Graduate students:

Asmeret Berhe, Fang-Ru Chang, Erin Conlisk, Molly Cross, Teresa Chuang, Perry de Valpine, Jennifer Dunne, Brian Feifarek, Michael Geluardi, Eric Hallstein, Ann Kinzig Julia Klein, Laurie Koteen, Lara Kueppers, Susan McDowell, Scott Saleska, Francesca Saavedra, Becky Shaw, Karin Shen, Tiffany Shih, Adam Smith, Margaret Torn, Andrew Wilcox

Postdocs:

Michael Loik, Paul Higgins, Marc Fischer, Uthara Srinivasan

Many other assistants (> 60):

Billy Barr, Wendy Brown, Tracy Perfors, Hadley Renkin, Kevin Taylor, Sarah McCarthy, …

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A reminder of the central prediction of GCMs:

What is the effect on global average surface temperature of doubling the atmospheric concentration of carbon dioxide?

The direct effect of heat absorption by the CO$_2$: $+1.2 \, ^\circ C$

The indirect (feedback) effects: $+0.3$ to $3.4 \, ^\circ C$

- melting ice and snow increases absorption of sunlight (ice-albedo effect)
- warmer air holds more water vapor, a greenhouse gas
- warmer air results in different cloud characteristics

TOTAL: $+1.5$ to $4.6 \, ^\circ C$

*Note: No Biology here!*
IMPACTS OF GLOBAL WARMING

*** Greater intensity, frequency & duration of harmful summer heat waves

*** Sea level rise of at least ½ m by 2100; loss of some island nations

*** Melting of glaciers and sea ice; loss of alpine and arctic habitat; polar bears!

*** Reduced snow pack; loss of irrigation water for crops

*** Coral reef degradation due to bleaching

*** Near unanimity among scientists active in the field; high level of confidence in predictions
MORE IMPACTS OF GLOBAL WARMING

** Increased intensity and possibly frequency of hurricanes and droughts

** Reduced crop yields because of extreme events and persistent drought

** Increased threat of major wildfires

** Consensus exists on the underlying science and facts; work needed to sharpen predictions
AND STILL MORE IMPACTS

* Sea level rise up to 40 feet because of Greenland and Antarctica ice melt ("bi-polar disorder"); catastrophic damage to huge numbers of people and to much coastal infrastructure

* Extinction episode comparable to K-T boundary; catastrophic loss of ecosystem services

* Major spread of infectious tropical and subtropical diseases to the mid-latitudes

* Agreement that the problem is real and of serious importance; data gaps and some basic science still to be resolved
Climate-Ecosystem Feedbacks

Do these ecological feedbacks matter?
Retreat of N. American Ice Sheet

Models with rock and silt surface predicts slow retreat

Rate of retreat (km y⁻¹)

Rock, Silt
a = 0.4

Surface Absorption
(1-albedo)
Retreat of N. American Ice Sheet: Evidence for vegetation-mediated feedback

Models without spruce trees cannot predict actual rate of retreat of continental ice sheet

The spruce trees weren’t following the ice north… they were chasing it!
The Vostok core data imply feedback

Orbital variations are the time keeper, but their magnitude is too weak to explain the magnitude of the huge climate variability.

$\text{CO}_2$ (and CH$_4$) release during slight warming must cause more warming!

And $\text{CO}_2$ (and CH$_4$) uptake during slight cooling must cause more cooling.

The mechanisms behind this feedback is not incorporated in our current GCM’s.
But where are the carbon and the methane coming from?

And can we assume that the mechanisms causing this feedback over the paleoclimate temperature range will still operate in the future climate?

And what other feedbacks to climate change may be lurking in the biosphere?
How can we learn about ecosystem responses to climate change?

