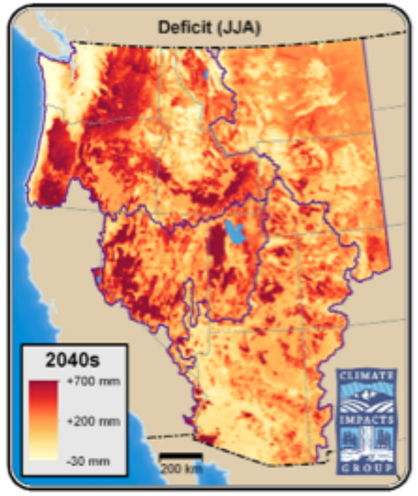
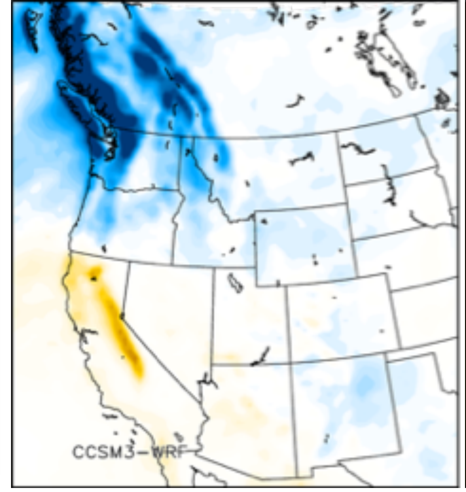
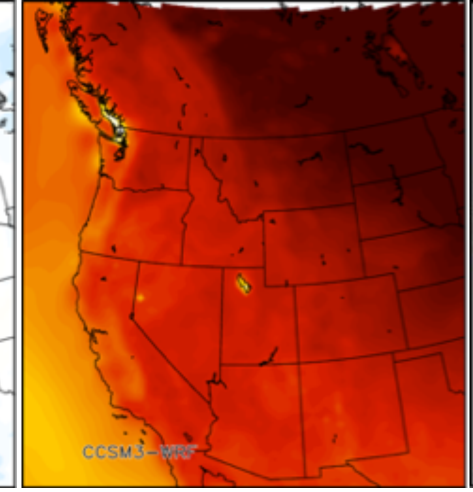
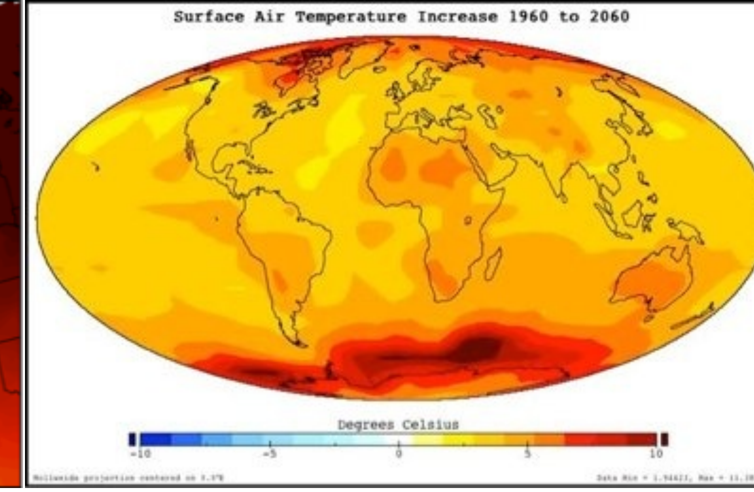








Modeling wildfire and air quality under climate change

Don McKenzie
Pacific WIldland Fire Sciences Lab
US Forest Service

with contributions from

- **Uma Shankar**
- Robert Keane
- Jeffrey Prestemon
- Natasha Stavros
- Robert Norheim
- Jeremy Littell

CMAS annual meeting

October 5, 2015

Rationale

- It's getting warm down here.

- Mean annual temperature rise may be stalling (but see 2014), but not hot extremes over land.

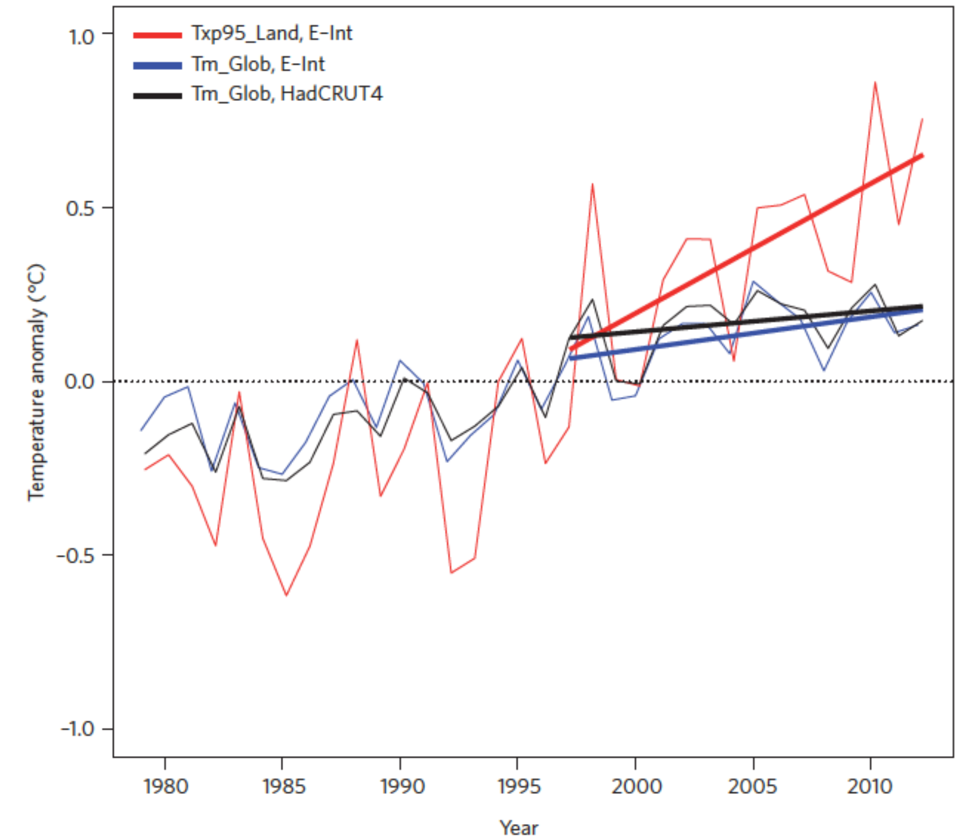
- More area is expected to burn.

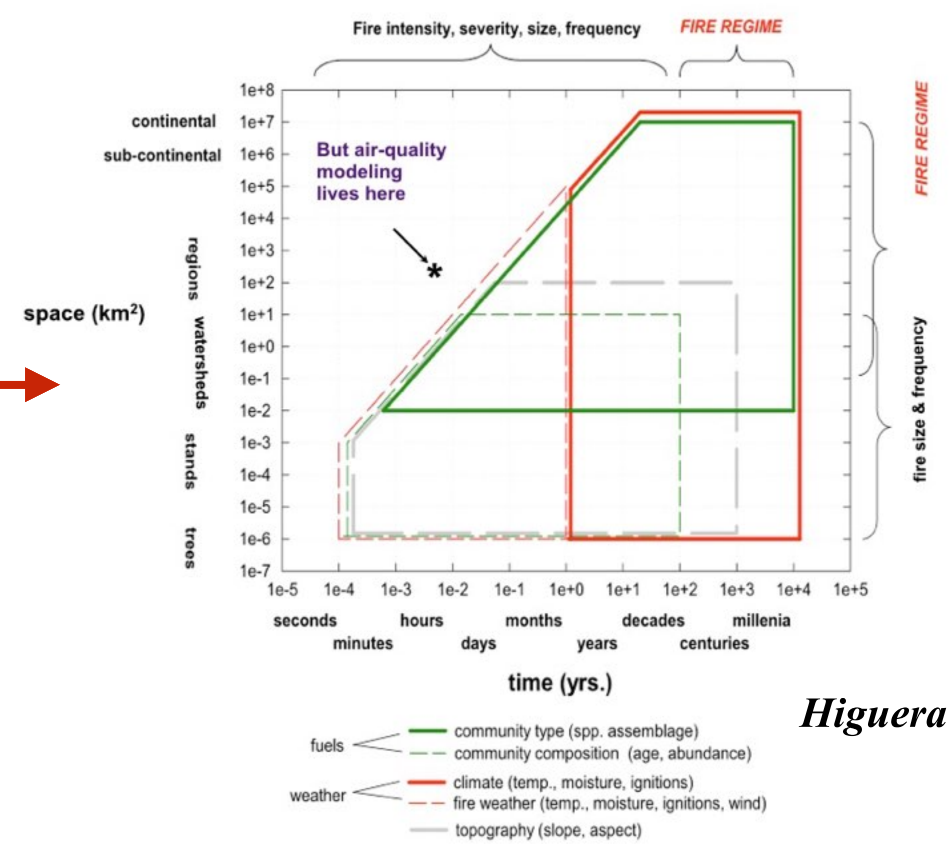
- Fires set up dynamic feedbacks, including some large positive ones, from affected ecosystems!

- Problem is multiscale in space and time; understanding it needs integration across multiple science domains.

- Challenges to scientific understanding and for policy decisions on mitigation and adaptation.

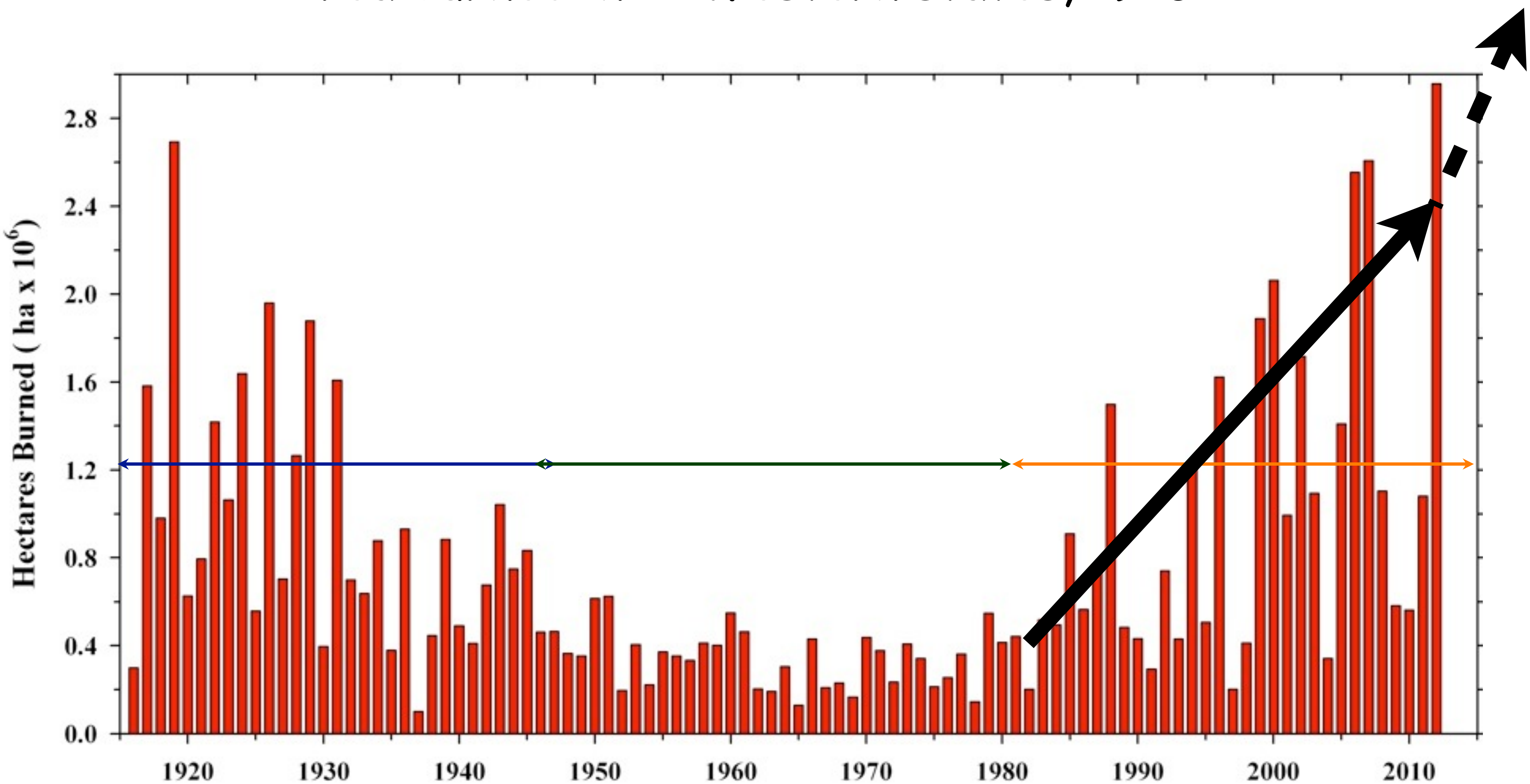
Seneviratne et al. (2014)





Higuera (2004)

Area burned in 11 Western states, 1916-2012

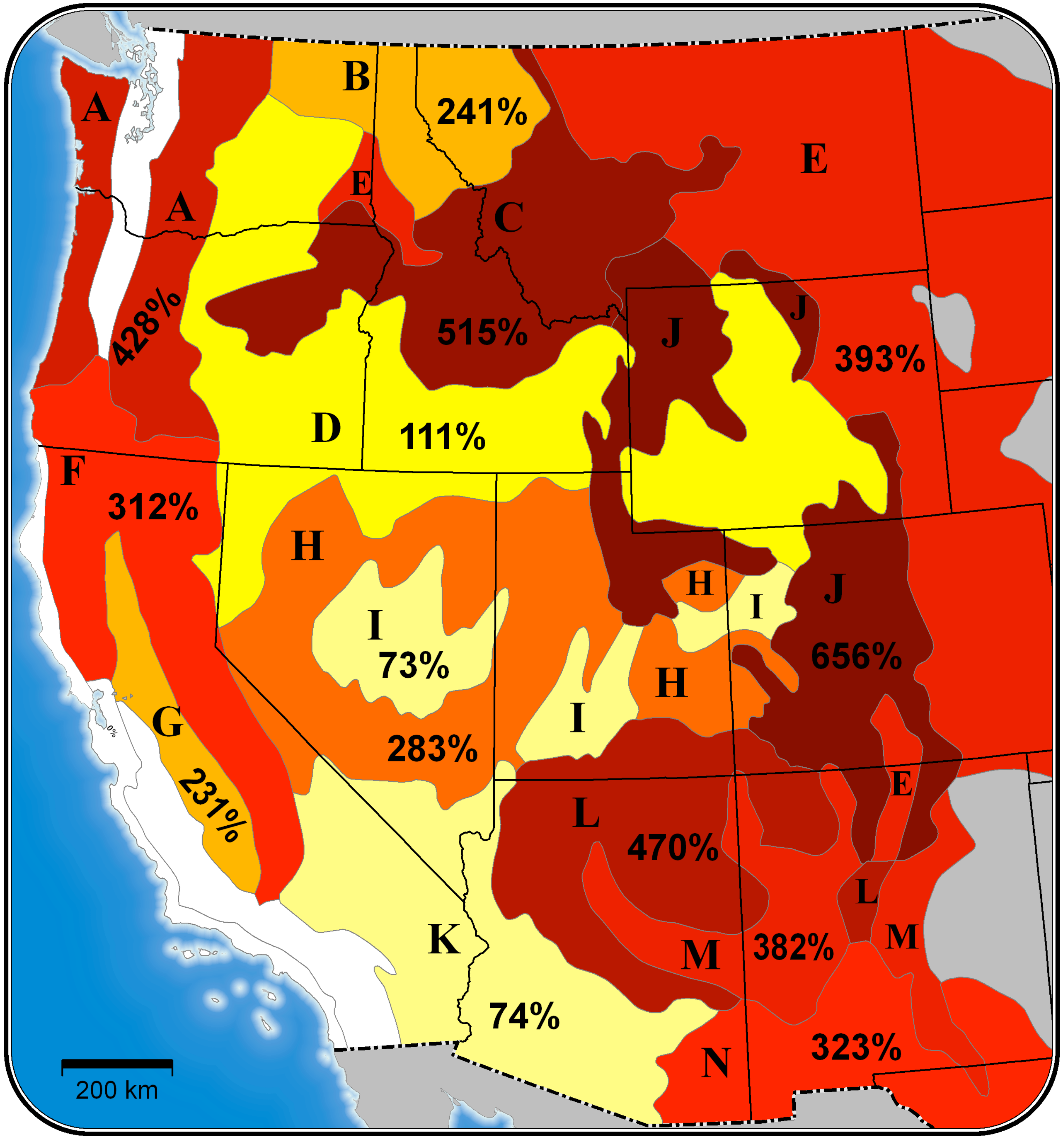


Period of post-conquest fire

Period of active fire suppression and fuel accumulation

Period of fire increase

Expectation: Hotter and drier = more fire!



- A - Cascade Mixed Forest
- B - Northern Rocky Mt. Forest
- C - Middle Rocky Mt. Steppe-Forest
- D - Intermountain Semi-Desert
- E - Great Plains-Palouse Dry Steppe
- F - Sierran Steppe-Mixed Forest
- G - California Dry Steppe
- H - Intermountain Semi-Desert / Desert
- I - Nev.-Utah Mountains-Semi-Desert
- J - South. Rocky Mt. Steppe-Forest
- K - American Semi-Desert and Desert
- L - Colorado Plateau Semi-Desert
- M - Ariz.-New Mex. Mts. Semi-Desert
- N - Chihuahuan Semi-Desert

If we just look at fire climatology…

- Statistical fire-area regression models from temperature and precipitation.
- Ensemble projection of sub-regional climate expected with +1C°.
- Forested or mountain ecoprovinces increase more than shrubland and grassland.

the West burns up many times over.

