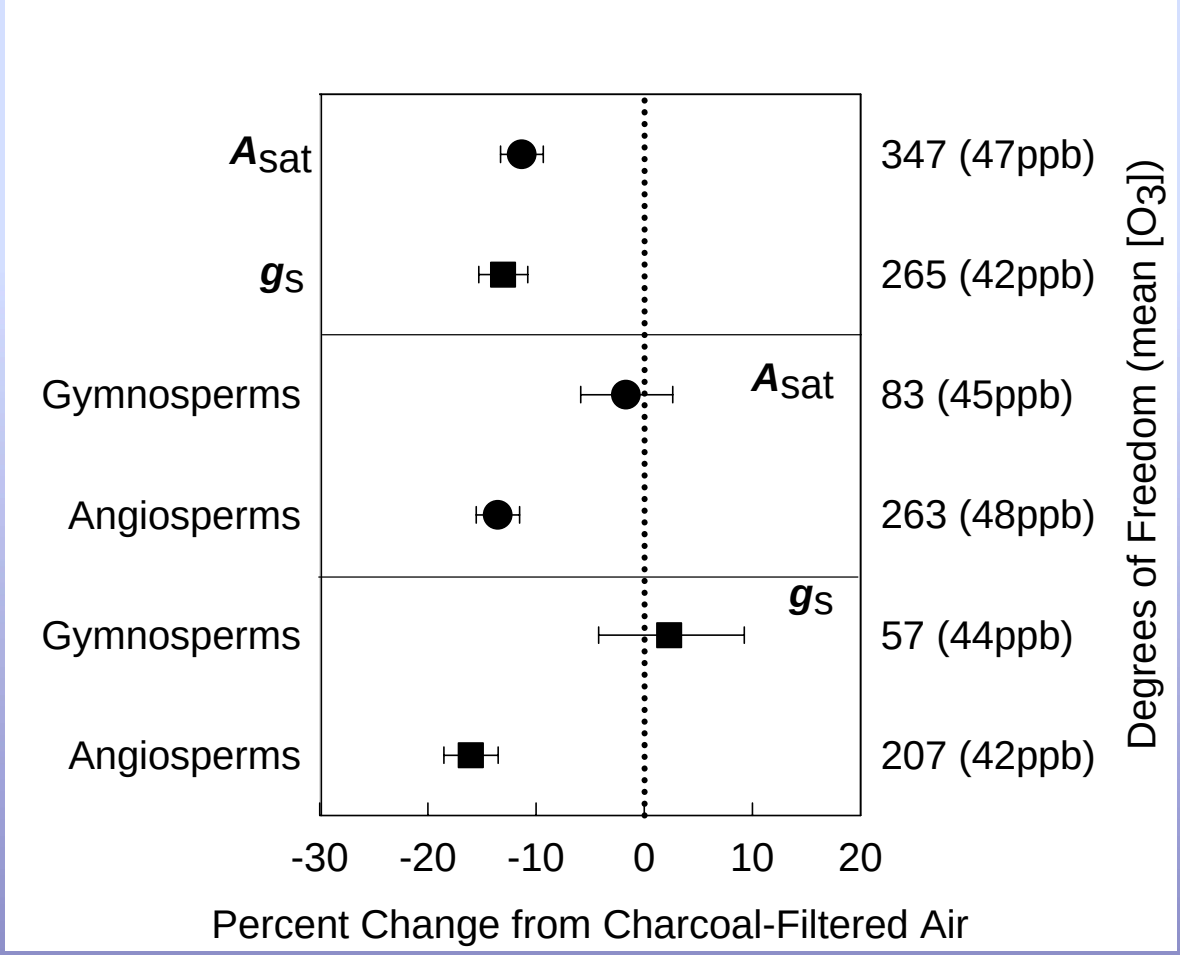

Current [O_3] / Pre-industrial [O_3]

Effect on Angiosperms

	A_{sat}		g_s	
Category	Q_B	p	Q_B	p
Genus	**136.91**	**<.001**	**112.93**	**<.001**
Additional treatment	**66.72**	**<.001**	**41.04**	**<.001**