1. Ecological patterns across different climates
   • natural climate variability in space (latitudinal, altitudinal)
   • natural inter-annual variability of climate
   • decadal to century ecological trends synchronous with global warming trends
   • paleoclimatic variability, combined with pollen records and other ecological reconstructions

2. Climate manipulation experiments, with control, allowing deduction of causal mechanisms

3. Mathematical models

Each approach has its advantages and its problems:

1. Applicable to large spatial scales, but potentially misleading.
2. Confined to plot-scale, but capable of identifying mechanisms.
3. Only as good as the observations!
### Possible Levels of Aggregation in Global Models

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
<th>Number of Entities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planet</td>
<td>Biomes</td>
<td>N=1</td>
</tr>
<tr>
<td>Single big leaf</td>
<td>Coarse Functional Groups</td>
<td>N ~ 10</td>
</tr>
<tr>
<td>N=1</td>
<td>Ecosystems Functional Groups</td>
<td>N ~ 1000’s</td>
</tr>
<tr>
<td>Community Patch</td>
<td>Species assemblage</td>
<td>N ~ millions</td>
</tr>
</tbody>
</table>

We hope we don’t have to go to this level of disaggregation. Certainly too crude.
A “longterm” warming experiment

The Rocky Mountain Biological Laboratory (RMBL)
Gothic CO (9600’)
Infra-red heaters (22 W m⁻²). Soil is warmer (+ 2°C), drier (-15% gravimetric). Experiment begun in 1990; heaters on day and night, year around.
A Typical Spring snow melt about weeks earlier than in control plots
The UC Berkeley long-term climate-warming experiment in the Colorado Rockies:

-30
-15
0
15
30
% Change in plant cover

forbs (e.g. daisies)
sagebrush

Also a 3-fold reduction in flowering success of shallow-rooted forbs in heated plots

Harte and Shaw, Science, 1995
Feedback # 1: climate-induced change in species composition can alter late-spring surface albedo

A 20% change in regional plant cover will have an effect on local summertime climate that is comparable to 2 x CO₂ forcing.

Darker plants cause warming.
Feedback # 2: methane consumption influenced by soil moisture

If warming → soil drying:

positive feedback  negative feedback

Potentially, this effect could result in a factor of 2 change in net methane emissions

Torn and Harte, Biogeochemistry, 1995
**Feedback # 3:** warming can alter ecosystem carbon storage, and thus change atmospheric CO₂

If this loss of carbon from heated soil is typical of soils around the world, it would result in a feedback effect comparable to several decades of fossil fuel burning.

*Saleska et al., Global Biogeochemical Cycles, 2002*
Something surprising occurred after these data were published:

Starting in ~ 2000, the control plots are losing soil carbon, somewhat like the heated plots did in 1991-1994!
Warming on the Tibetan Plateau

- decreased plant species diversity and vegetative production
- decreased ecosystem services (*medicinal & forage plants*)
- shrub expansion / woody encroachment

Critical pastoral resources in Tibet are vulnerable to warming.

Land management (grazing) can partially mediate warming effects.

Part 3: The challenge of scaling up

The feedback linkages in the meadow are very complex. And we have barely begun to look at:

- **Other Habitats** (tundra, desert, savannah, temperate forests, boreal forests, tropics, freshwater, marine …)
- **Larger Spatial Scales** (emergent phenomena?)
- **Animals** (grazers, pollinators, …)
- **Carbon Dioxide increase** (water use efficiency, growth stimulation)
- **Nitrogen Deposition** (N addition can increase carbon storage)
- **Land Use Changes** (albedo, water exchange …)
- **Invasive Species** (influence on carbon storage (Laurie Koteen’s work), albedo, water exchange)
- **Genetic differences between populations** (influences shifts in community composition)
Species matter!
Response to climate vs. effect on soil carbon turnover

<table>
<thead>
<tr>
<th>Response to Climate</th>
<th>Effect on Carbon turnover</th>
<th>Medium lignin:N</th>
<th>Lower lignin:N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow rooted</td>
<td>Forb: Erigeron speciosus</td>
<td></td>
<td>Forb: Delphinium nuttallianum</td>
</tr>
<tr>
<td>(sensitive to drought)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep rooted</td>
<td>Forb: Ligusticum porteri</td>
<td></td>
<td>Forb: Helianthella quinquinervis</td>
</tr>
<tr>
<td>(less sensitive to drought)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
We also need to know how species will re-locate in response to climate change

Bioclimate Models Rely on the Climate-Envelope Concept:

Each species has a set of temperature/precipitation parameters, which are determined from where it is now found and which determine where it will be found in the future.