Littell et al. (forthcoming)

(more to the story, but that's another talk)

The largest fires cause most of the trouble

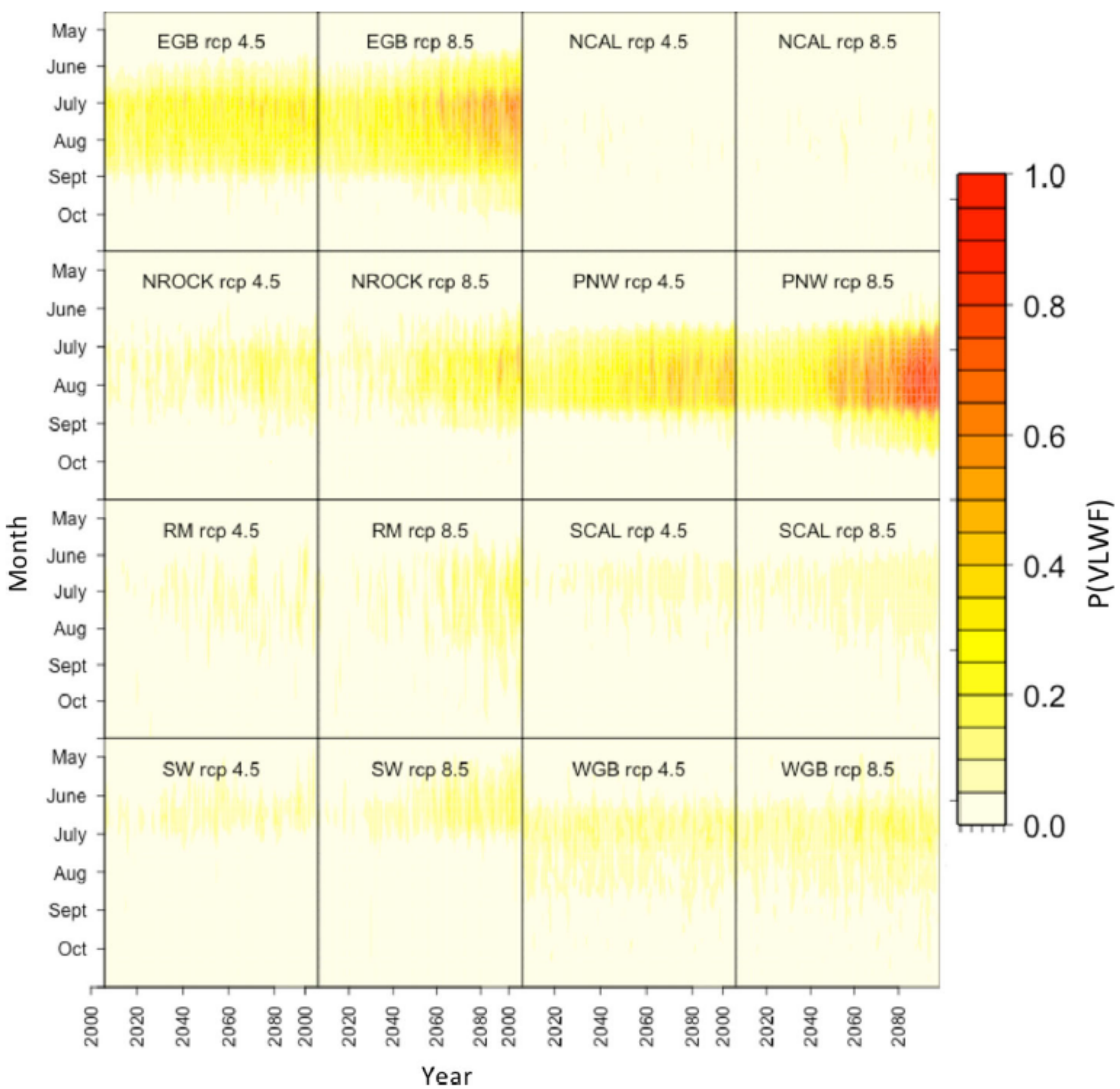
2011 Las Conchas Fire, NM

2000 Cerro Grande Fire, NM

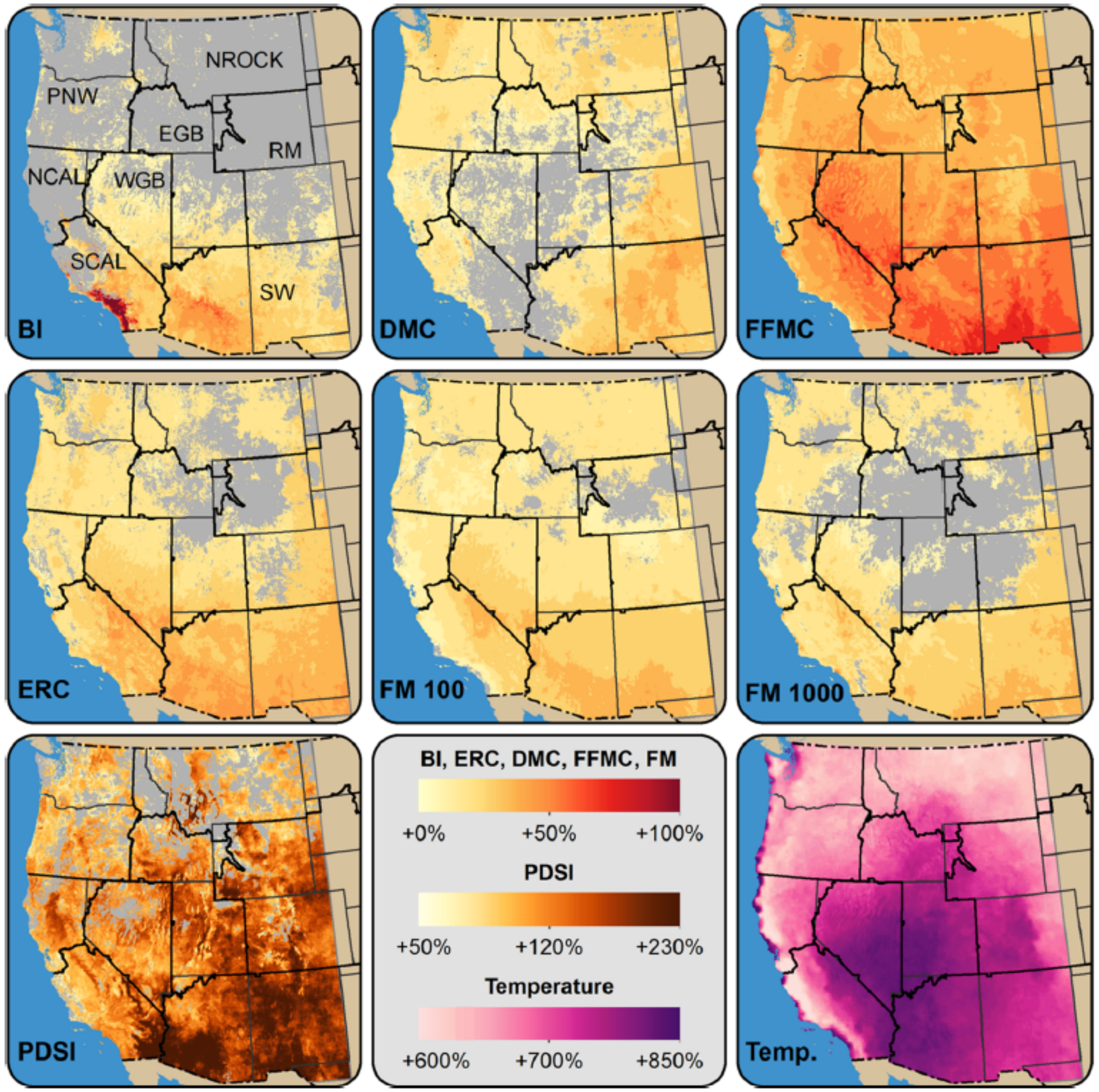
2014 Carleton Complex Fire, WA

Probability of megafires increases

Some ecoregions are affected more, e.g., Pacific Northwest



Big %changes in fire weather, even for RCP 4.5 in 2040s.

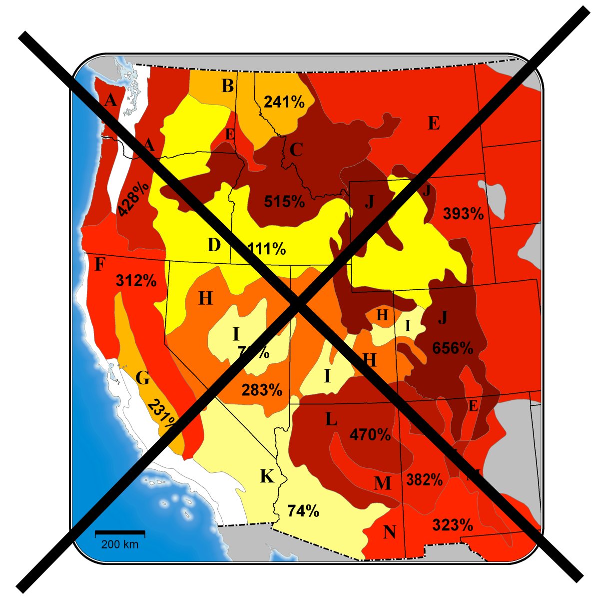


Stavros et al. (2014) Climatic Change 126:455–468

Good news, bad news

- The West is not burning up
  - Fires run out of real estate
  - “Hotter and drier = more fire” breaks down in the drier.

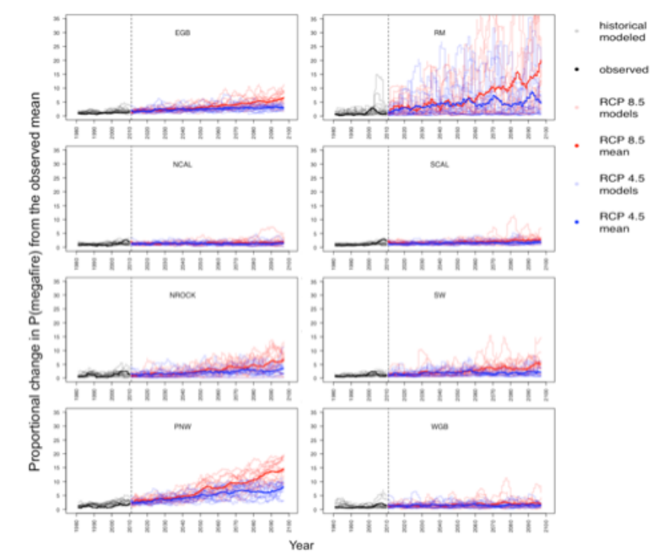
(Krawchuk & Moritz 2011, McKenzie & Littell 2011)



- But unprecedented losses
  - Iconic ecosystems.
  - Increased probability of large destructive fires.

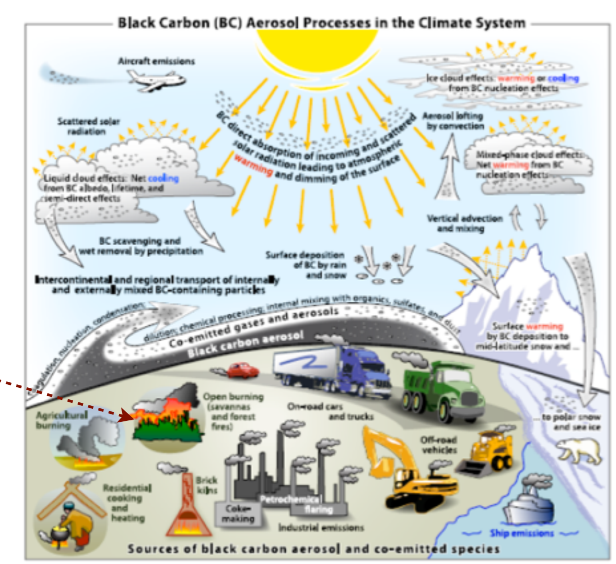
(Stavros et al. 2014)

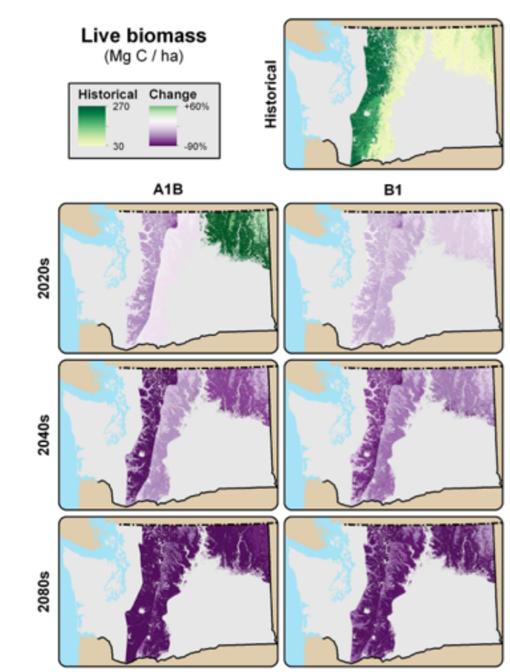
P(megafire)



- Positive feedbacks
  - The West as a carbon source
  - Biomass-burning aerosols
  - Loss of ET cooling

(Raymond & McKenzie 2012, Swann et al. 2012, Bond et al. 2013)

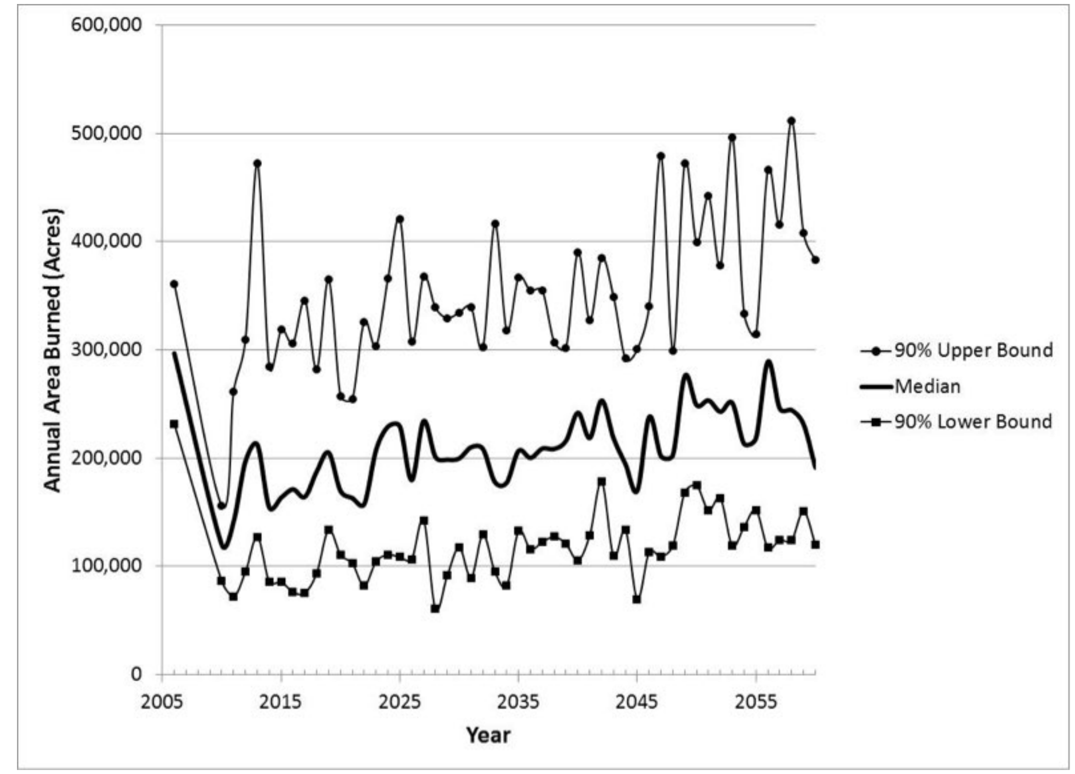


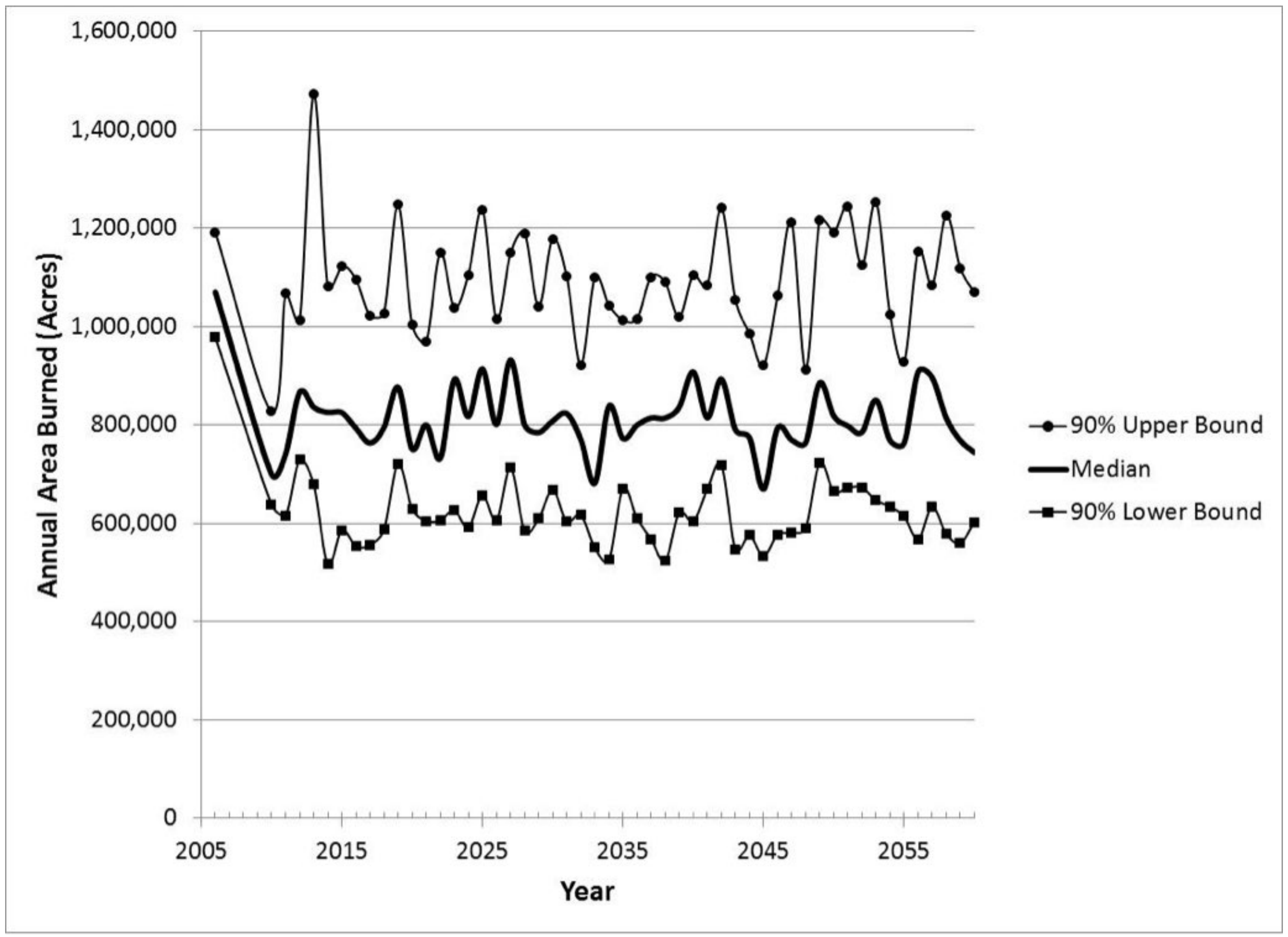


• and the Southeast may see less fire

- Lightning-ignited fires will increase a bit.
- but human-ignited fires will decrease a bit more.