Current $[O_3]$ /Pre-industrial $[O_3]$

Genus	A_{sat} % Change	A_{sat} 95% CI	A_{sat} df	A_{sat} $[O_3]$	g_s % Change	g_s 95% CI	g_s df	g_s $[O_3]$
Overall Effect	-11	-13 to -9	347	47	-13	-15 to -11	265	42
Gymnosperms	-2	-6 to 3	83	45	2	-4 to 9	57	44
Picea	4	-4 to 12	23	33	12	2 to 24	23	39
Pinus	-3	-7 to 2	58	49	-6	-14 to 3	33	48
Angiosperms	-14	-16 to -12	263	48	-16	-18 to -13	207	42
Fagus	-5	-11 to 2	14	33	-16	-27 to -3	8	36
Fraxinus	-17	-22 to -12	38	42	-9	-16 to -2	35	42
Populus	-24	-28 to -21	60	57	-27	-31 to -22	36	41
Prunus	-5	-9 to -1	59	54	-12	-19 to -4	19	44
Quercus	0	-8 to 9	22	42	-1	-5 to 6	36	43
Viburnum	-20	-23 to -15	36	41	-27	-32 to -22	36	41

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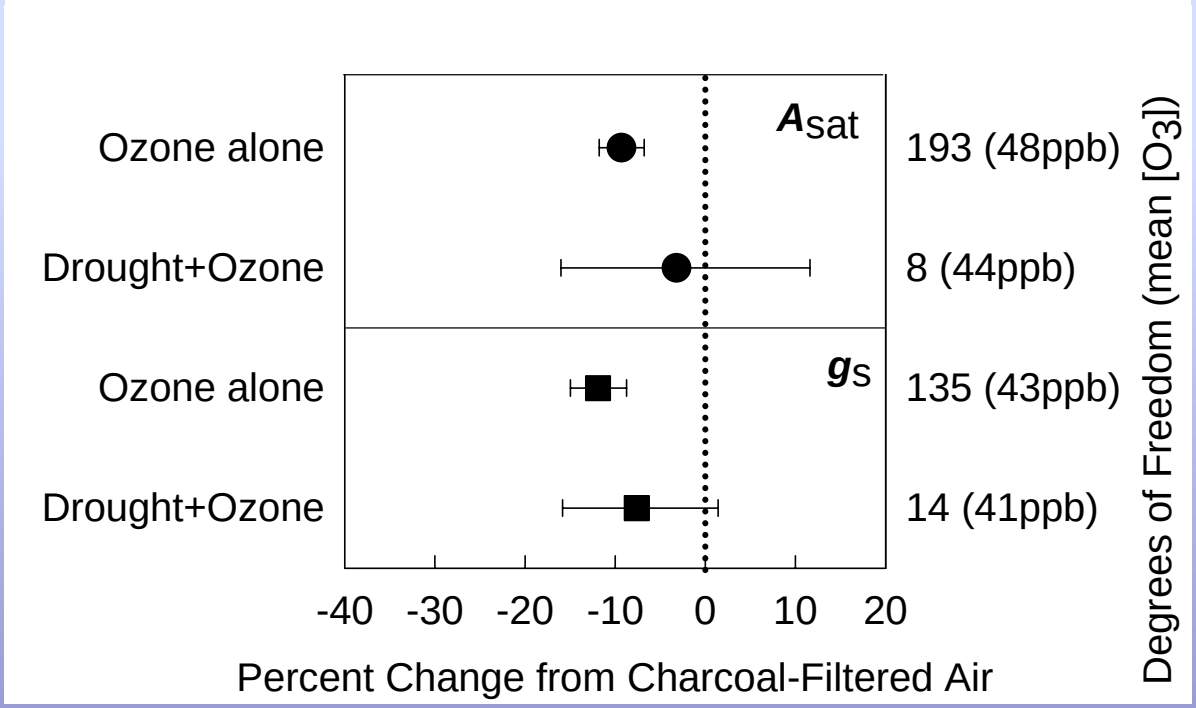
Populus	-24	-28 to -21	60	57	-27	-31 to -22	36	41
Prunus	-5	-9 to -1	59	54	-12	-19 to -4	19	44
Quercus	0	-8 to 9	22	42	-1	-5 to 6	36	43
Viburnum	-20	-23 to -15	36	41	-27	-32 to -22	36	41

Current [O_3] /Pre-industrial [O_3]

Effect of Drought + Ozone on Angiosperms



Current [O_3] / Pre-industrial [O_3]