Yes, but:

• Assumption of unlimited dispersal
• Disregard for phenotypic variation
Using IBIS, a climate-ecosystem model developed by Jon Foley, and assuming 5 alternative assumptions about plant dispersability, we modeled ecosystem-mediated carbon and energy flux feedbacks.

Mean total global carbon storage (Pg-C) in plants and soil for each IBIS simulation (4 x CO2 forcing)

<table>
<thead>
<tr>
<th>Dispersal Scenario</th>
<th>Biomass Carbon (Pg)</th>
<th>Soil Carbon (Pg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>control climate and vegetation</td>
<td>715</td>
<td>1688</td>
</tr>
<tr>
<td>all plants free to disperse</td>
<td>561</td>
<td>972</td>
</tr>
<tr>
<td>no dispersal</td>
<td>274</td>
<td>810</td>
</tr>
<tr>
<td>dispersal only within grid cell</td>
<td>405</td>
<td>819</td>
</tr>
<tr>
<td>grasses and shrubs free to disperse, not trees</td>
<td>390</td>
<td>1001</td>
</tr>
<tr>
<td>dispersal only to adjacent grid cells</td>
<td>485</td>
<td>980</td>
</tr>
</tbody>
</table>

P. Higgins and J. Harte, *BioScience, 2006*
Phenotypic Variability across a Species Range

a simple illustration of why it matters:

Assuming no migration or dispersal:

1. **no local adaptation**: only pop. 1 and part of pop. 2 lost
2. **local adaptation**: every population lost and species goes extinct!

D. Jensen, PhD thesis, UC Berkeley, showed that option 2 is more appropriate for white fir in the CA Sierra; but Perkins et al., show no effect for Fir in Rockies.
Summary of the major factors that make the challenge of predicting ecosystem responses to climate change so daunting:

1. **Species matter**
   (Response-to-Climate traits ≠ Effects-on-Climate traits)

2. **Phenotypic differences within species may matter** (The species ‘climate envelope’ concept needs to be pushed)

3. **Dispersal patterns matter**
   (yet we know little about empirical dispersal distributions.)

The dilemma of climate-ecosystem coupling In a nutshell:

**Ecology**: require fine spatial resolution but can get by with simple math

**Atmospheric Dynamics**: require coarse spatial resolution because the conventional math (Navier-Stokes etc.) is not simple
Summary

• Analysis suggests that ecosystems will change dramatically in response to climate change and that these changes will cause feedbacks to the climate.

• Some of these feedbacks are not incorporated in our current climate models; if they were, we would predict even greater warming in the future.

• Ecosystem warming experiments shed some light on these issues, but ...

• Climate models will have great difficulty reliably incorporating ecological feedbacks to global warming because of the complexity of ecosystems.
ECOLOGICAL FEEDBACKS to CLIMATE

Atm. Greenhouse Gases

F6

Radiation Balance

F4

Microbial CH₄ Oxidation

Soil T (+)
Soil M (-)
Meltdate (earlier)

F5

Albedo

NPP

Woody Growth

Species Composition

Litter Quality

Litter Quantity

Soil Decomposition

F3

F2

F1
**ECOLOGICAL FEEDBACKS to CLIMATE**

Atm. Greenhouse Gases

Radiation Balance

F1: T,M $\rightarrow$ decomposition $\sim 0$

F2: meltdate $\rightarrow$ forb/shrub $\rightarrow$ litter quality

F3: meltdate $\rightarrow$ forb/shrub $\rightarrow$ litter quantity

F4: meltdate $\rightarrow$ woody growth

F5: meltdate $\rightarrow$ forb/shrub $\rightarrow$ albedo

F6: soil M $\rightarrow$ microbial oxidation of CH$_4$

Microbial CH$_4$ Oxidation

Soil Decomposition

Species Composition

NPP

Litter Quantity

Litter Quality

Soil T (+) Soil M (-) Meltdate (earlier)