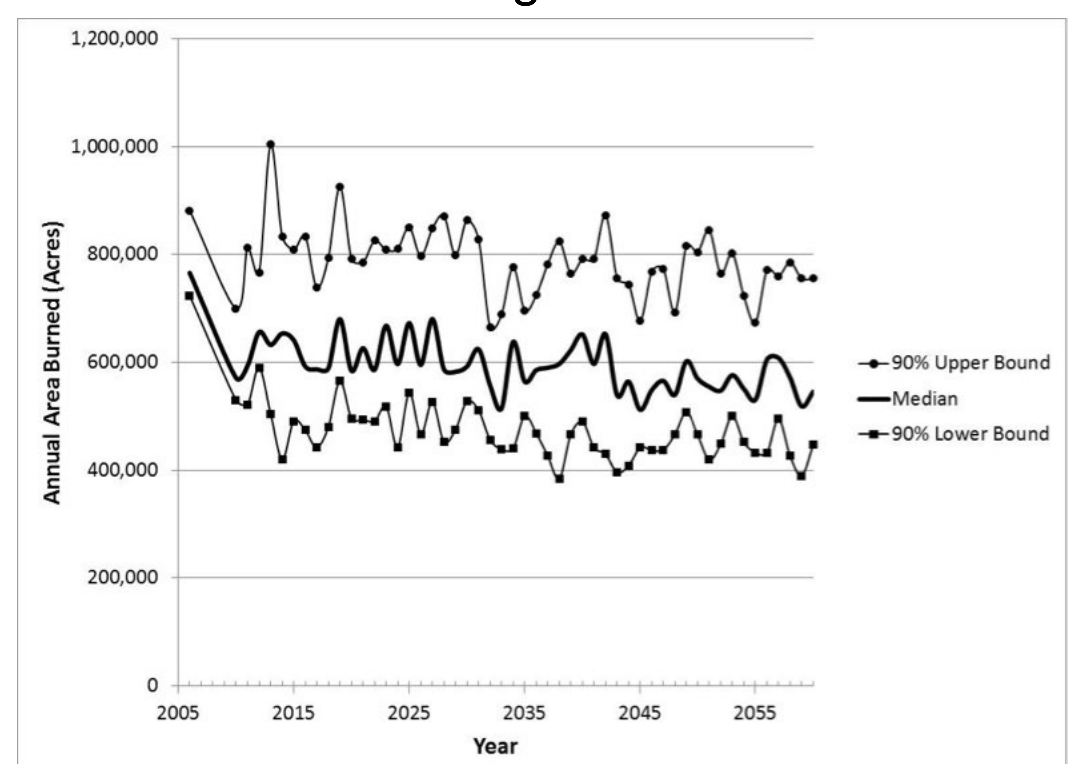
Lightning-ignited fires





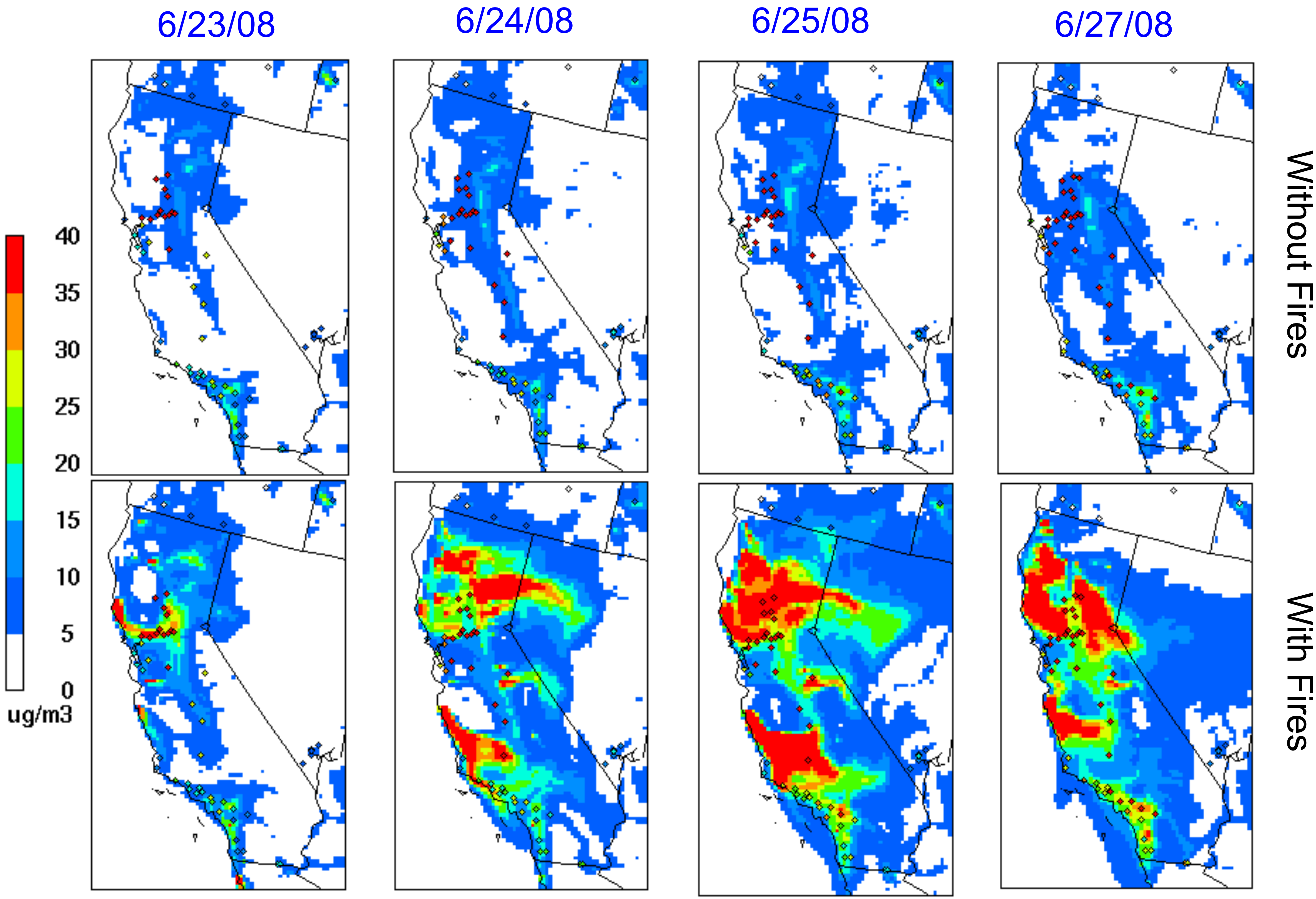
All fires

Human-ignited fires



Prestemon et al. (2015) IJWF in review

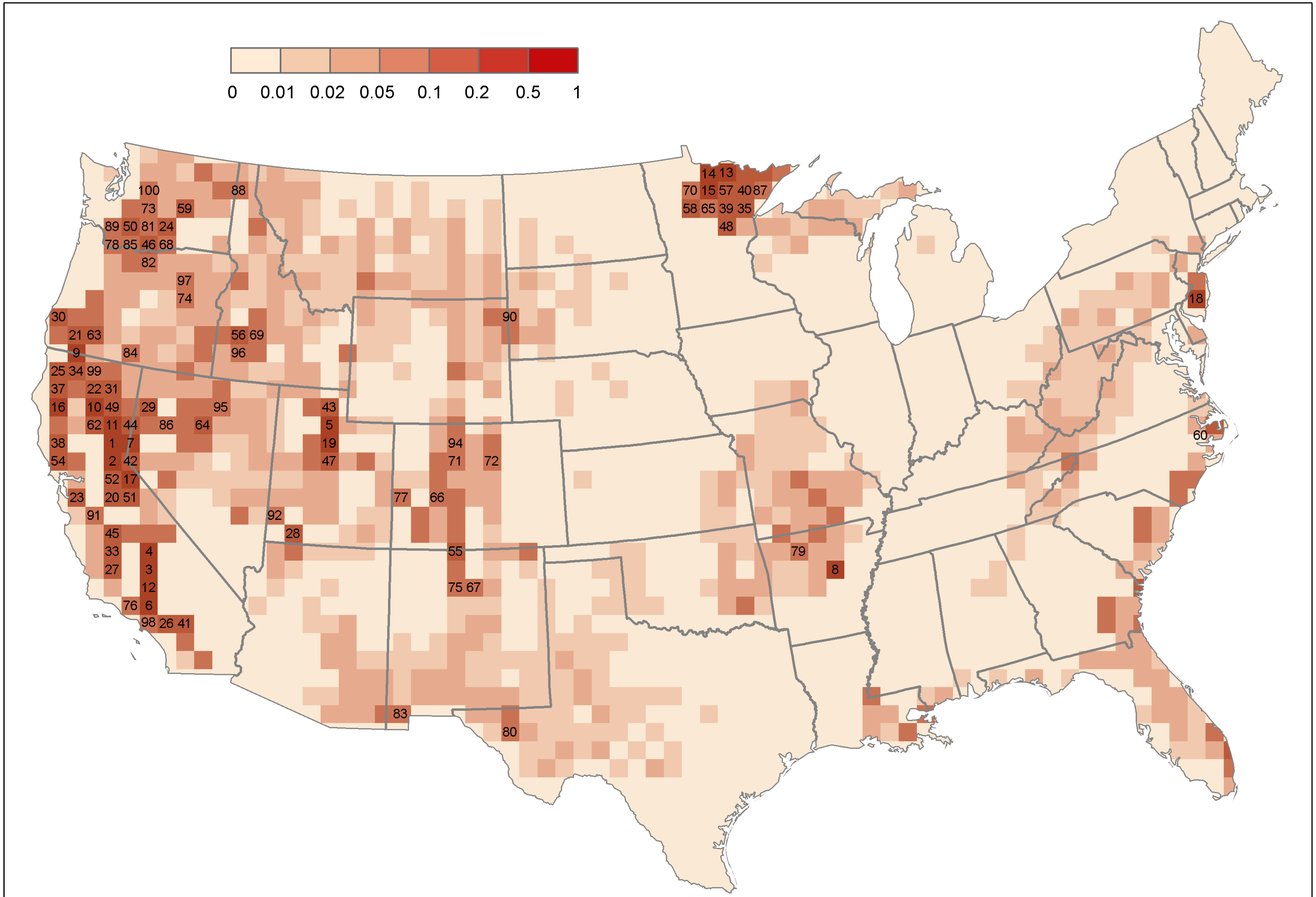
Wildfire emissions affect daily-average $PM_{2.5}$



Courtesy of the Office of Research and Development, U.S. EPA

Relativized future "smoke potential"

based on megafire likelihood and simulated trajectories



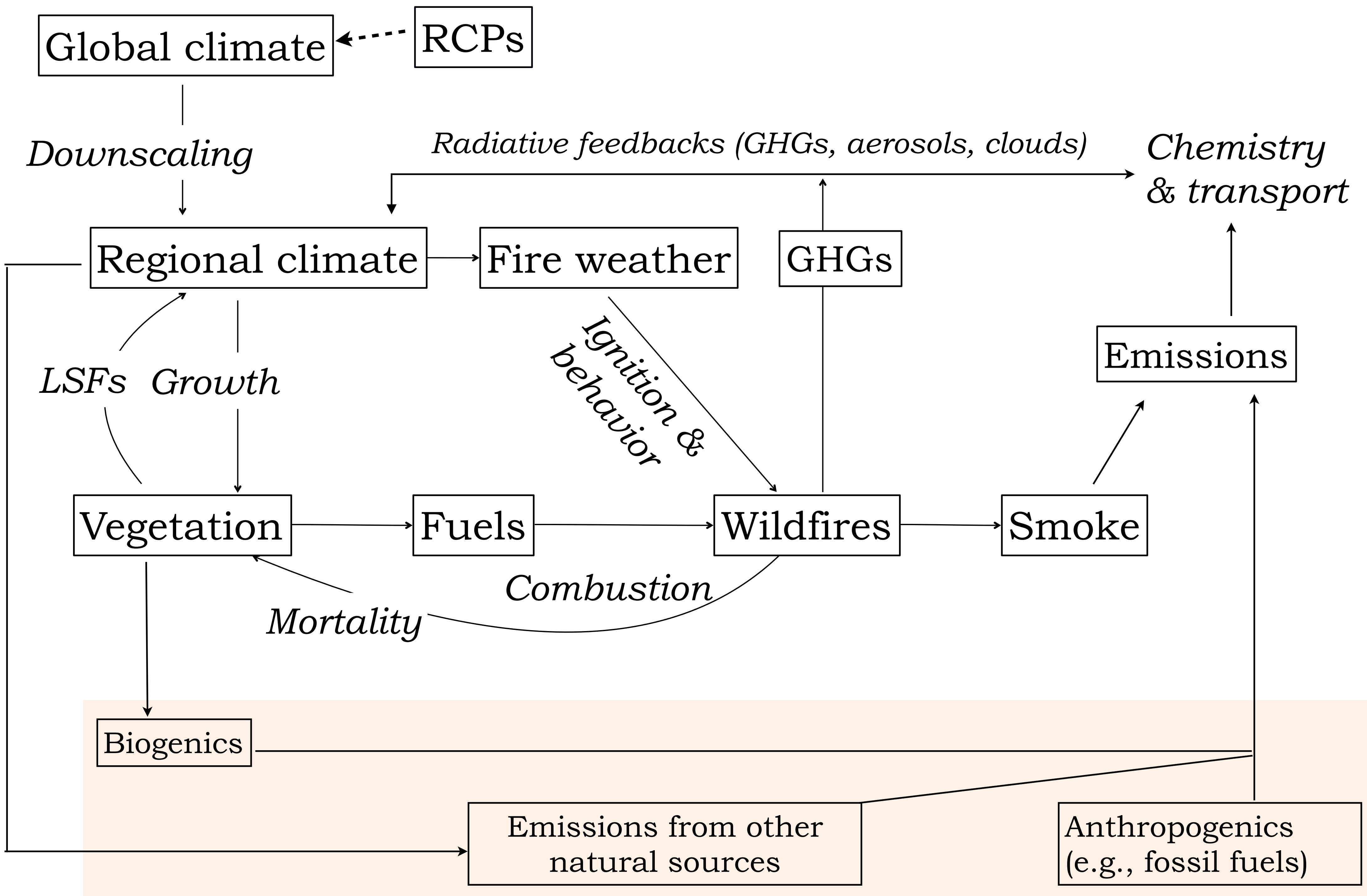
Larkin et al. (2015)

Potential consequences for climate change (global) and human health (local)

- Fires increase ambient concentrations of *short-lived climate-forcing pollutants* (black carbon, organic aerosol, SO_4, O_3, NH_3).
- Impact on the global radiation budget (heating or cooling) is highly dependent on the land cover, e.g., forest vs. grass and woodland (Swann et al. 2012, Bond et al. 2013).
- PM chemical composition may play as important a role as concentrations in health impacts; PM from fires is particularly toxic (Wegesser et al. 2009).