- Photosynthesis and stomatal conductance are reduced by current ambient ozone
  - Negative impact on angiosperm Asat and gs
  - No effect on gymnosperm Asat or gs
  - Genus differ in response
  - Drought may cancel the impact

Meta-analysis: Three point perspective

- How bad have things gotten since pre-industrial times?
  - Current [O_3] / Pre-industrial [O_3]
- How bad might things get under elevated concentrations projected for later this century relative to pre-industrial times
  - Future [O_3] / Pre-industrial [O_3]
- How bad will things get tomorrow relative to today?
  - Future [O_3] / Current [O_3]

Future [O_3] / Pre-industrial [O_3]

	A_{sat}		g_s	
Category	Q_B	p	Q_B	p
Angiosperms vs. Gymnosperms	0.88	0.387	2.52	0.157
Genus	**26.77**	**0.041**	**38.53**	**0.006**
Increasing [O_3]	**24.17**	**0.001**	**13.21**	**0.018**
Additional treatment	**26.40**	**0.002**	**17.07**	**0.012**

Future $[O_3]$ / Pre-industrial $[O_3]$

	A_{sat}				g_s			
Genus	% Change	95% CI	df	$[O_3]$	% Change	95% CI	df	$[O_3]$
Overall Effect	-19	-21 to -16	455	86	-10	-13 to -6	276	91
Gymnosperms	-17	-21 to -12	160	92	-6	-12 to 0	109	96
Abies					2	-19 to 28	9	110
Picea	-8	-17 to 2	54	76	5	-4 to 16	45	90
Pinus	-21	-27 to -15	93	97	-17	-24 to -9	53	100
Angiosperms	-20	-23 to -16	294	82	-12	-16 to -7	166	88
Betula	-15	-23 to -8	48	86	1	-8 to 10	38	98
Fagus	-21	-32 to -8	17	49	-23	-35 to -8	11	57
Liriodendron	-10	-29 to 15	12	58	-10	-35 to 24	10	60
Populus	-21	-26 to -16	120	79	-19	-28 to -9	40	104
Prunus	-28	-34 to -21	52	106	-100			
Quercus	-3	-17 to 14	22	77	-15	-24 to -6	36	80

Future $[O_3]$ / Pre-industrial $[O_3]$

	A_{sat}				g_s			
Genus	% Change	95% CI	df	$[O_3]$	% Change	95% CI	df	$[O_3]$
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Quercus	-3	-17 to 14	22	77	-15	-24 to -6	36	80

Future $[O_3]$ / Pre-industrial $[O_3]$

Genus	A_{sat} % Change	A_{sat} 95% CI	A_{sat} df	A_{sat} $[O_3]$	g_s % Change	g_s 95% CI	g_s df	g_s $[O_3]$
Overall Effect	-19	-21 to -16	455	86	-10	-13 to -6	276	91
Gymnosperms	-17	-21 to -12	160	92	-6	-12 to 0	109	96
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Quercus	-3	-17 to 14	22	77	-15	-24 to -6	36	80

Future $[O_3]$ / Pre-industrial $[O_3]$

	A_{sat}				g_s			
Genus	% Change	95% CI	df	$[O_3]$	% Change	95% CI	df	$[O_3]$
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Future $[O_3]$ / Pre-industrial $[O_3]$

	A_{sat}				g_s			
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Populus	-21	-26 to -16	120	79	-19	-28 to -9	40	104
Prunus	-28	-34 to -21	52	106	-100			
Quercus	-3	-17 to 14	22	77	-15	-24 to -6	36	80