Albedo

Woody Growth
ECOLOGICAL FEEDBACKS to CLIMATE

Atm. Greenhouse Gases

F6: meltdate → woody growth

F5: meltdate → forb/shrub → albedo

F4: soil M → microbial oxidation of CH₄

F3: meltdate → forb/shrub → litter quantity

F2: meltdate → forb/shrub → litter quality (-)

F1: T,M → decomposition

Species Composition

Litter Quality

Litter Quantity

Soil Decomposition

Microbial CH₄ Oxidation

Soil T (+) Soil M (-) Meltdate (earlier)

Radiation Balance

NPP

Woody Growth

Albedo
ECOLOGICAL FEEDBACKS to CLIMATE

Atm. Greenhouse Gases

Radiation Balance

F4: meltdate → woody growth

F5: meltdate → forb/shrub → albedo

F6: soil M → microbial oxidation of CH₄

F1: T,M → decomposition

F2: meltdate → forb/shrub → litter quality

F3: meltdate → forb/shrub → litter quantity (+)

F4: meltdate → woody growth

F5: meltdate → forb/shrub → albedo

F6: soil M → microbial oxidation of CH₄
ECOLOGICAL FEEDBACKS to CLIMATE

Atm. Greenhouse Gases

Radiation Balance

- Soil T (+)
- Soil M (-)
- Meltdate (earlier)

F4(-)

Albedo

Woody Growth

NPP

Species Composition

Litter Quantity

Litter Quality

Soil Decomposition

Microbial CH₄ Oxidation

F1: T,M → decomposition
F2: meltdate → forb/shrub → litter quality
F3: meltdate → forb/shrub → litter quantity

F4: meltdate → woody growth (-)

F5: meltdate → forb/shrub → albedo

F6: soil M → microbial oxidation of CH₄
**ECOLOGICAL FEEDBACKS to CLIMATE**

**Atm. Greenhouse Gases**

F4: *meltdate* → woody growth
F5: *meltdate* → forb/shrub → albedo (+)
F6: soil M → microbial oxidation of CH₄

**Radiation Balance**

Soil T (+)  Soil M (-)  Meltdate (earlier)

**Albedo**

NPP

**Woody Growth**

**Species Composition**

Litter Quality
Litter Quantity

**Soil Decomposition**

F1: *T,M* → decomposition

F2: *meltdate* → forb/shrub → litter quality

F3: *meltdate* → forb/shrub → litter quantity

F4: *meltdate* → woody growth

**F5:** *meltdate* → forb/shrub → albedo (+)

**F6**
ECOLOGICAL FEEDBACKS to CLIMATE

Atm. Greenhouse Gases

Radiation Balance

F6(+,-)

Microbial CH₄ Oxidation

F1: T,M → decomposition

F2: meltdate → forb/shrub → litter quality

F3: meltdate → forb/shrub → litter quantity

F4: meltdate → woody growth

F5: meltdate → forb/shrub → albedo

F6: soil M → microbial oxidation of CH₄ (+,-)
ECOLOGICAL FEEDBACKS to CLIMATE

Atm. Greenhouse Gases

Radiation Balance

Microbial CH₄ Oxidation

Soil T (+)

Soil M (-)

Meltdate (earlier)

Albedo

Woody Growth

Species Composition

NPP

Litter Quality

Litter Quantity

Soil Decomposition

Magnitudes and Overall Sign of Feedbacks:

SHORT-TERM (years to decade):  \( F3(+) > F5(+) > F4(-) > F2(-), F6 (+) > F1 \sim 0; (+) \)

LONG-TERM (decade to century):  \( F5(+), F2 (-) > F3(+), F4(-), F6(+) > F1 \sim 0; (?) \)