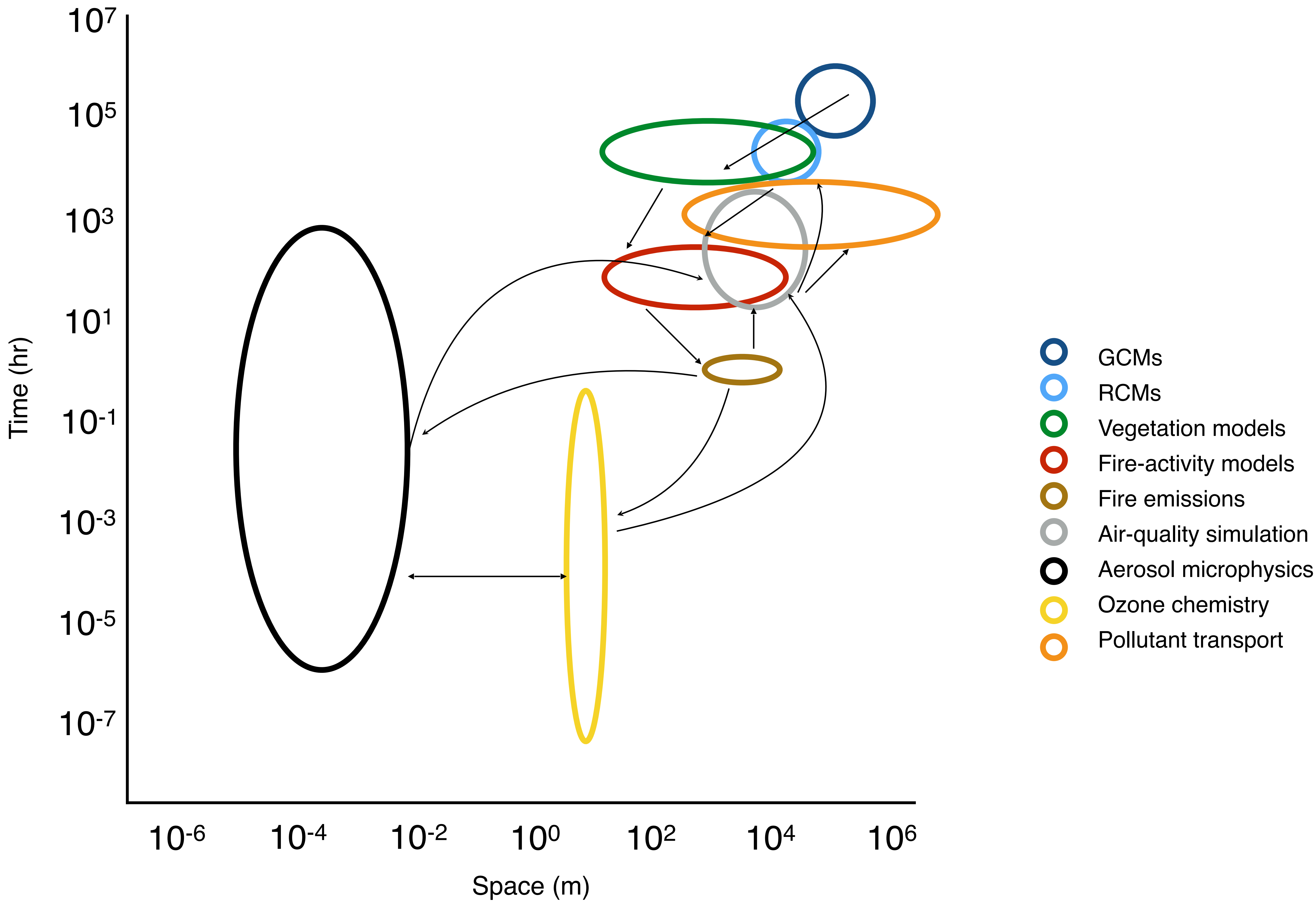
and regional (haze)

Framework for regional-scale modeling



Much more detail in open-access review paper: type "earths future smoke consequences" into google search bar. :-)

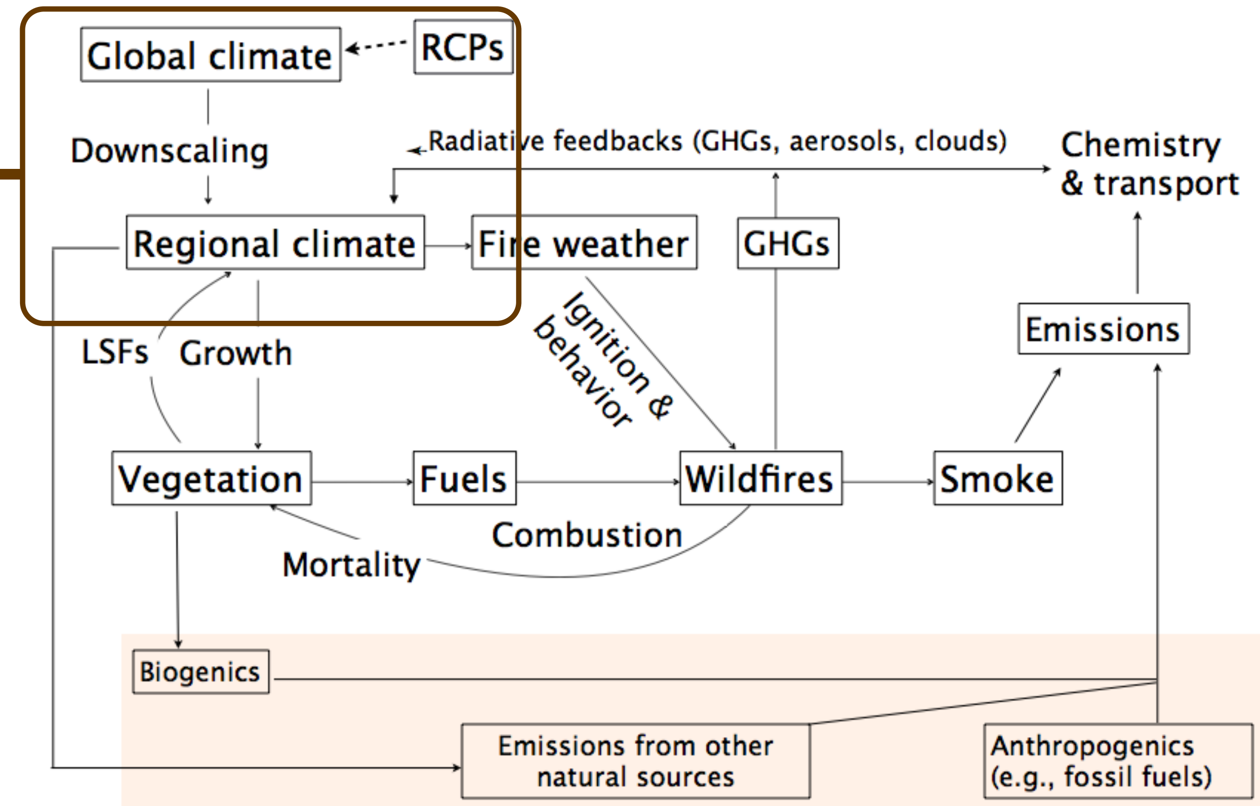
Spatial & temporal scales of modeled processes

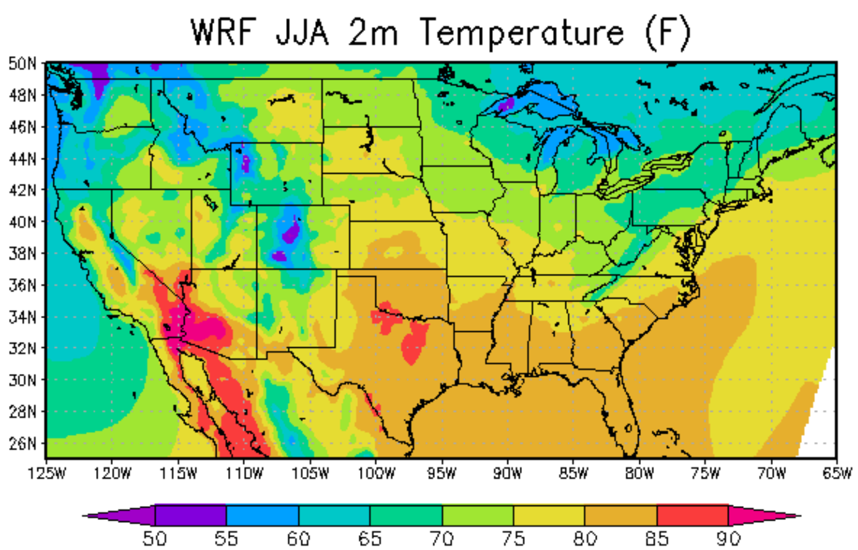


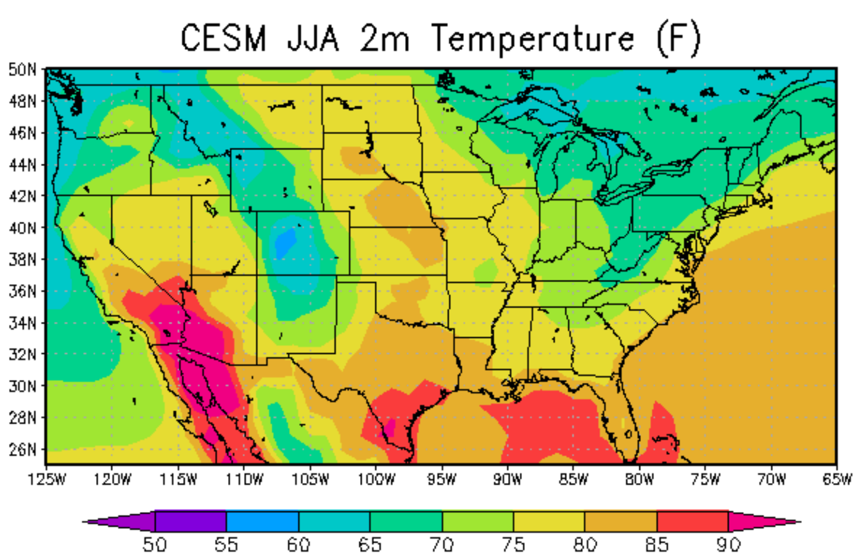
Downscaling of Climate

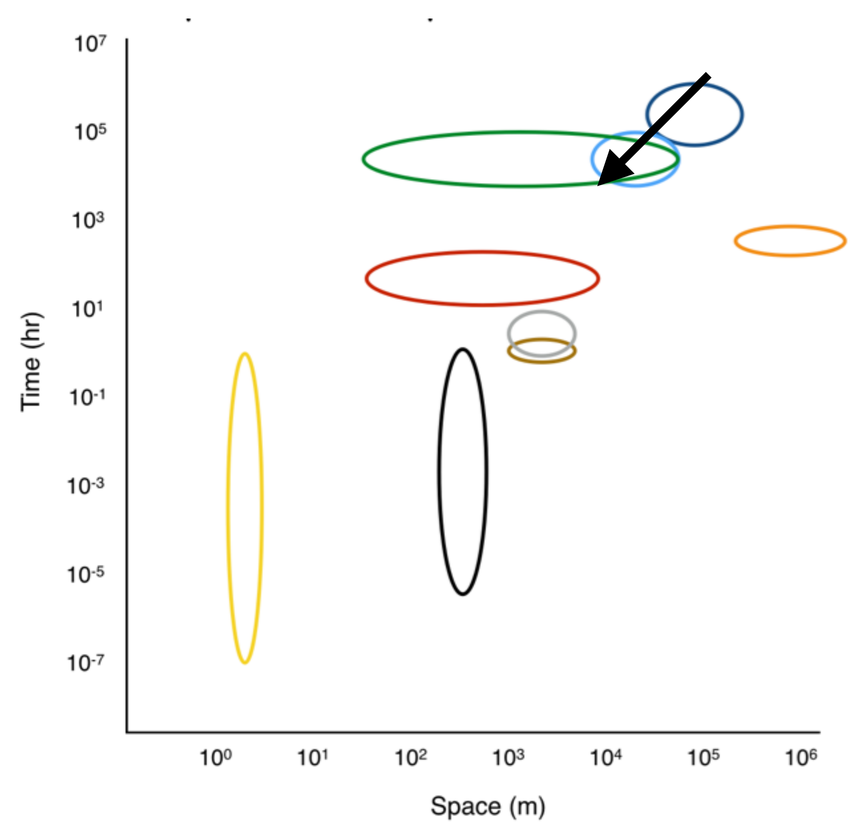
Regional Climate Modeling

- Provide high spatial and temporal resolution for meteorological variables not available from GCMs.
- Provides more realistic representation of fire related weather and extreme events (resolution- and scale-appropriate physics)
- Number of simulations (ensembles) limited by expense
- Typically atmosphere-only models, missing dynamic coupling to other components (e.g., surface hydrology, oceans, chemistry)



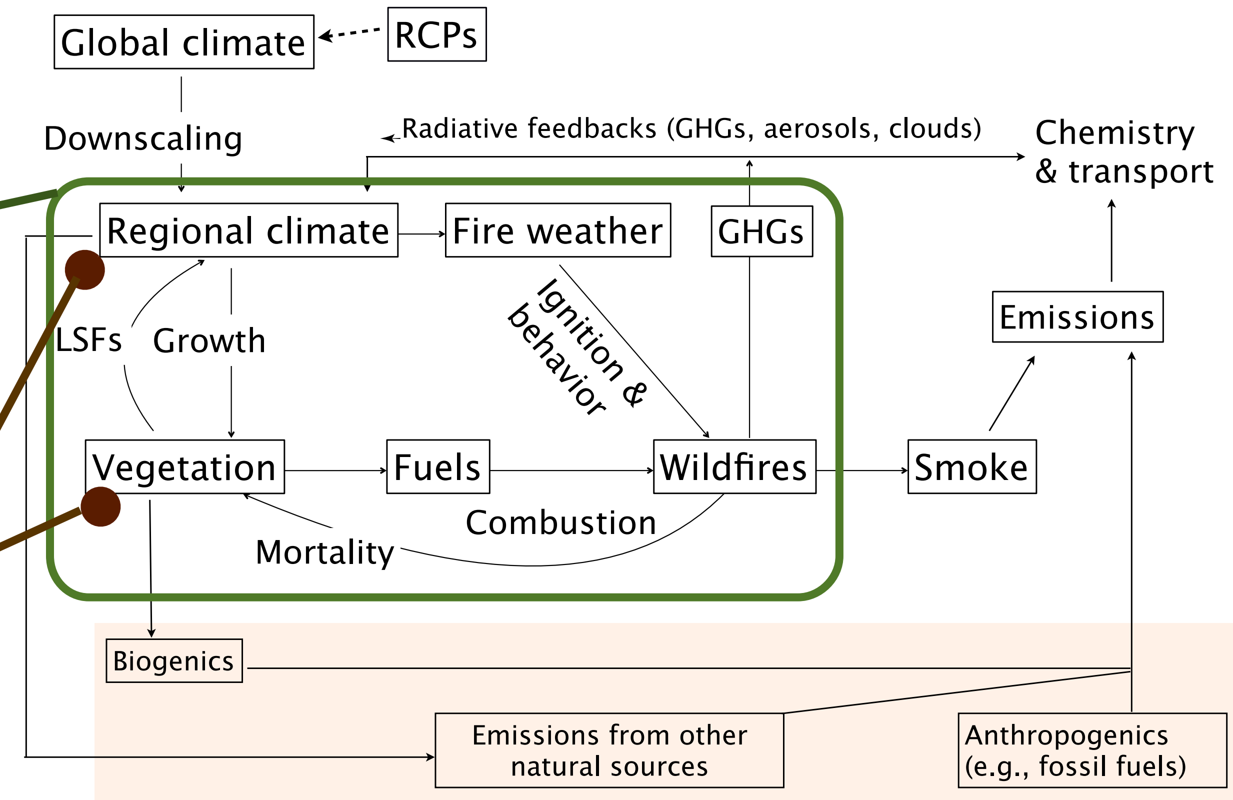






Scaling domain and direction (if any) of model process

Vegetation models



Dynamic models

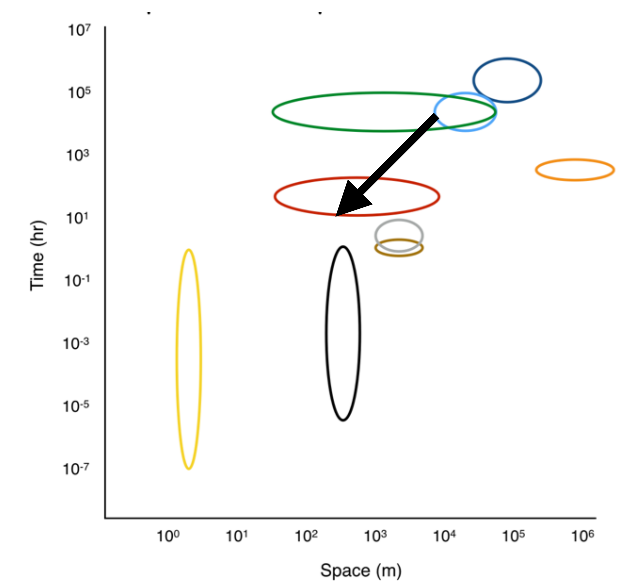
- e.g., DGVMs, at regional scales.
- Vegetation limited to plant functional types.
- May include explicit modules for fire behavior and effects.
- No fire spread or other contagious processes.

Empirical approaches

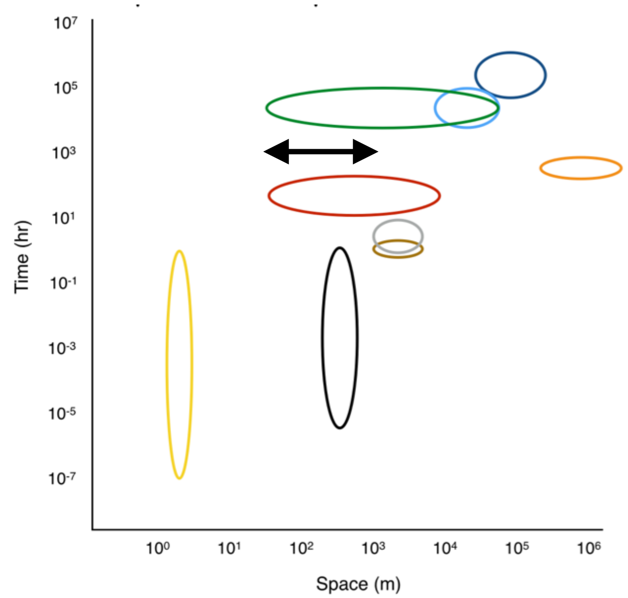
- Bioclimatic envelope models.
- Species-level resolution.
- No dynamic changes in vegetation or feedbacks.