Future $[O_3]$ / Pre-industrial $[O_3]$

	A_{sat}				g_s			
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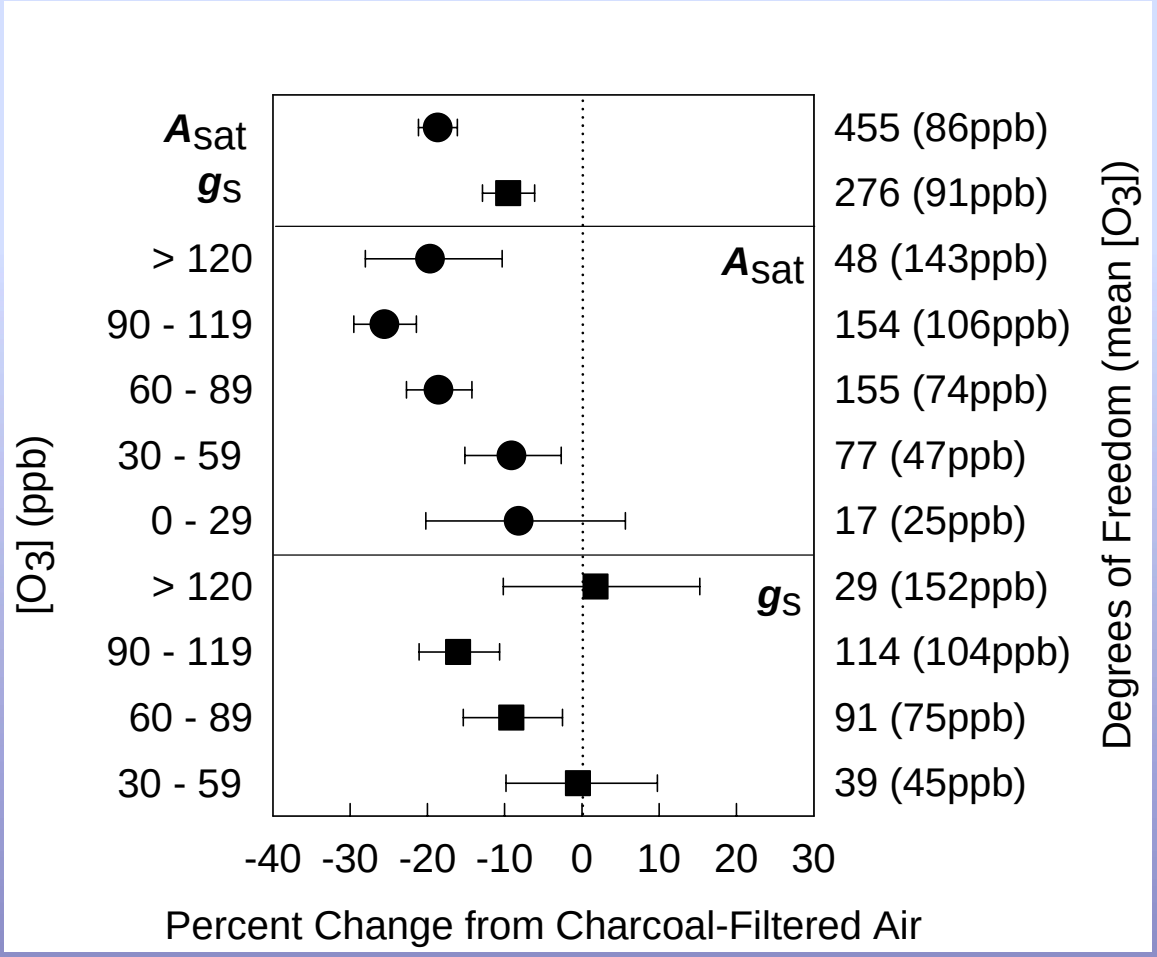
Quercus	-3	-17 to 14	22	77	-15	-24 to -6	36	80

