Announcements

Graduate Homework #2 due today

Breakout #2 on Thursday, 10/7:
- Undergrad presentations in class with Julie (presenters can turn in homework late)
- Grad discussion in Gould-Simpson 209 (assigned reading is posted)

Reminder: Undergrad Presentations on Thursday

• Drivers of Deforestation in tropical Africa
  Hannah Foster, Breana Quesada
• Global Change impacts on plant productivity
  Robert Newman, Tara Bonestroo, Benjamin Vernon
• Are tropical forests a source or a sink of atmospheric CO₂?
  Molly Hoak, Kali Lucy
• Do invasive species influence southwestern ecosystems?
  Billy Linker, Jessica Thompson
The Water cycle and climate in Terrestrial Ecosystems

I. The Global Water cycle & Climate change
II. Impacts of changes in Water cycle
III. Water and ecosystems

I. The Global water cycle

Atmosphere: 13,000

Lakes: 230,000

Ice: $33 \times 10^6$

Oceans: $1.350 \times 10^9$

Soil water: 120,000

Vegetation: 10,000

Groundwater: $15.3 \times 10^6$

Freshwater available for interaction with terrestrial biosphere is small

In km$^3$ (pools) and km$^3$/yr (fluxes)
I. The Global water cycle

Atmosphere: 13,000 km³

Atmospheric supply to Land (precipitation) is greater than land return to atmosphere (evapotranspiration)

Opposite it

Precip: 1
Evaporation: 425,000 km³
Oceans: 1.350 x 10⁹ km³

Plants power water return to atmosphere on land

Runoff: 40,000

Ocean water powers land precip

Soil water: 120,000 km³

Vegetation: 10,000 km³

Ice: 33 x 10⁶ km³

Lakes: 230,000 km³

Precip: 385,000 km³

Evaporation: 425,000 km³

Transpiration

Groundwater: 15.3 x 10⁶ km³

Soil water: 120,000 km³

Oceans: 1.350 x 10⁹ km³

In km³ (pools) and km³/yr (fluxes)
Facts about the global water cycle

- Global precip: 385,000 (ocean) + 111,000 (land)
  \[496 \times 10^3 \text{ km}^3 \div 510 \times 10^6 \text{ km}^2 = 0.97 \times 10^{-3} \text{ km}\]

- Land area is 148 \times 10^6 \text{ km}^2 \rightarrow 111 \div 148 = 0.75 \text{ m}
  - Comparison: Tucson gets 0.30 m,
  - tropical forests 2 or 3 m

Earth surface area

\[\approx 1 \text{ meter of precip (global average)}\]
I. The Global Water Cycle and Climate Change
(Effects of Climate change on water cycling)

Recall from climate lectures:

Robust drying of the subtropics, 20-35N&S.

Note: Stippling is where model predictions are consistent: the multimodel average change exceeds the standard deviation among models
Effects of Climate Change on PRECIPITATION, by season:

(IPCC, 2007)

Consistent winter drying in S.W. N. America

Possible seasonal drying in Amazon

II. Impacts of Changes in the Water cycle

- Impacts on temperature (evaporation is latent heat flux)
  (e.g. reductions in evaporation reduce removal of heat via water flux, inducing temperature increases)

- Patterns of plant growth

(From last time)
II. Impacts of Changes in the Water cycle

- Impacts on temperature (evaporation is latent heat flux)
  (e.g. reductions in evaporation reduce removal of heat via water flux, inducing temperature increases)

- Patterns of plant growth

- water mediates the cycling of many other elements
  - Carbon cycling, through influence on plants
  - flow of water transports other elements

- Weathering of rock

- In general, many aspects of human society
  - agriculture
  - drinking water supply

Humans now use >1/2 of global river flow (Postel et al., 1996)

11 Long-term research sites:
ARC = Arctic Tundra
NWT = Niwot Ridge, CO
JRN = Journada
SEV = Sevilleta
CDR = Cedar Creek
KNZ = Konza Prairie
SGS = Shortgrass Steppe
KBS = Kellogg Biol. Station
BNZ = Bonanza Creek
HBR = Hubbard Brook
HFR = Harvard Forest
Focus on ecosystems

Water Inputs to Ecosystems
• Precipitation
  – THE major water input to most ecosystems
• Groundwater (in some ecosystems)
• Fog deposition (in some ecosystems)

What controls water loss from ecosystems (runoff to ocean or return to the atmosphere)?