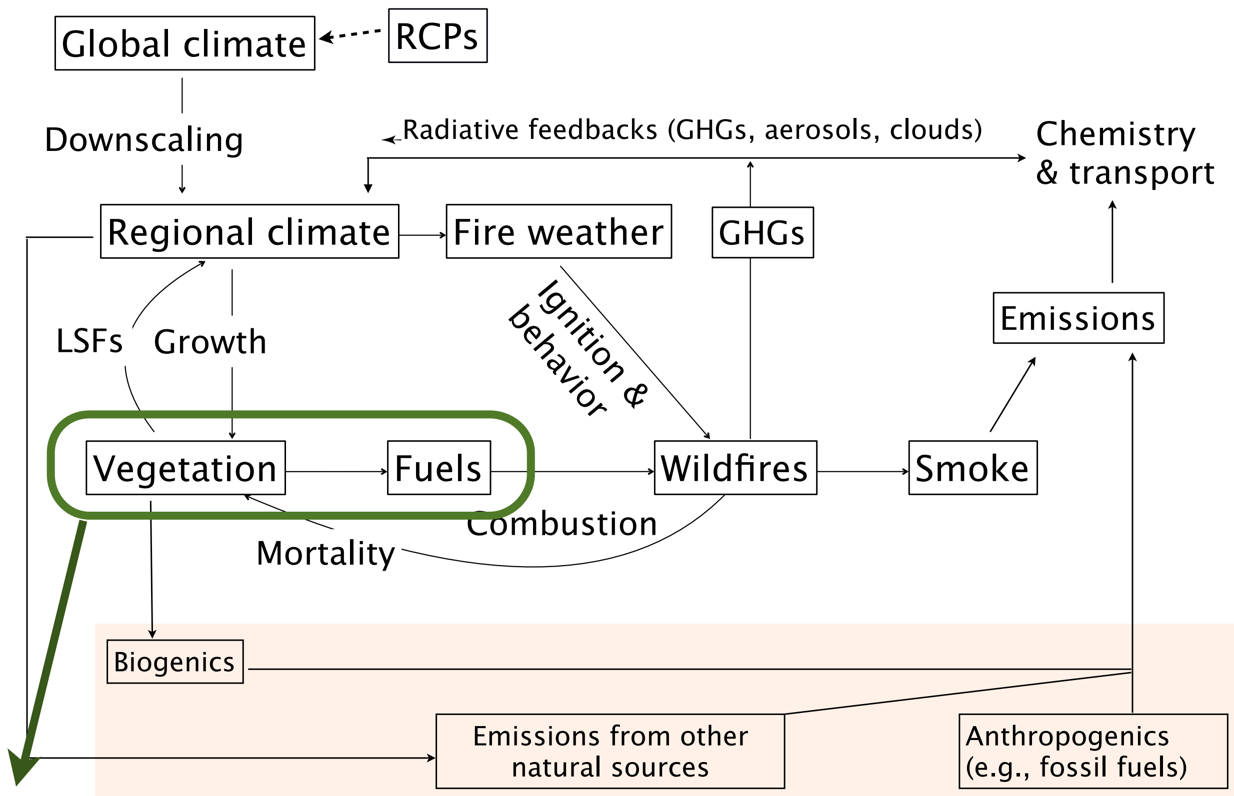
Finer-scale landscape models

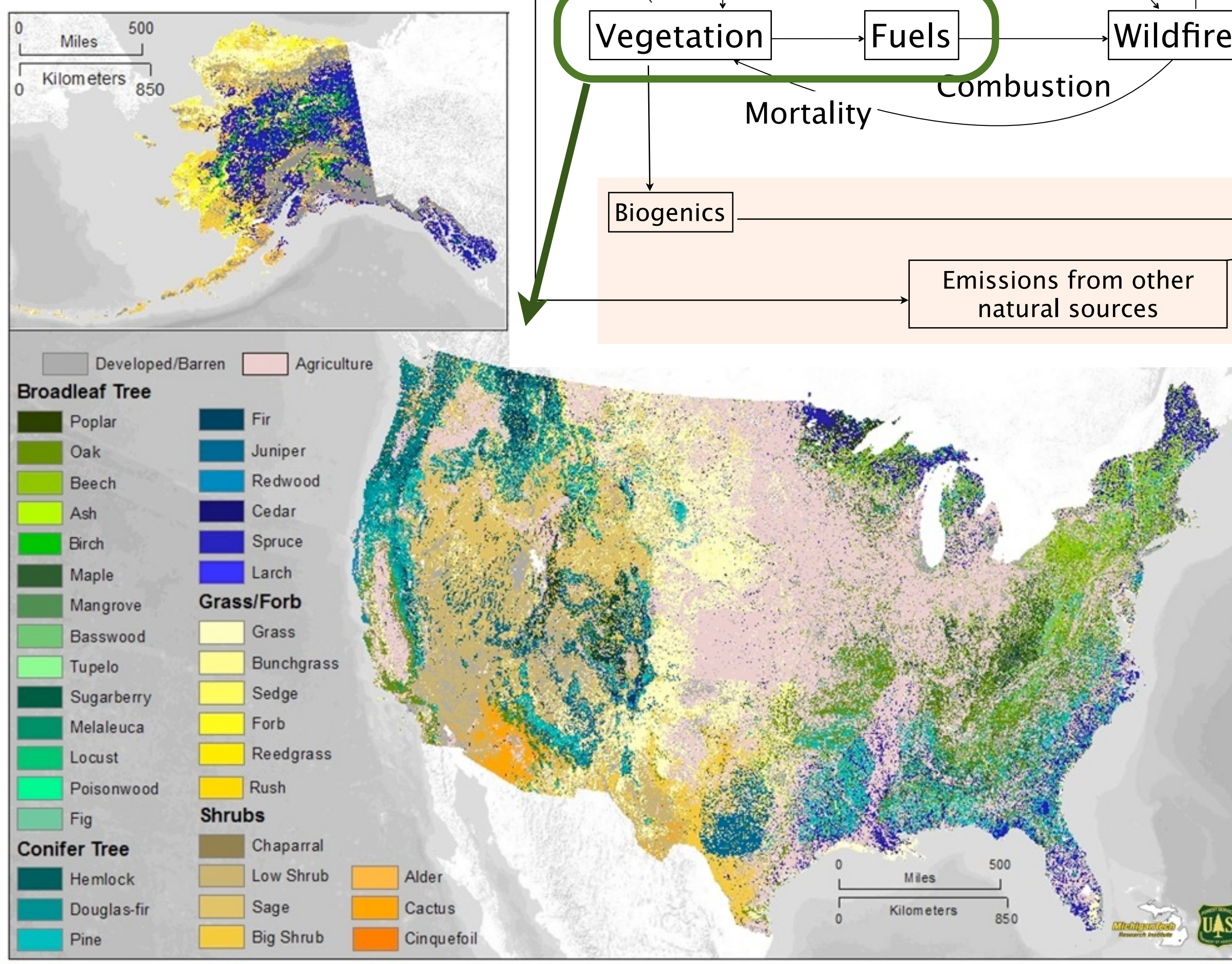
- Species-level resolution.
- Fire spread, contagion.
- Not computationally feasible at regional scale.

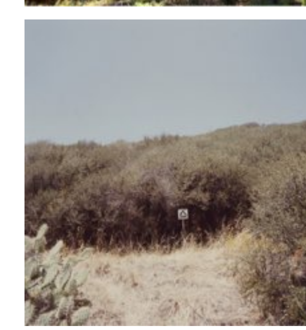


Fuel mapping



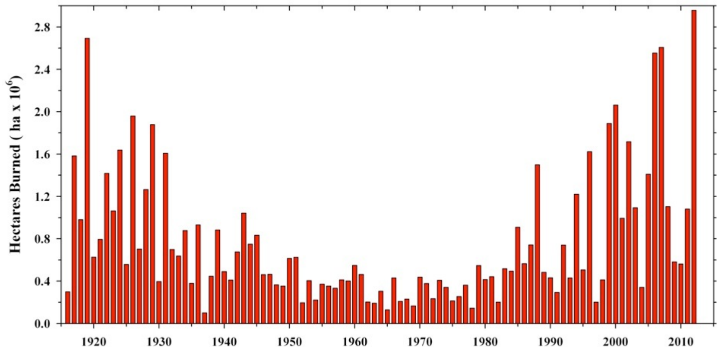


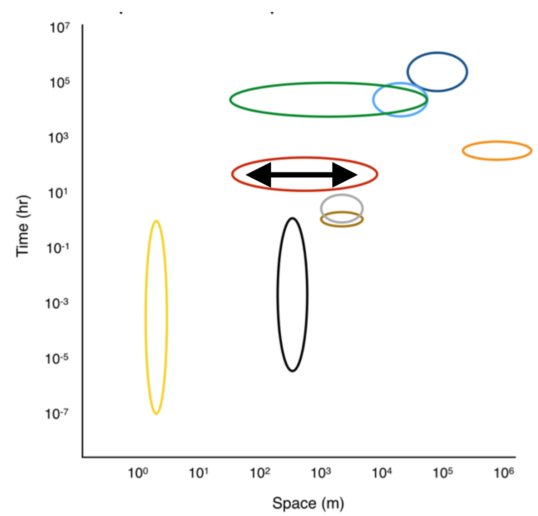


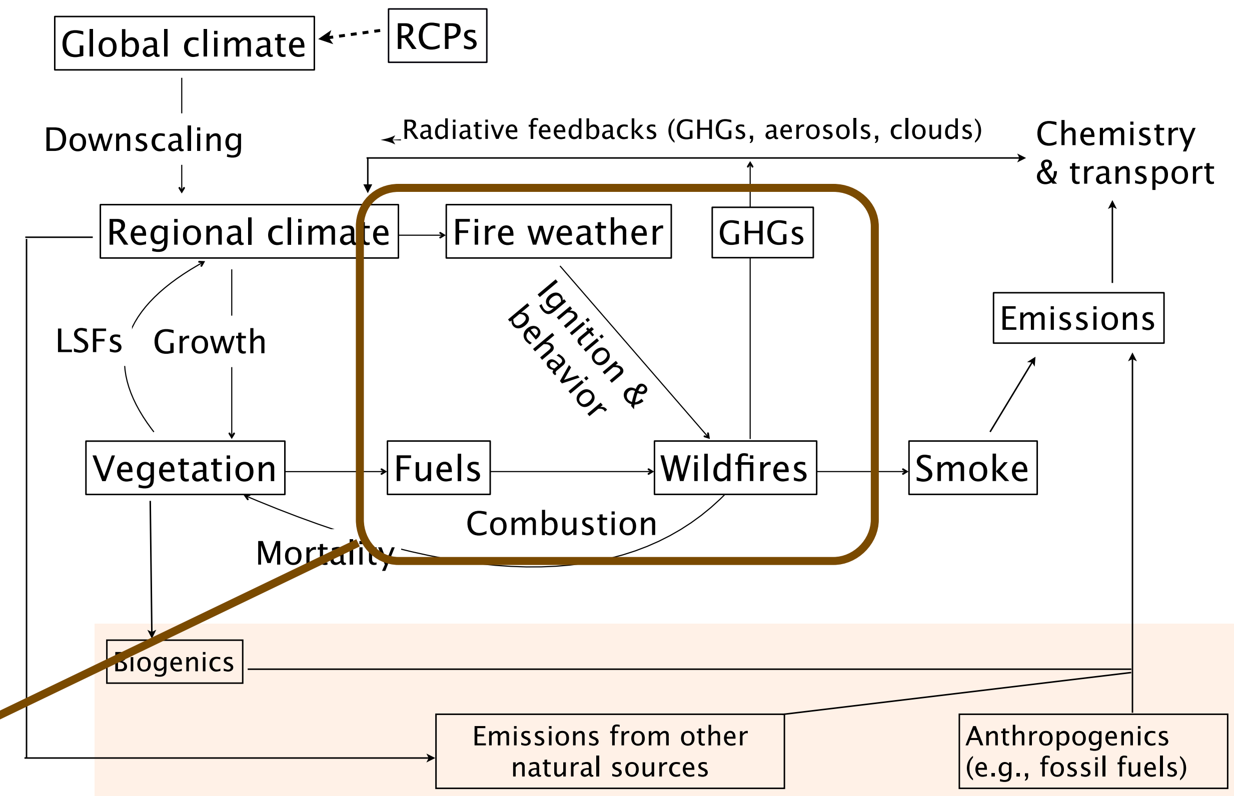


- Variability at multiple scales.
- Crosswalks from vegetation.
- Need to update fuel from future vegetation. Models that use the current fuel layers are wrong from the start.
- Understory fuels difficult to estimate from overstory (visible via remote sensing).
- Scale mismatches make “validation” difficult.

Predicting fire





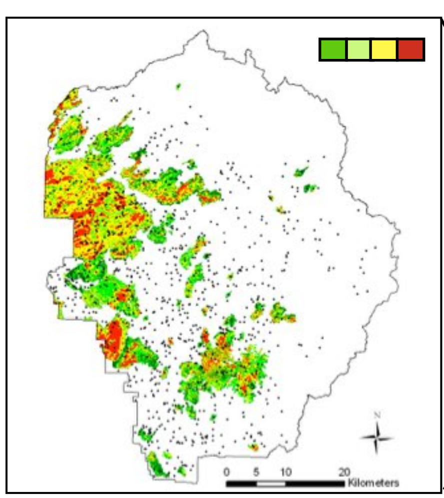


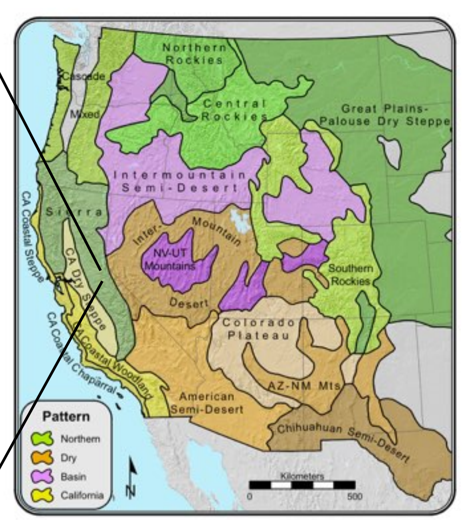
Fire climatology

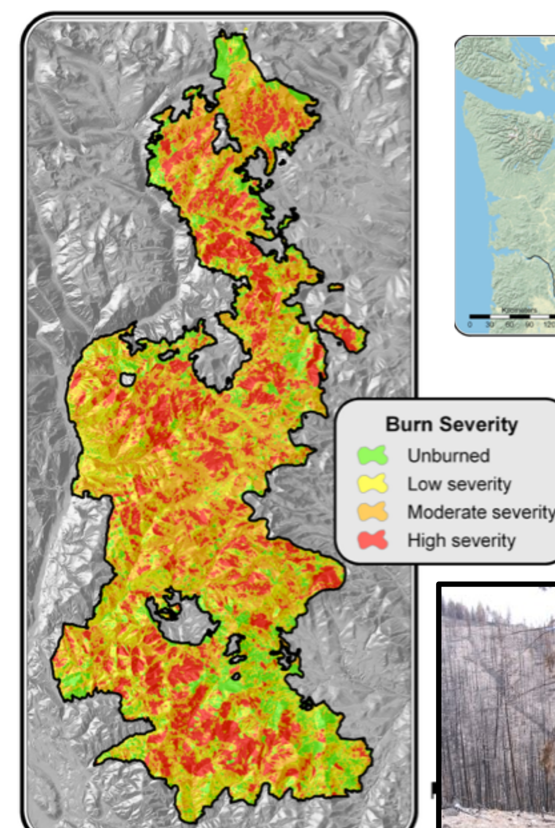
- Climatic controls on fire regimes.
- Top-down (climate) vs. bottom-up (topography, fuels) controls.
- Changing scales of inference: watersheds to ecoregions.

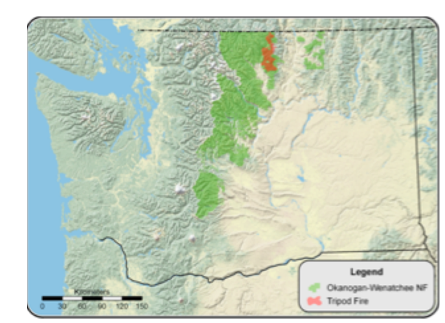
Fire weather

- Fire starts: convective storms, dry lightning.
- Fire spread: relative humidity, wind, fuel connectivity, slope.
- Fire duration & fire progression: consecutive days of fire weather.