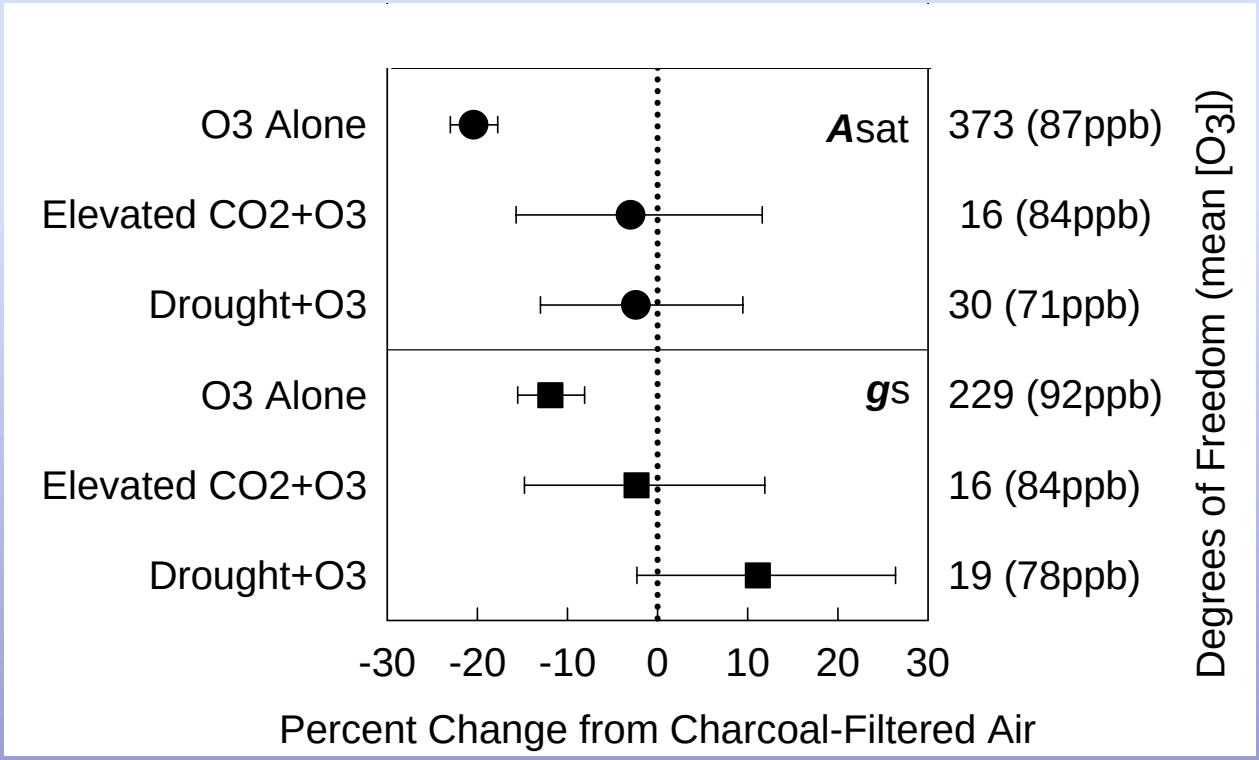
Future [O_3] / Pre-industrial [O_3]

Effect of Increasing Ozone



Future [O_3] / Pre-industrial [O_3]

Effect of Drought and Elevated CO_2



Future [O_3] / Pre-industrial [O_3]

- Photosynthesis and stomatal conductance are reduced by ozone projected for the future
  - Negative impact on both gymnosperm and angiosperm Asat and gs
  - Genus differ in response
  - Asat and gs decrease further when ozone increases
  - Drought, Elevated CO_2 may cancel the impact

Meta-analysis: Three point perspective

- How bad have things gotten since pre-industrial times?
  - Current [O_3] / Pre-industrial [O_3]
- How bad might things get under elevated concentrations projected for later this century relative to pre-industrial times
  - Future [O_3] / Pre-industrial [O_3]
- How bad will things get tomorrow relative to today?
  - Future [O_3] / Current [O_3]

Future [O_3] / Current [O_3]

	A_{sat}		g_s	
Category	Q_B	p	Q_B	p
Angiosperms vs. Gymnosperms	1.98	0.256	2.30	0.178
Genus	**24.67**	**0.083**	19.52	0.103
Increasing [O_3]	**34.31**	**0.001**	**14.18**	**0.030**
Additional treatment	5.92	0.563	5.23	0.535

Future $[O_3]$ / Current $[O_3]$

Genus	A_{sat} % Change	A_{sat} 95% CI	A_{sat} df	A_{sat} $[O_3]$	g_s % Change	g_s 95% CI	g_s df	g_s $[O_3]$
Overall Effect	-18	-20 to -15	348	81	-6	-10 to -3	252	71
Gymnosperms	-16	-19 to -12	134	87	-10	-15 to -4	101	82
Picea	-16	-22 to -10	55	73	-7	-15 to 1	60	77
Pinus	-16	-21 to -10	76	94	-13	-22 to -3	40	90
Angiosperms	-19	-22 to -16	213	77	-4	-9 to 1	150	63
Acer	-20	-31 to -8	14	67	4	-12 to 22	12	68
Betula	-14	-22 to -6	43	45	8	-2 to 18	52	40
Fagus	-11	-20 to -2	19	53	-12	-26 to 5	11	57
Liriodendron					-6	-41 to 50	7	68
Populus	-26	-32 to -20	40	89				
Prunus	-24	-30 to -19	50	108				
Quercus	-7	-17 to 5	22	77	-11	-19 to -2	38	80