→ PLANTS!

Plant water loss: via Stomata

Leaf openings through which CO2 is taken in and water is lost
Plant water loss: via Stomata

*Leaf openings through which CO2 is taken in and water is lost*

**Leaf X-section**

**Leaf surface**

How does water moves through plants and leaves?

**Fundamental trade-off: Carbon-in ↔ water-out**

**Global terrestrial water-use efficiency (WUE) for carbon:**

\[
WUE = \frac{\text{NPP}}{\text{evapotranspiration}} = \frac{60 \text{ PgC/yr}}{71,000 \text{ Pg H2O/yr}} = 1.28 \text{ mmol C fixed / mole water lost}
\]
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Global Change PREDICTION: $\uparrow$CO2 $\rightarrow$ $\uparrow$WUE $\rightarrow$ less ET $\rightarrow$ more runoff

The Global water cycle

Global Change PREDICTION: $\uparrow$CO2 $\rightarrow$ $\uparrow$WUE $\rightarrow$ less ET $\rightarrow$ more runoff
Controls over Evapotranspiration range from long-to-short term

Long-term: State factors
Intermediate: Interactive controls
Short-term: Indirect and direct physiological controls

Potential Evapotranspiration

- The evapotranspiration rate of a short green crop, completely shading the ground, of uniform height and with adequate water status in the soil profile.
- A reflection of the **energy** available to evaporate water, and of the **wind** available to transport the water vapour from the ground up into the lower **atmosphere**. When water is not limiting, actual ET approaches potential ET.
- The ratio P/PET (precip over PET) is a fundamental indicator of water limitation.
III. Impacts of changes in climate and resources on ecosystems

A. Methods: satellite-based detection of ecosystem processes

B. Global trends in climate & drought, and their impact on terrestrial ecosystem NPP

Terrestrial Water Limitation

Number of Months where Precipitation < Potential Evapotranspiration
Blue = Never
Darker Orange = Increasing number of months (1-12)

Data from Ahn and Tateishi 1994; Cramer on going
Methods Interlude: Plant Carbon gain (GPP, NPP) estimated from satellites

Basic idea:

→ Leaf area/chlorophyll content are good predictors of canopy Ps
→ We can see plant canopies from space

When sunlight strikes objects, certain wavelengths are absorbed and other wavelengths are reflected.

For example, chlorophyll absorbs much of the visible radiation (VIS) (especially red) and very little in the near-infrared (NIR)

By contrast, bare soil, and non-vegetated surfaces absorb much less of the VIS wavelengths and relatively more NIR (compared to chlorophyll)

Methods: satellite instruments measure canopy “greenness”

Reflectance Spectrum of green leaf
Reflectance Spectrum of Non-veg surface

ρ ('rho') = reflectance

↑ Chlorophyll  ↑ leaf structure
↓ reflectance  ↑ reflectance
Methods: satellite instruments measure canopy "greenness"

\[ \text{NDVI} = \frac{\rho_{\text{nir}} - \rho_{\text{red}}}{\rho_{\text{nir}} + \rho_{\text{red}}} \]

(in Practice: the Normalized Difference Vegetation Index)

State of the art reflectance measurements:
MODIS: Moderate Resolution Imaging Spectroradiometer

Main instrument aboard the Terra satellite, launched Dec 1999

Terra MODIS views the entire Earth's surface every 2 days, acquiring data in 36 spectral bands (groups of wavelengths)

With satellite inputs, can now estimate:
GPP = NDVI (photosynthetic capacity) \times \text{incoming light}
NPP = GPP + modeled estimate of plant respiration
B. Global trends in climate and their impact on terrestrial ecosystem NPP

Reminder: NPP “Limitation”

if, when you add water, NPP increases, then
NPP is ‘limited’ by water

if, when you increase temperature, NPP increases, then
NPP is ‘limited’ by temperature

if, when you add a resource (e.g. nitrogen, CO₂), NPP increases, then
NPP is ‘limited’ by that resource
Geographic distribution of resource constraints on NPP

Source: Satellite-based modeling study by Nemani et al. (2003)

Trends in Growing season average Temperature (1982-1999)


Source: Nemani et al. (2003)

Net effect: Global NPP increased by 6% (40% of that in the tropics)

Source: Nemani et al. (2003)

What happened since 1999?