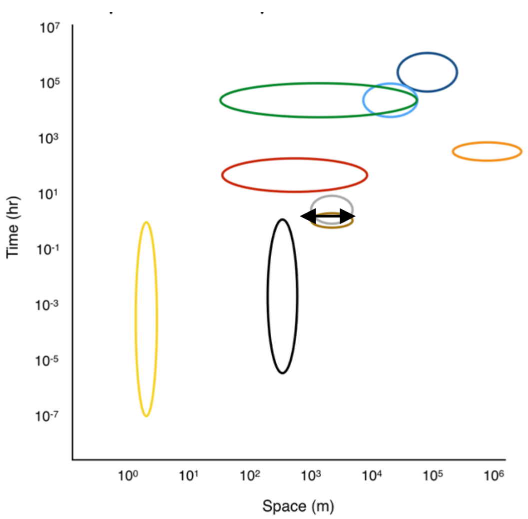


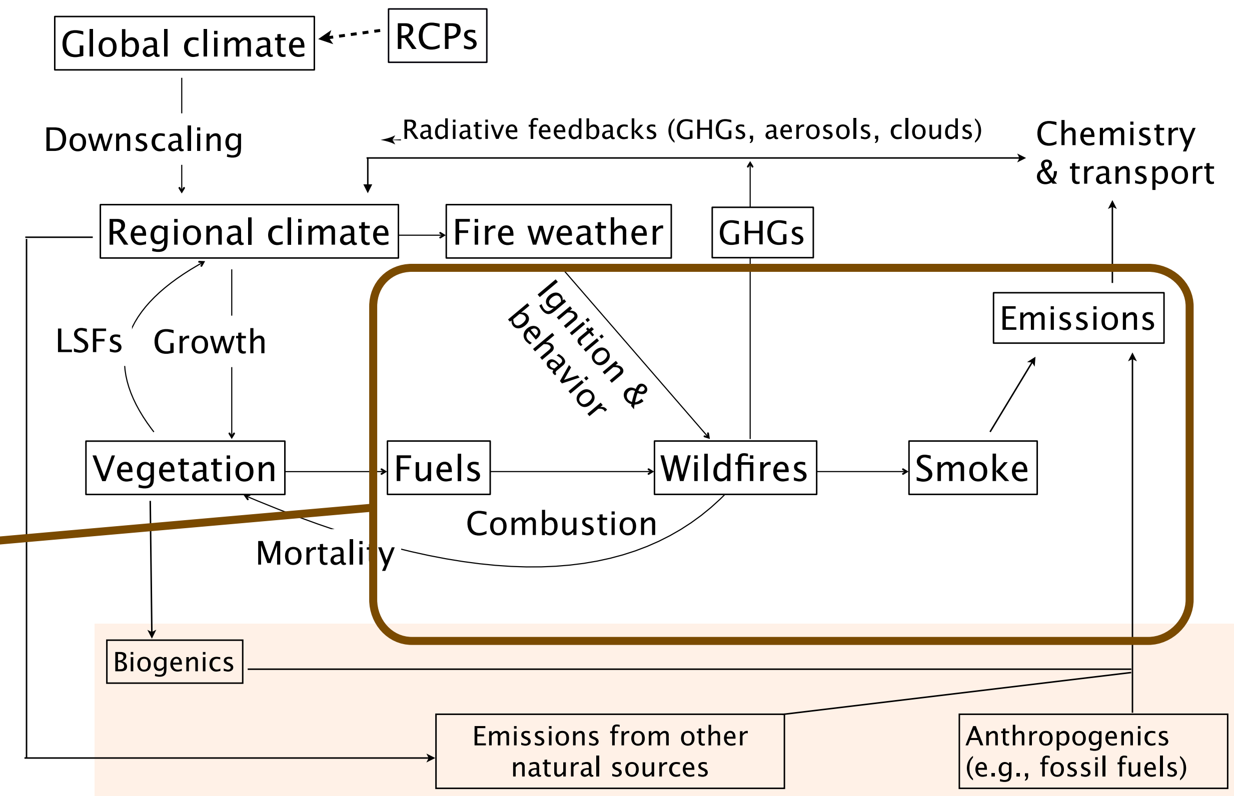




Fire severity: patchy at local scales

Consumption and emissions





Fuel consumption

- Fuel condition (flammability ~ moisture)
- Fuel abundance
- Fuel connectivity

Smoke emissions

- Combustion phase (flaming, smoldering, residual smoldering)
- Fuel chemistry
- Diurnal profile

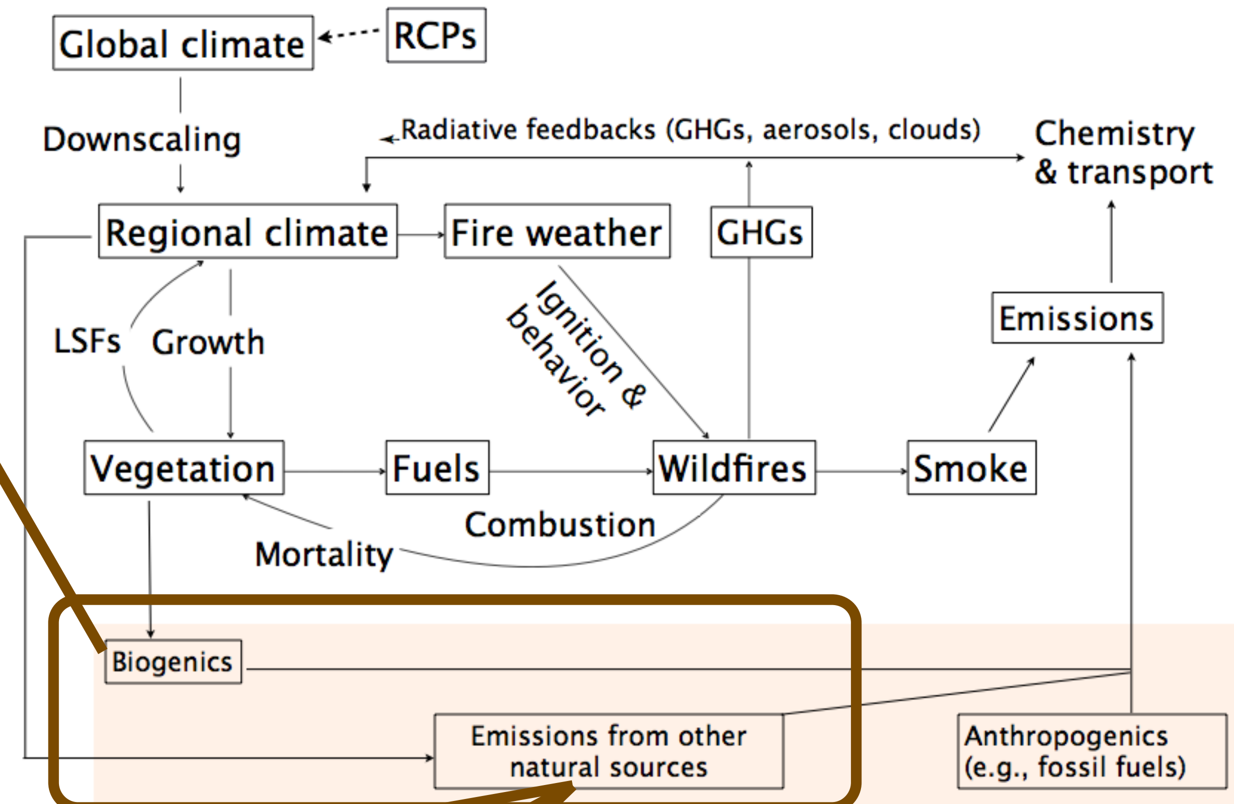
Emissions factors used in Consume

Emissions Factors by Pollutant (lb/ton)

Fuel Type	Combustion	PM	PM10[b]	$PM_{2.5}$	CO	CO_2	CH_4	NMHC
Default	Flaming	23	15	13	90	2522	3	5
(Average of all	Smoldering	34	24	19	209	2285	11	10
factors)	Residual	34	24	19	209	2285	11	10
BROADCAST-BURNED SLASH (Ward et al. 1989)								
Douglas-fir/hemlock	Flaming	24.7	16.6	14.9	143	3385	4.6	4.2
(n=12)	Smoldering	35	27.6	26.1	463	2804	15.2	8.4
	Residual	35	27.6	26.1	463	2804	15.2	8.4
Hardwoods	Flaming	23	14	12.2	92	3389	4.4	5.2
(n=8)	Smoldering	38	25.9	23.4	366	2851	19.6	14
	Residual	38	25.9	23.4	366	2851	19.6	14
Ponderosa & lodgepole pine	Flaming	18.8	11.5	10	89	3401	3	3.6
(n=3)	Smoldering	48.6	36.7	34.2	285	2971	14.6	9.6
	Residual	48.6	36.7	34.2	285	2971	14.6	9.6
Mixed conifer	Flaming	22	11.7	9.6	53	3458	3	3.2
(n=3)	Smoldering	33.6	25.3	23.6	273	3023	17.6	13.2
	Residual	33.6	25.3	23.6	273	3023	17.6	13.2
Juniper	Flaming	21.9	15.3	13.9	82	3401	3.9	5.5
(n=6)	Smoldering	35.1	25.8	23.8	250	3050	20.5	15.5
	Residual	35.1	25.8	23.8	250	3050	20.5	15.5
BROADCAST-BURNED BRUSH (Hardy et al. 1998)								
Sagebrush	Flaming	45	31.8	29.1	155	3197	7.4	6.8
(n=4)	Smoldering	45.3	29.6	26.4	212	3118	12.4	14.5
	Residual	45.3	29.6	26.4	212	3118	12.4	14.5
Chaparral	Flaming	31.6	16.5	13.5	119	3326	3.4	17.2
(n=9)	Smoldering	40	24.7	21.6	197	3144	9	30.6
	Residual	40	24.7	21.6	197	3144	9	30.6
NEW EMISSIONS FACTORS (S. Baker personal communication, Missoula Fire Laboratory)								
Western Pine	Flaming	na	na	13.82	81.65	1663.32	2.89	2.77
(n=53, n=57)[c]	Smoldering	na	na	14.43	141.47	1551.59	6.25	3.77
	Residual	na	na	14.43	141.47	1551.59	6.25	3.77
Minnesota Oak	Flaming	na	na	10.02	61.19	1709.21	1.66	1.92
(n=7)	Smoldering	na	na	10.45	109.06	1609.45	6.64	3.75
	Residual	na	na	10.45	109.06	1609.45	6.64	3.75
Minnesota Pine	Flaming	na	na	11.71	64.62	1694.33	2.03	2.03
(n=4, n=5)[c]	Smoldering	na	na	13.44	90.77	1644.78	3.09	2.61
	Residual	na	na	13.44	90.77	1644.78	3.09	2.61
Southern Pine	Flaming	na	na	11.44	72.79	1680.72	2.04	2.48
(n=77, n=78)[c]	Smoldering	na	na	9.91	119.34	1601.54	3.76	4.04
	Residual	na	na	9.91	119.34	1601.54	3.76	4.04
Sage	Flaming	na	na	12.92	126.35	1589.82	3.12	4.35
(n=8)	Smoldering	na	na	8.36	184.22	1452.55	11.92	14.28
	Residual	na	na	8.36	184.22	1452.55	11.92	14.28
Minnesota Grass	Flaming	na	na	12.18	61.35	1698.00	2.12	3.82
(n=16, n=7)[c]	Smoldering	na	na	10.75	109.37	1629.92	4.32	4.25
	Residual	na	na	10.75	109.37	1629.92	4.32	4.25
Arizona Piles	Flaming	na	na	7.74	52.66	1714.61	3.28	3.56
(n=49, n=27)[c]	Smoldering	na	na	21.05	130.37	1544.93	11.03	6.78
	Residual	na	na	21.05	130.37	1544.93	11.03	6.78

[a] Fire-average values are weighed-averages based on measured carbon flux.
[b] PM10 values are calculated, not measured, and are derived from known size-class distributions of particulates using PM and PM2.5.
[c] Flaming and smoldering sample sizes, respectively

Emissions from Non-fire Sources



Speciated emissions of gas and aerosol precursors

- Deciduous trees (isoprene)
- Coniferous trees (terpenes)

Volcanic emissions

- SO_2
- Ash
- CO_2

Wind-blown dust

- Si
- Fe
- Ca
- Mg
- Al
- etc.

Sea Spray

- Na
- Cl
- DMS

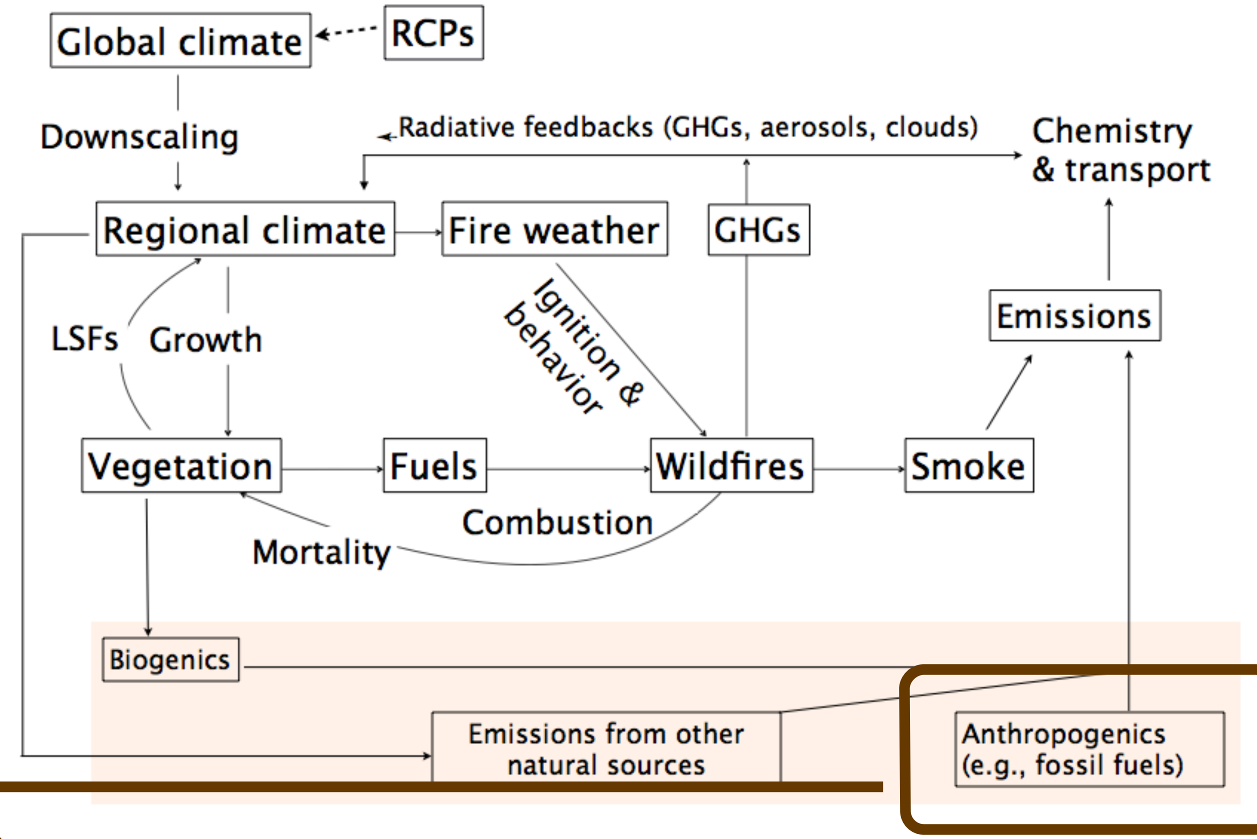
Non-fire Source Emissions (2)