Future $[O_3]$ / Current $[O_3]$

Genus	A_{sat} % Change	A_{sat} 95% CI	A_{sat} df	A_{sat} $[O_3]$	g_s % Change	g_s 95% CI	g_s df	g_s $[O_3]$
Overall Effect	-18	-20 to -15	348	81	-6	-10 to -3	252	71
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Future $[O_3]$ / Current $[O_3]$

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Future $[O_3]$ / Current $[O_3]$

Genus	A_{sat}				g_s			
	% Change	95% CI	df	$[O_3]$	% Change	95% CI	df	$[O_3]$
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Future $[O_3]$ / Current $[O_3]$

Genus	A_{sat}				g_s			
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Future $[O_3]$ / Current $[O_3]$

Genus	A_{sat}				g_s			
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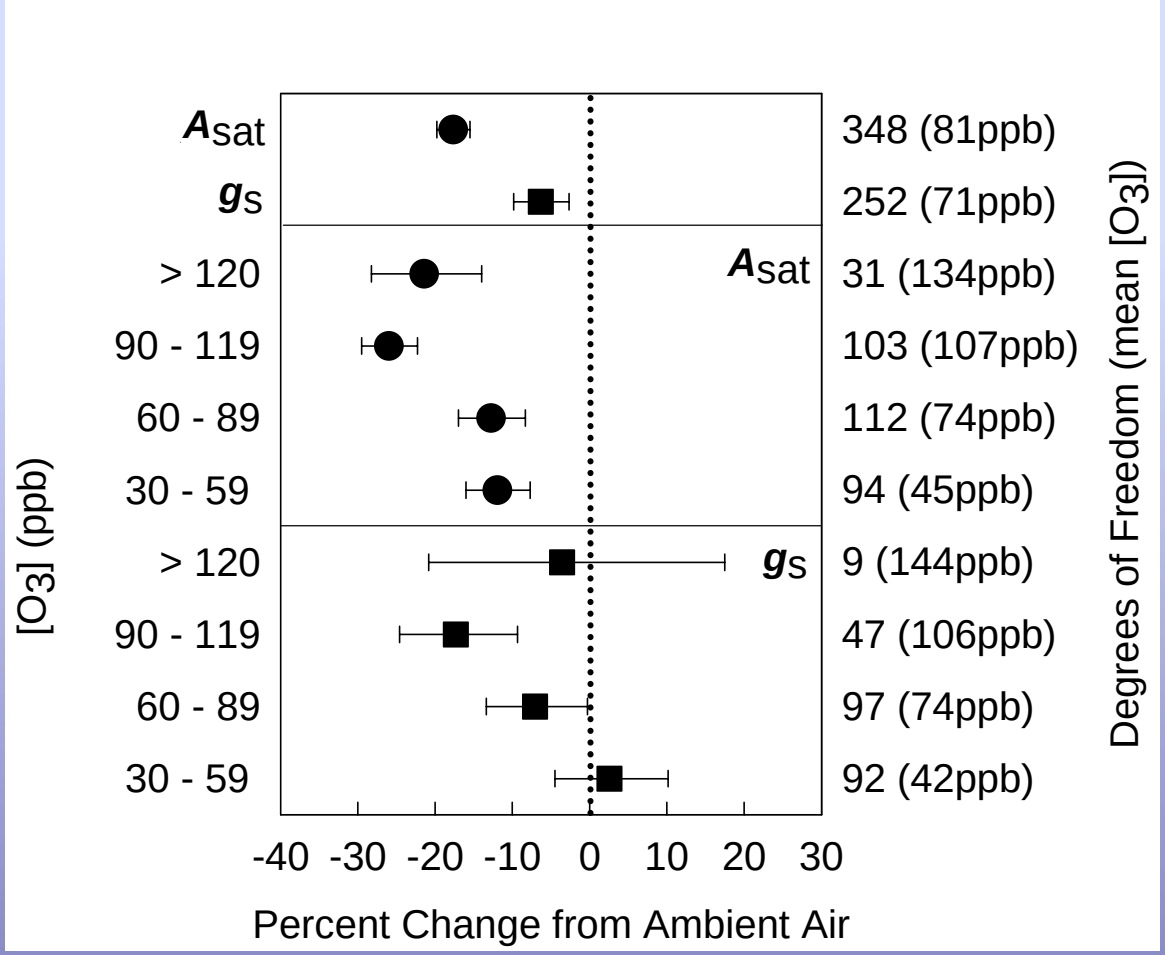
Future [O_3] / Current [O_3]