Growing season mean Temperature trend (2000-2009, °C /yr)

Zhao and Running (2010)
What happened since 1999?

North Hemisphere
Y = 0.128·X - 224.44
Northern hemisphere systems, NPP is temperature-limited

South Hemisphere
Y = -0.183·X + 388.566
In hotter southern hemisphere (and tropics), NPP is more water-limited; ↑ temp drives ↑ Evap-Transp. drives water stress

Global:
Y = -0.055·X + 164.124
A slight reversal of the trend seen in the 1990s

Note correlation with atmospheric CO2

Zhao and Running (2010)
Example of water cycle coupling between ecosystems and climate change

1. What is the fate of the Amazon forest? (important locally and globally)

What is the future of Amazon forests under climate change?

Forest? ...

or Savanna?
**Global Climate Change predicted to cause Amazonian Drought**

Dec-Jan-Feb

June-July-Aug

“probability” of substantial drought
(>20% reduction in dry-season rainfall)

"probability" = proportion of 23 GCMs that showed rainfall decline (2080-2099 vs. 1980-1999) for IPCC AR4 mid-range emissions scenario (A1B)

Malhi et al. (2008)

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**One prominent climate model (Hadley Center GCM) simulates loss of the Amazon forest around 2050**

Changes in vegetation carbon, Hadley Ctr. Model

**Contributing factors to extreme Amazon drought in the Hadley model world:**

- Ecophysiological feedbacks
- Changes in vegetation = changes in land surface ('biogeophysical feedbacks')
- Carbon-cycle feedbacks

Cox et al., 2000; Betts et al., 2004
A second GCM Model study: two different stable states for vegetation in the Amazon?

Could we lose the Amazon forests?
→ Changes in hyrdological cycling are key
**The Forest moisture pump**

Internal recycling:
Local Evapotranspiration supplies moisture for local precipitation
25-35% of Amazon basin
Precipitation comes from evapotranspiration within the basin

Eltahir and Bras, 1994

- Local and large-scale forest moisture pumps reinforce, create strong positive feedback
- Can be disrupted. Some mechanisms:

  **Human Land-Use change:**
  - 1. Deforestation removes forests: reduces ET, reducing precip
  - Drought-induced Tree death

  **Climate change increases:**
  - 2. El Nino Southern Oscillation (ENSO):
    - reduces precip, reducing ET
    - Drought-induced Tree death

  **Elevated CO2:**
  - 3. Increased Stomatal closure:
    - reduces ET, reducing precip
    - Drought-induced Tree death
Experimental Test of the effects of increased drought on Amazon rainforest

Diverting rainfall in the subcanopy, before it reaches ground (full 1-ha plot)

Amazon Rainforest in central Eastern Brazil

Rainfall diverted primarily in the wet season

Photos: Dan Nepstad
Experimental Test of the effects of increased drought on Amazon rainforest

Surprising results:
- Understory trees were not much affected (expected that they would be the first to go, because of shallow roots)
- Large trees suffered high mortality – eventually (but it took 3 years!)

Nepstad et al., 2007
Summary

The Water cycle is changing with climate
The Water cycle is intimately coupled to ecosystems through stomata of plant leaves
Water-cycle—ecosystem coupling is evident now, and may be strongly affected by future climate change

Example: the Amazon forest
- models simulate large-scale forest dieback
- Outstanding Question: what does it take to “break” an Amazon forest? And Can climate change do it?
- Amazon Dry-down experiment (Nepstad et al., 2007): takes 3 years to get large-tree mortality