Power Generation

- SO_2 and SO_4 (SO_x)
- NO and NO_2 (NO_x)
- CO_2

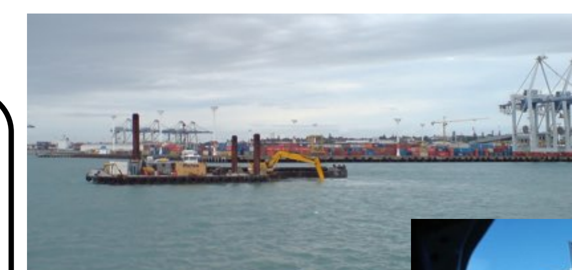
Oil and gas refinement

- VOCs
- NO_x



Agricultural Burning

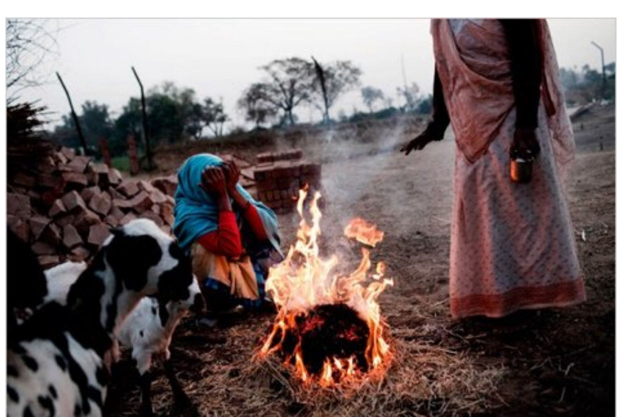
- OC
- EC
- NH_3



Vehicle exhaust

- NO_x
- CO_2
- Soot

and many more…

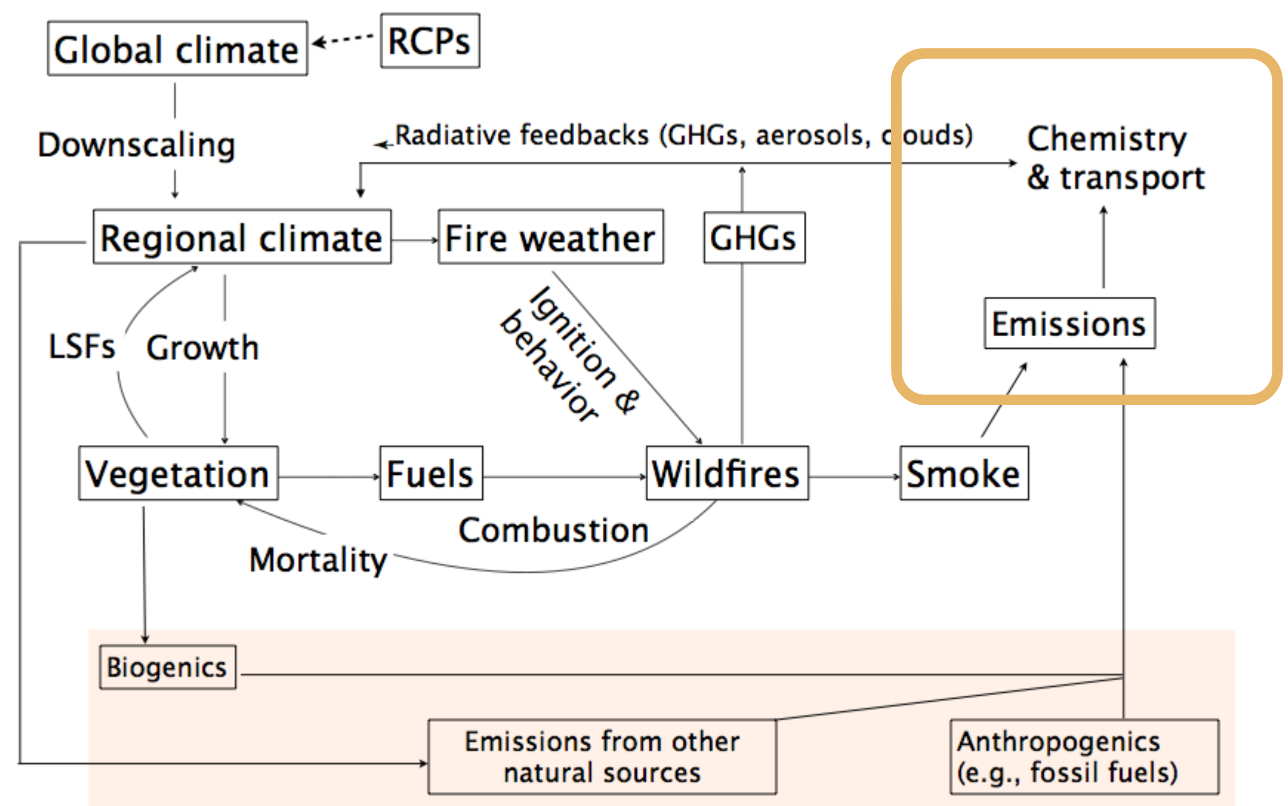


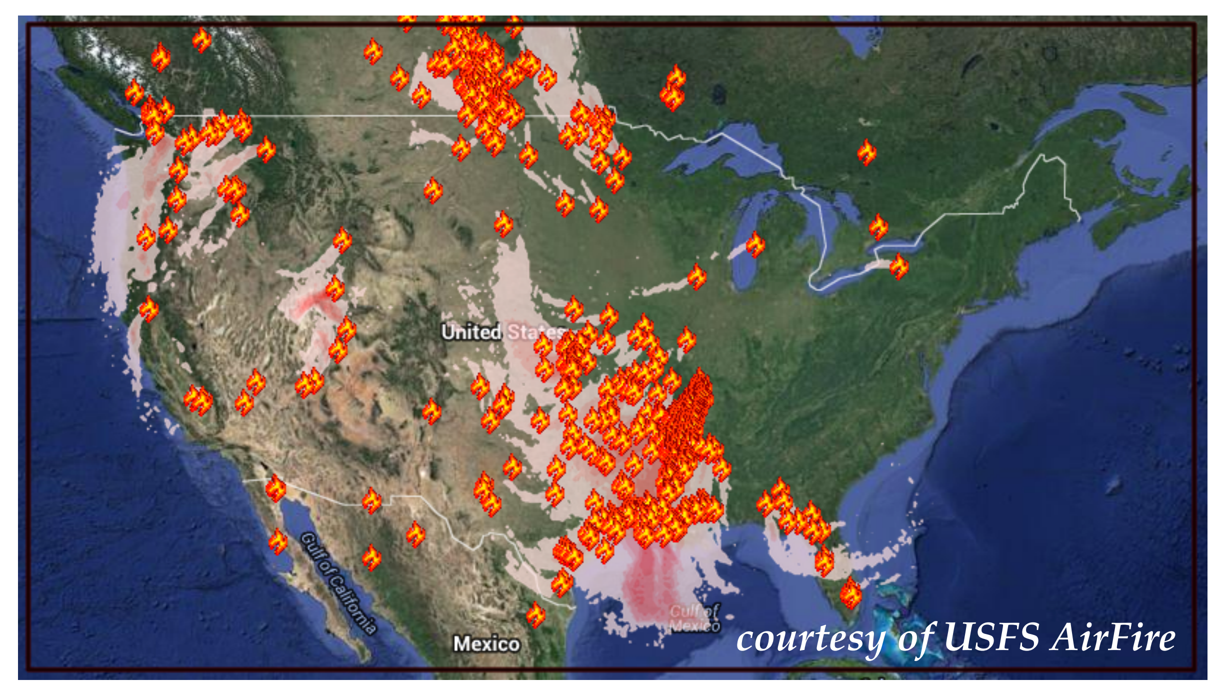
Cook stoves

- OC
- EC
- NH_3

Insert your air quality model here!

October 6, 2015	
	Grumman Auditorium
7:30 AM	Registration and Continental Breakfast
8:00 AM	A/V Upload for Oral Presenters
	***Fine Scale Modeling and Applications*, chaired by Jim Kelly (US EPA) and Jeremy Avise (CARB)**
8:30 AM	High-Resolution Simulations with CMAQ for Improved Linkages with Exposure Models **Martin Otte**, Chris Nolte, Robert Walko
8:50 AM	Comparison of Fine-Scale Modeling Techniques: Going from a 12-km to a 250-m grid resolution **Josephine Bates**, et al.
9:10 AM	Fine Scale Modeling of Ozone Exposure Estimates using a Source Sensitivity Approach **Cesunica Ivey**, Lucas Henneman, Yongtao Hu, Armistead Russell
9:30 AM	CMAQ-Urban: UK fine scale air quality modelling for dynamic human exposure studies **Nutthida Kitwiroon** and Sean Beevers
9:50 AM	Break
10:20 AM	Fine-scale characterizing the premature death associated with exposure to PM2.5 from onroad sources **Shih Ying Chang**, Saravanan Arunachalam, Marc Serre, Vlad Isakov
10:40 AM	Bridging the gap between the mesoscale and the neighborhood scale when characterizing heat stress in major cities in the US for current and future climate conditions **Adel Hanna**, Jason Ching, Joseph P. Pinto
11:00 AM	Fine Scale Modeling to Assess the Air Quality Impact of Vessels and Port Activity: Application to the Port of Savannahs Garden City Terminal Yongtao Hu, **M. Talat Odman**, Michael E. Chang, Armistead G. Russell, Hope Moorer
11:20 AM	C-LINE and C-PORT: Community scale tools for Near-source Impact Assessment **Saravanan Arunachalam**
11:40 AM	
12:00 PM	Lunch, Trillium Room
	***Air Quality, Climate and Energy*, chaired by Dan Loughlin (US EPA) and Jason West (UNC-Chapel Hill)**
1:00 PM	Air Quality Impacts of Damage Based Emissions Fees **Kristen E Brown**, Daven K Henze, Jana B Milford
1:20 PM	Assessing the Impacts of Emissions from Oil and Gas Extraction on Urban Ozone and Associated Health Risks **Shannon Capps**, et al.
1:40 PM	Integrated economic and climate projections of U.S. air quality benefits from avoided climate change **Fernando Garcia-Menendez**, Rebecca K. Saari, Erwan Monier, Noelle E. Selin
2:00 PM	Insights into future air quality: a multipollutant analysis of future scenarios using the MARKAL model **Julia Gamas** and Dan Loughlin
2:20 PM	Quantifying co-benefits of CO2 emission reductions for the US: An Adjoint sensitivity analysis **Marjan Soltanzadeh**, Robyn Chatwin-Davies, Amanda Pappin, Amir Hakami
2:40 PM	Break
3:10 PM	Expected ozone benefits from EGU NOx reductions **Timothy Vinciguerra**, et al.



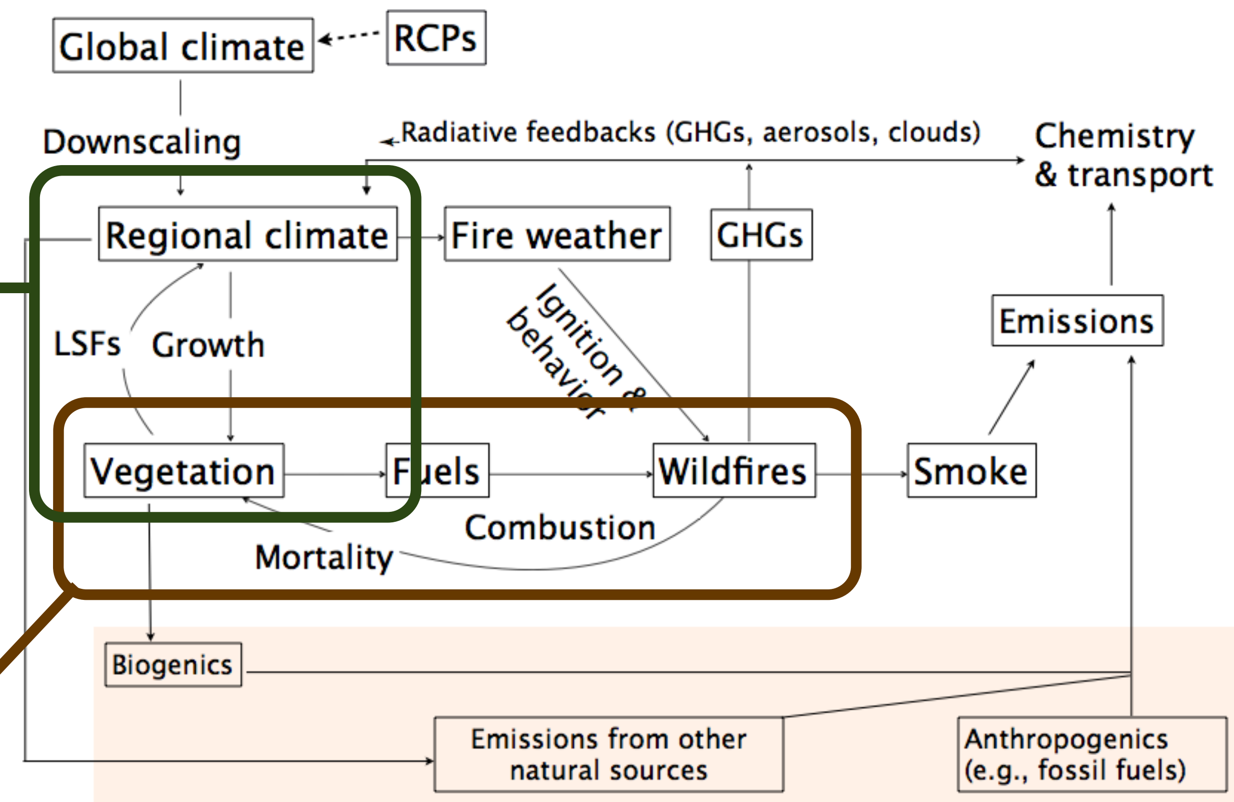


Feedbacks (1)

Feedbacks from vegetation to climate

✦Changing radiation budgets with loss of cover or type conversion

- May increase surface albedo (–)
- May decrease carbon sink (+)
- Air-surface exchange due to increased evaporation (+/–)
- Biogenic secondary organic aerosol radiative feedback (–)



Feedbacks from fire to vegetation

- Depending on severity, fires can be a strong negative feedback on subsequent fires. (–)
- Dependent on vegetation type. (+/–)
- Time-dependent, because fire is.
- Possible conversion of vegetation type with changes in fire frequency or severity in response to climate. (+/–)

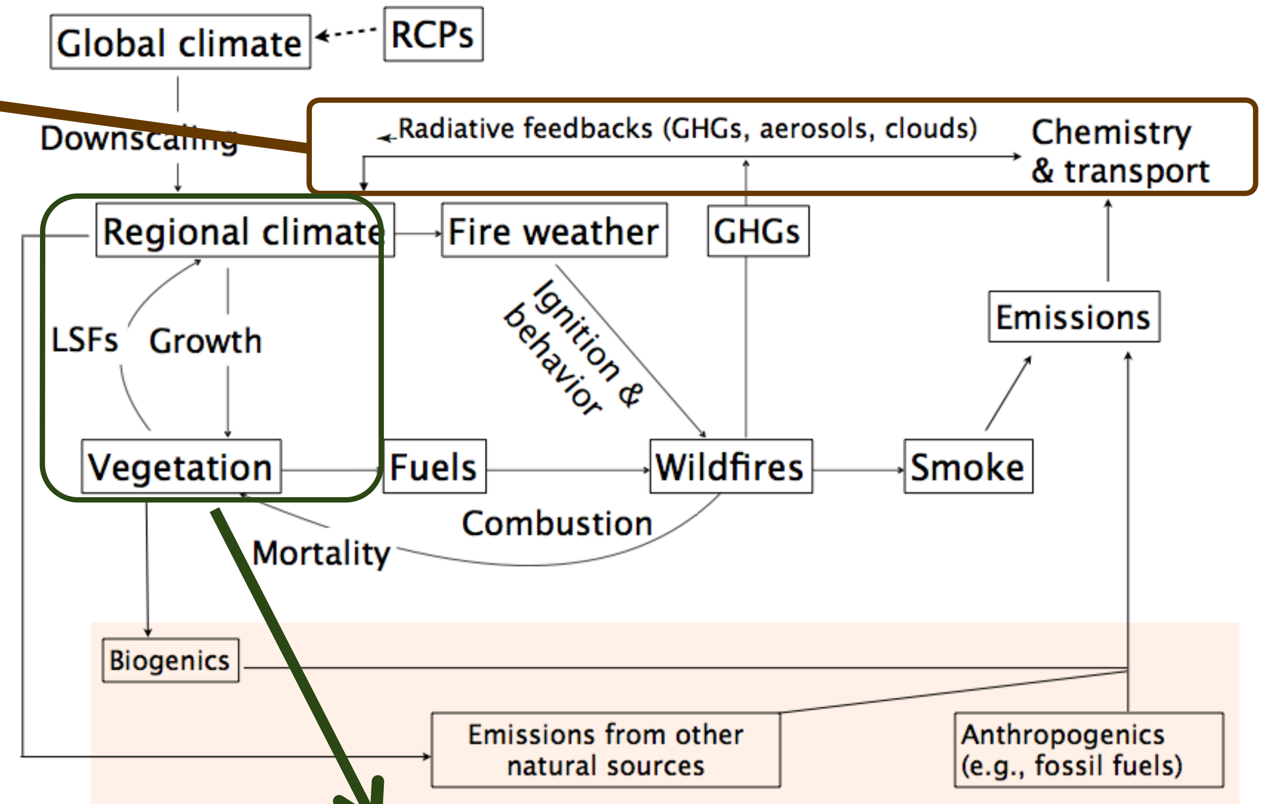
Swann et al. (2012)

Feedbacks (2)

Feedbacks from chemistry to climate

✦ Changing radiation budgets with fire emissions

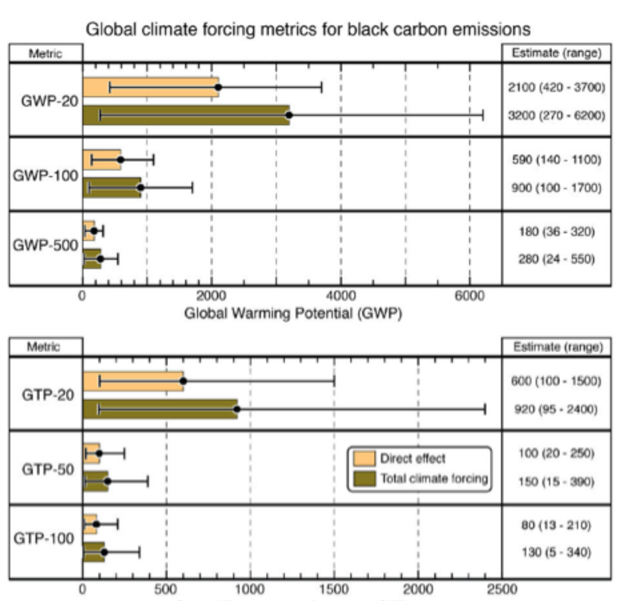
- Radiative forcing (RF) of CO_2, O_3 and H_2O (+) emitted directly or formed from precursors in smoke plumes
- Direct RF of black carbon (+), brown carbon aerosol (+/–)
- Indirect RF of aerosols from enhancing cloud albedo, lifetime (–)
- Semi-direct effect of black carbon on clouds (+/–)
- Short atmospheric lifetime for O_3 and aerosols compared to CO_2 → a high degree of spatial and temporal variability



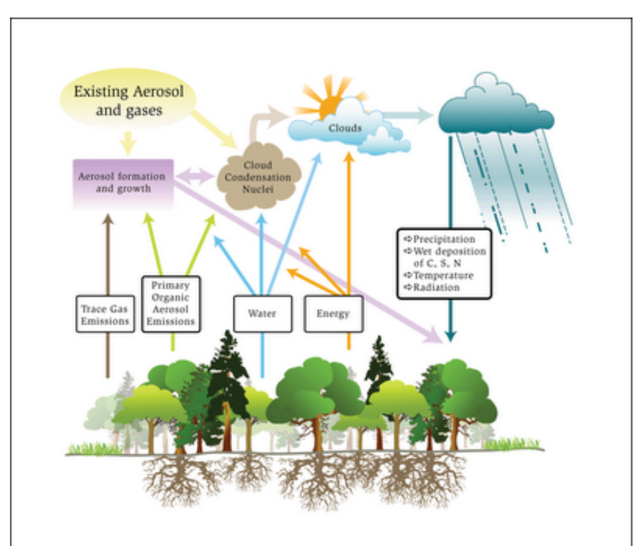
Feedbacks from vegetation to chemistry

✦ Changing atmospheric composition with vegetation

- As vegetation types change emission fluxes of isoprene, terpenes would change
- May shut down biogenic emissions in burn scar areas
- Affects oxidant and SOA budgets



Bond et al. (2013)



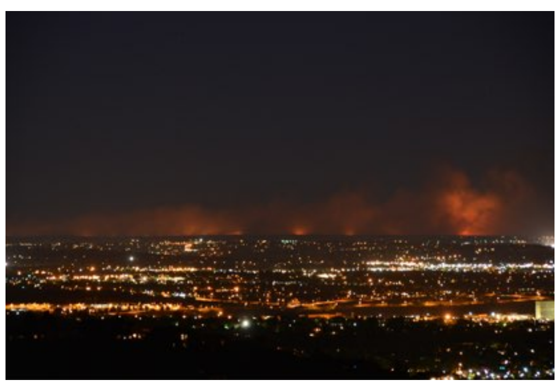
Wiedinmyer (2013)