Effect of Increasing Ozone



Future [O_3] / Current [O_3]

- Photosynthesis and stomatal conductance are reduced by projected ozone relative to today
  - Negative impact on both gymnosperm and angiosperm Asat and gs
  - Genus differ in Asat response
  - Lack of gs response in angiosperms
  - Asat and gs decrease further when ozone increases

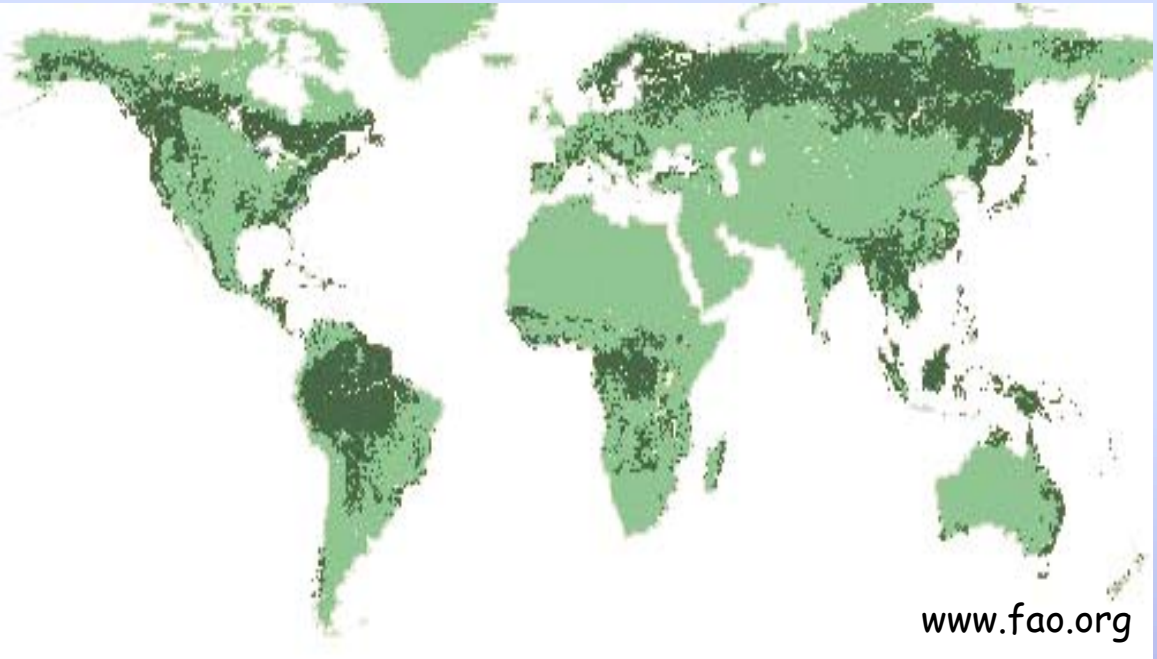
What is the consensus? Photosynthesis

	A_{sat}		
	Present/Past	Future/Past	Future/Present
Overall Effect	-11	-19	-18
Gymnosperms vs. Angiosperms	Difference	No Difference (nd)	nd
Gymnosperms	-2	-20 to -17	-19 to -16
Angiosperms	-14		
Genus	Varies: nd to -24	Varies: nd to -28	Varies: nd to -26
Increasing [O_3]		Decreases	Decreases
Ozone alone	-10	-20	
Drought & ECO_2	nd	nd	???

What is the consensus? Stomatal Conductance

	g_s		
	Present/Past	Future/Past	Future/Present
Overall Effect	-13	-10	-18
Gymnosperms vs. Angiosperms	Difference	No Difference (nd)	nd
Gymnosperms	nd	-12 to -6	-16 to -19
Angiosperms	-16		
Genus	Varies: 12 to -27	Varies: nd to -23	Varies: nd to -26
Increasing [O_3]		Decreases	Decreases
Ozone alone	-11	-11	
Drought & Elevated CO_2	nd	nd	???

Global Forest Distribution



Reduced photosynthetic CO_2 uptake capacity,
today and tomorrow,
with potential to lead to further warming.