Human-related feedbacks

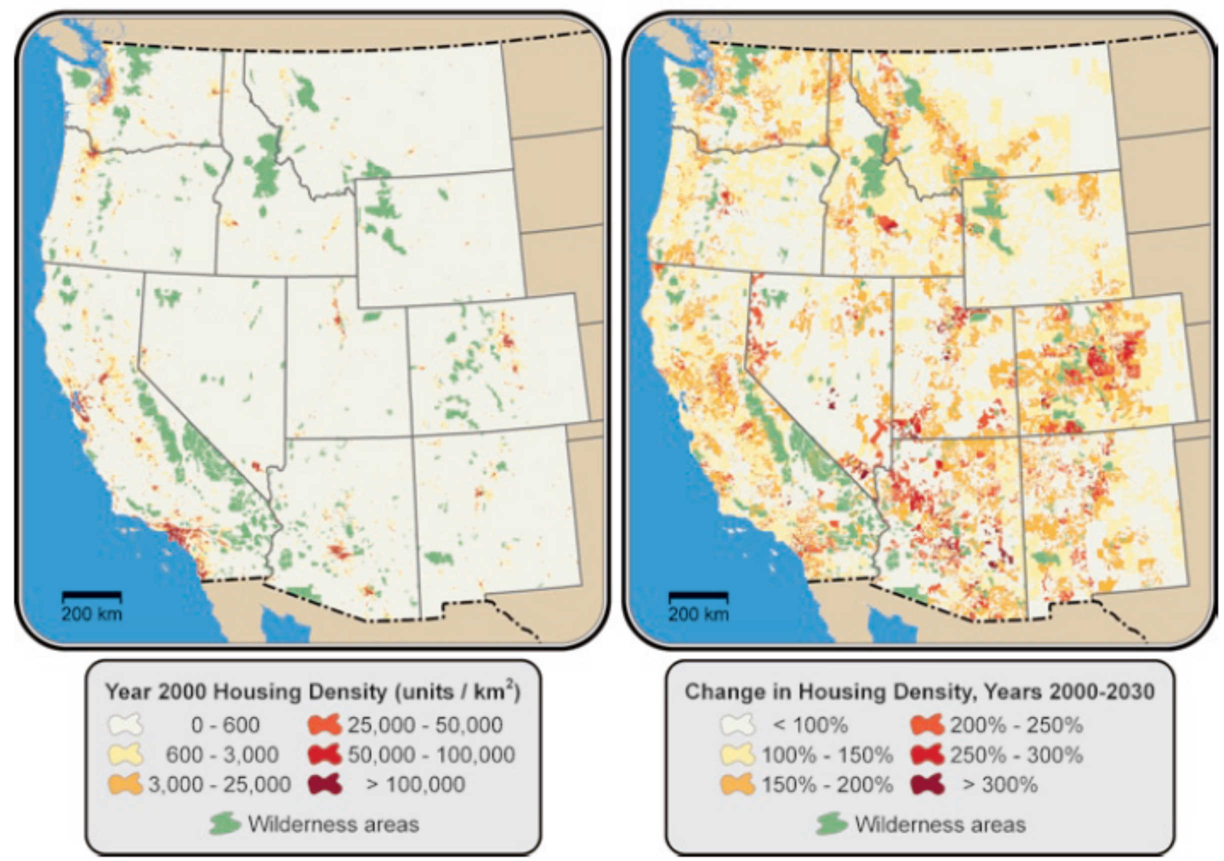
Changes in the wildland-urban interface (WUI)

Carol Miller et al. (2011)

- Spatial pattern and complexity within WUI.
- Demographics and broader-scale patterns.
- Effects on fire suppression.



Photos by Ahodges7 & U8oL0 (Wikimedia)



Feedbacks to fire probability

- Predictors of arson.
- Recreational land use.
- Commercial logging and thinning, or explicit fuel treatments, can change fire probability in the WUI and elsewhere.

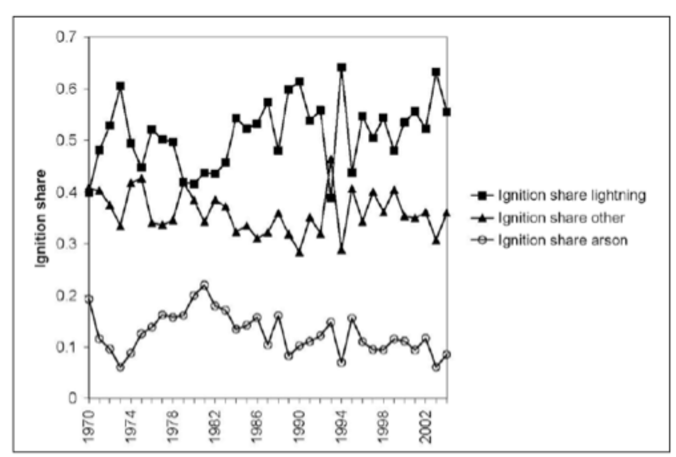


Figure 3—Share of wildland arson, lightning, and other wildfire ignitions on national forests, 1970-2004. (Source: USDA Forest Service 2007)

Prestemon & Butry (2007)

Model evaluation (1)

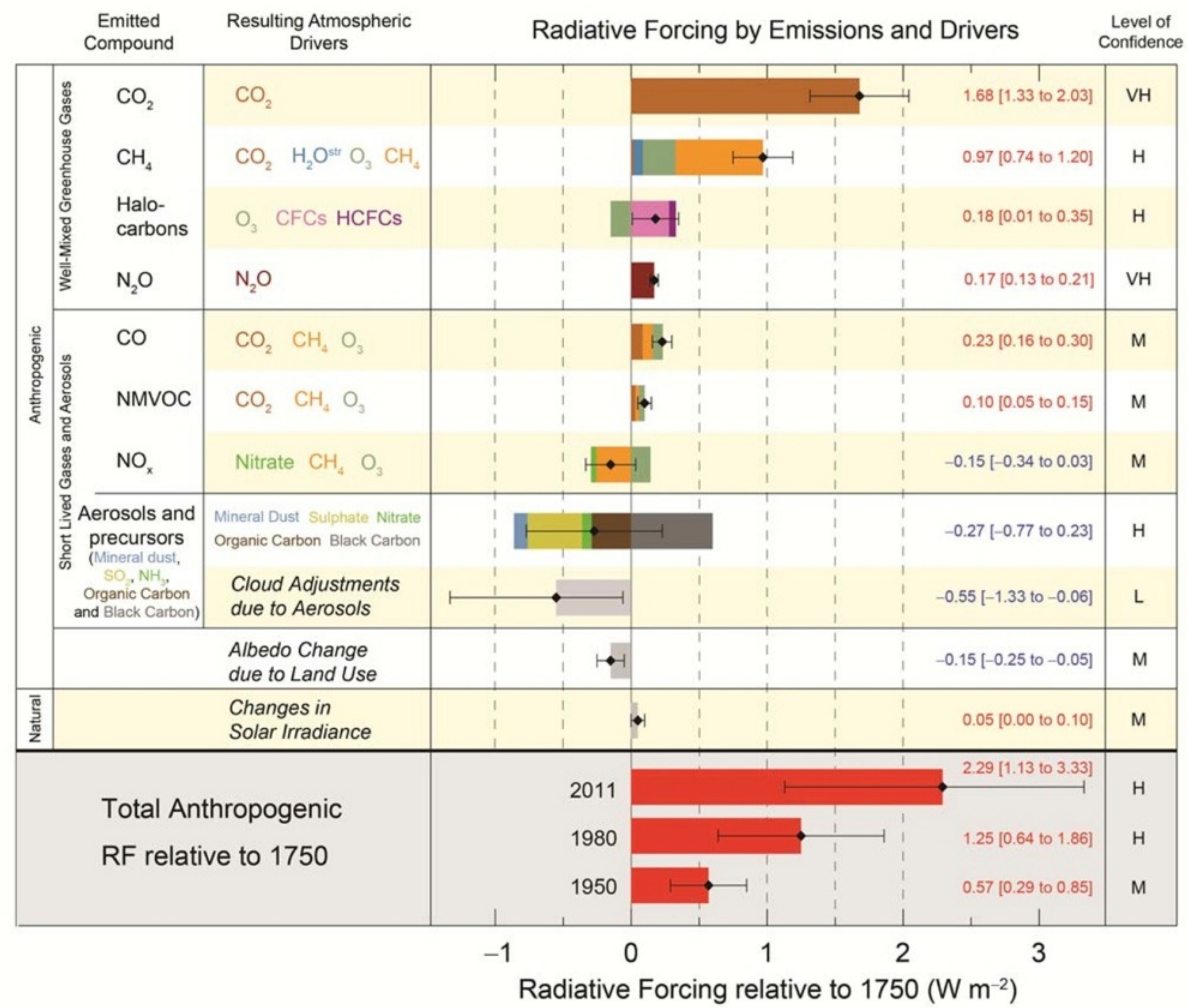
- Four broad criteria for acceptable performance from the system
  - Minimizing the cumulative effects of errors, uncertainties, and biases, e.g., scale mismatch
  - Algorithmic and computational feasibility
  - Transparency of outcomes: did you get the right answer for the right reasons?
  - Robustness to future projections
- Ultimately the system needs to match the needs of the assessment (obviously no model fits all)

these 3 slides are "IMHO"

Model evaluation (2)

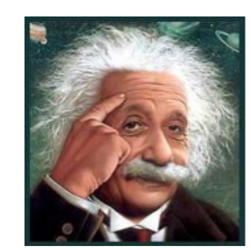
What to do in the absence of observations: with some lessons learned from the IPCC

- ✤ Embrace uncertainty
  - Take advantage of model differences.
  - Ensembles or model averaging.
  - Decide which uncertainties you can live with.
- ✤ Use multiple lines of evidence
  - e.g., Holocene fire, historical fire, fire observations.
  - Evaluate outcomes at multiple scales.
- ✤ Don't expect added complexity to reduce uncertainty.
  - Tradeoffs between complexity and replication.
  - Cumulative error may increase, but confidence in error bounds also increases.



these 3 slides are "IMHO"

Modeling Guidelines

- Coupled is better than disconnected, especially in modeling vegetation, fuel, and fire emissions in an evolving climate
- Distributions are better than points
  - But don't regress away the extremes
  - Decide when to use ensemble means rather than preserve the variability
- Watch out for scale mismatches
- Keep it as simple as possible but no simpler 

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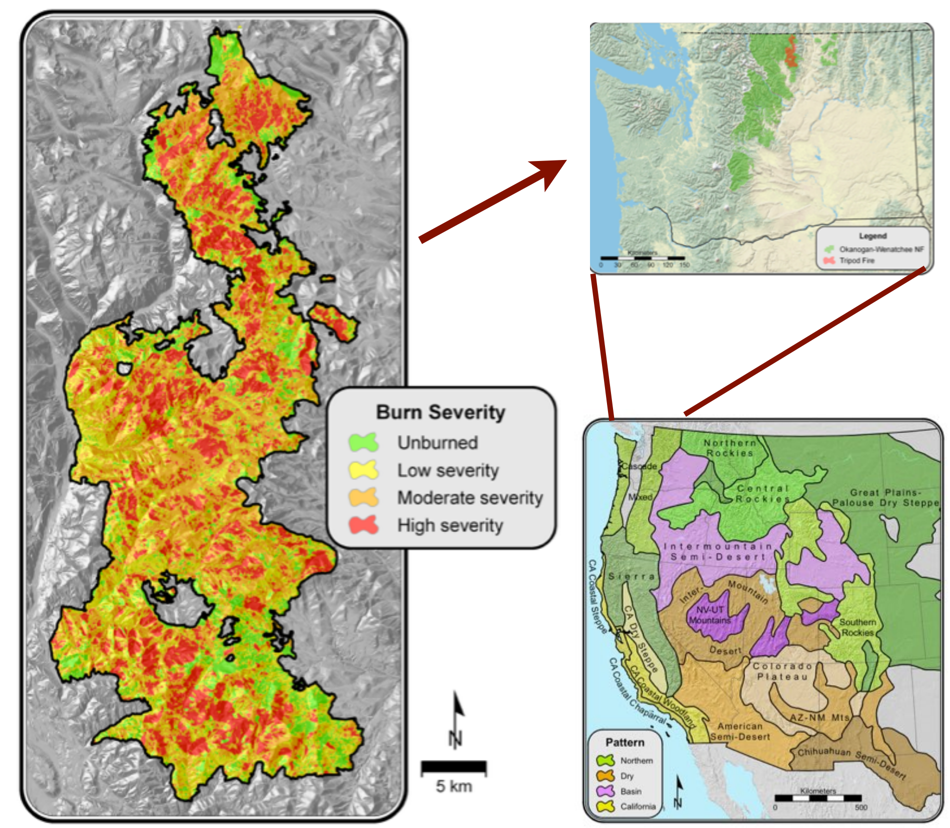
Research needs (1): fire and vegetation

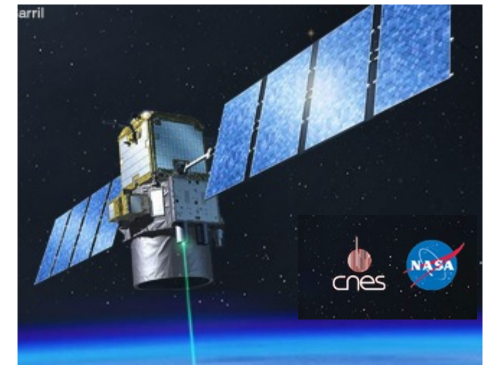
- Representing processes across scales
  - Contagion, fire spread, fire-fuel interactions on landscapes.
  - Species-specific responses of vegetation.
  - Key processes intractable to model at regional scales.

- Account for thresholds and tipping points
  - Proposed indicators of both cover a small percentage of (less interesting) cases.
  - Fire-vegetation interactions and feedbacks produce non-linear behavior.
  - Evaluate outcomes at multiple scales (e.g., thresholds may appear only at certain scales, by certain metrics).

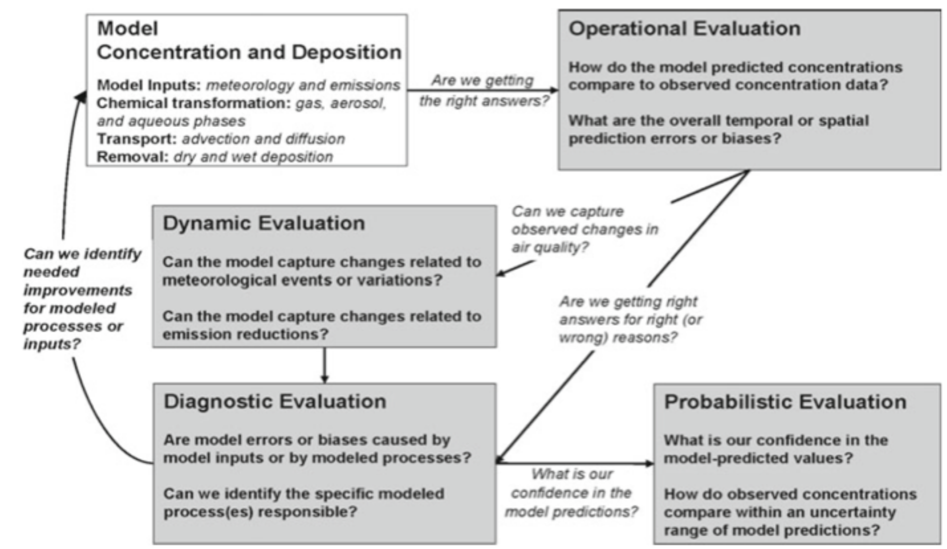


Research needs (2): air quality and climate

- Better observations of short-lived climate forcers.
  - Brown carbon and other emissions from fires.
  - Role of biogenic emissions in surface cooling (e.g., NOAA SE nexus).

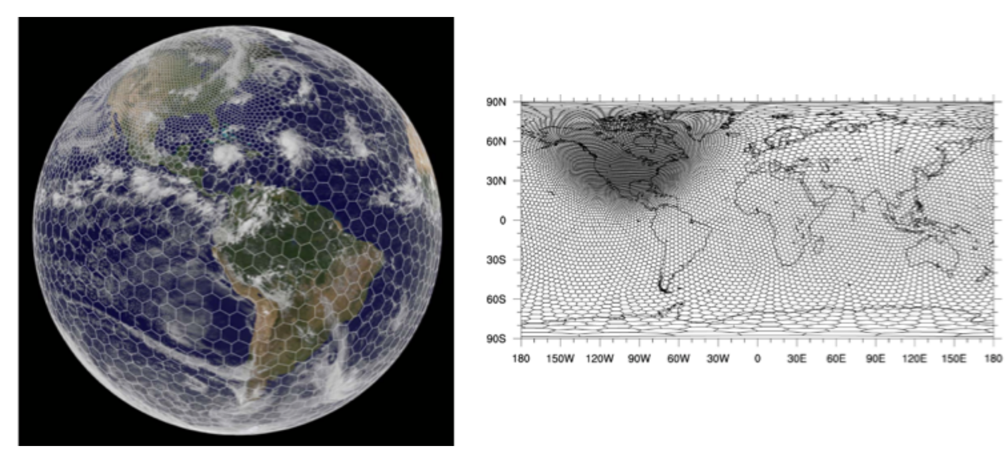


- Probabilistic evaluation of air-quality models.
  - Stochastic variation within ensembles, and Bayesian model averaging.
  - Incorporating feedbacks in ensembles with coupled modeling.



Dennis et al. (2010)

- Regional climate feedbacks to the larger circulations.
  - Next-generation RCMs with hexagonal grids might address this?
  - Need better coupling to ocean circulations in RCMs.



Skamarock et al. (2011) (NCAR)

The end