APRIL 3, 2006
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SPECIAL REPORT GLOBAL WARMING
TIME
BE WORRIED. BE VERY WORRIED.
Climate change isn't some vague future problem—it's already damaging the planet at an alarming pace. Here's how it affects you, your kids and their kids as well
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HOW IT THREATENS YOUR HEALTH
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UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Long Lab:
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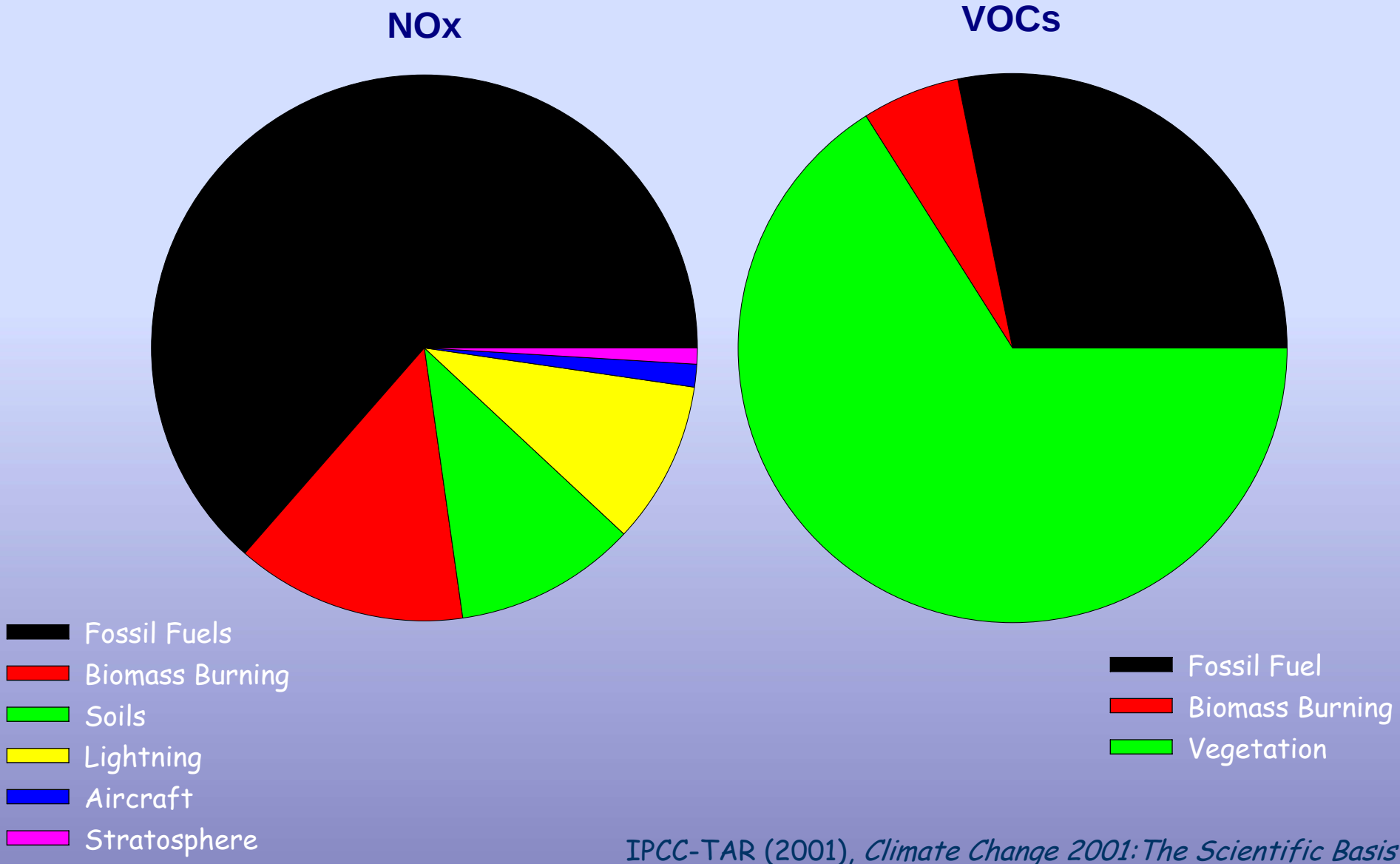
Undergraduates:
Kasey Bryant
Katie Ciccodicola
Leslie Morrison
Janel Woods

Sources of O_3 Precursor Emissions (%)



IPCC-TAR (2001), *Climate Change 2001: The Scientific Basis*