Terrestrial Ecosystem Carbon Exchange

• Objectives
  – Terrestrial Ecosystem Carbon Cycling
    • Flux and storage of C across the SPAC in terrestrial ecosystems
  – Response of Tropical Forests to Rising Temperature
    • Hawaiian Tropical Montane Wet Forests as a Model Study System
Why should we care about C cycling?

- C is the energy currency of all ecosystems
  - Plant (autotrophic) production is the base of almost all food/energy pyramids
  - Underlies all ecosystem goods & services
- Plant C cycling, to a large extent, controls atmospheric CO$_2$ concentrations (i.e., climate)
  - 3-4x as much C in terrestrial ecosystems as the atmosphere
  - Tropical forests account for ~25% of global terrestrial biomass and ~35% of global terrestrial productivity
- C is fundamental to soil processes (i.e., SOM)
  - Belowground resources are a primary control over all ecosystem processes

Terrestrial Ecosystem Carbon Exchange

- Terrestrial metabolism: the “breathing” of Earth

![Graph showing terrestrial ecosystem carbon exchange](image)
Terrestrial Ecosystem Carbon Exchange

- Key to understanding biological C cycling
  - Law of Conservation of Mass
    - mass can neither be created nor destroyed, although it may be rearranged in space, or it may be changed in form
    - Inputs = Outputs + \(\Delta\)Storage
    - Inputs - Outputs = \(\Delta\)Storage
  - C that enters an ecosystem can change form, be stored, or be released back to the atmosphere
    - Stored C can move from one pool to another
  - C cycling best understood in terms of pools (storage) and fluxes (flows)
Terrestrial Ecosystem Carbon Exchange

- C enters via photosynthesis
  - Gross Primary Production (GPP)
    - Total C input via photosynthesis
  1. Accumulates in ecosystems (C pools/storage/sequestration) as:
    (a) plant biomass; (b) SOM & microbial biomass; or (c) animal biomass
  2. Returned to the atmosphere via
    (a) respiration (R; autotrophic or heterotrophic); (b) VOC emissions; or (c) disturbance
  3. Leached from or transferred laterally to another ecosystem

The C Bank Account

How do you measure GPP?
- Measure & Sum individual components
  - Need measurements of all individual components
  - Only ~30-40 studies globally

Chapin et al. (2011)
Terrestrial Ecosystem Carbon Exchange

- Net primary production (NPP)
  - NPP = GPP – $R_{\text{plant}}$
  - Net annual C gain (or loss) by plants
  - ANPP, ANPP$_{\text{wood}}$, ANPP$_{\text{foliage}}$, BNPP, etc.
  - Units of C (or biomass) / unit area / unit time
    - g C m$^{-2}$ yr$^{-1}$

\[ \text{Net annual C gain (or loss) by plants} = \text{ANPP, ANPP}_{\text{wood}}, \text{ANPP}_{\text{foliage}}, \text{BNPP, etc.} \]

Terrestrial Ecosystem Carbon Exchange

- Measuring NPP
  - NPP = $\Delta$biomass + litterfall
    - Biomass from allometric equations
    - Litterfall from litter traps
  - Need to account for biomass increment and loss because plant tissue is continually shed
    - NPP$_{\text{foliage}}$ = $\Delta$Leaf Bio. + Leaf Litter
    - NPP$_{\text{wood}}$ = $\Delta$Wood Bio. + Wood Litter

\[ \text{NPP} = \Delta \text{biomass} + \text{litterfall} \]

\[ \Delta \text{biomass} = \text{Biomass from allometric equations} \]

\[ \text{litterfall} = \text{Litterfall from litter traps} \]

\[ \Delta \text{Leaf Bio.} + \text{Leaf Litter} \]

\[ \Delta \text{Wood Bio.} + \text{Wood Litter} \]
Terrestrial Ecosystem Carbon Exchange

• $R_{growth}$ (growth/construction)
  – Total C cost = C in new biomass + C used to generate that biomass
  – Varies widely by compound
    • Function of concentration & cost
    • Protein rich (leaves), structural (wood), and defense
  – How do you measure $R_{growth}$?
    • $\sim 0.25 \times$ NPP
      – Total C cost = $\sim 1.23$g CHO per 1 g of biomass produced

Terrestrial Ecosystem Carbon Exchange

• $R_{maint}$ (maintenance of existing biomass)
  – Repair of non-growing tissues & ion transport
    • Protein turnover ($\sim 85\%$)
    • Membrane lipids
    • $R_{ion}$ (ion transport across membranes)
  – How do you measure $R_{maint}$?
    • Correlations with temperature and/or N content
Terrestrial Ecosystem Carbon Exchange

- **TBCF (Total Belowground Carbon Flux)**
  - Measuring BNPP and $R_{\text{below}}$ is exceedingly difficult
    - Would also miss a lot of C that goes to other components
  - TBCF is the total amount of C that plants send belowground
    - Root production + root respiration + C to symbionts + rhizodeposition
  - Based on conservation of mass
    - Direct measurement of all C inputs, outputs & Δstorage except what can’t be directly measured
      - $\text{TBCF} = F_s - F_A + (\Delta C_s + \Delta C_R + \Delta C_L)$

Terrestrial Ecosystem Carbon Exchange

- **TBCF (Total Belowground Carbon Flux)**
  - TBCF is as easy as taking a bath…

\[
\text{TBCF} = F_s - F_A + (\Delta C_s + \Delta C_R + \Delta C_L)
\]

Giardina & Ryan (2002)
Terrestrial Ecosystem Carbon Exchange

- Net ecosystem production (NEP)
  - Net annual C gain (or loss) by an ecosystem (over short time scales)
  - \( \text{NEP} = \text{GPP} - R_{\text{ecosystem}} \)
  - \( \text{NEP} = \text{NPP} - R_{\text{hetero}} \)
    - ~Same as NEE
  - What is missing?

Terrestrial Ecosystem Carbon Exchange

- Net Ecosystem Carbon Balance (NECB)
  - Net annual C gain (or loss) by an ecosystem (over longer time scales)
  - \( \text{NECB} = \text{GPP} - R_{\text{ecosystem}} - (F_{\text{disturb}} + F_{\text{leach}} + F_{\text{emissions}}) \)
  - Both natural & anthropogenic disturbances
  - Best way to estimate C sequestration

Chapin et al. (2011)
Terrestrial Ecosystem Carbon Exchange

• C storage in terrestrial ecosystems is C that is not in the atmosphere
  – C storage is ultimately what many managers & policy makers are interested in
  – Dynamic balance between the input, output and partitioning of C
    • C Partitioning is the fraction of GPP that goes to a particular component
• Funding
  – National Science Foundation; USDA Forest Service, PSW Research Station; University of Hawaii at Manoa, College of Tropical Agriculture and Human Resources

• People
  – Collaborators: Drs. Christian Giardina, Paul Selmants, Susan Crow, Greg Asner, Kristen Freeman, etc.
  – Technicians: Mike Long, Kevin Kaneshiro, Scott Laursen, Kainana Francisco, Kaimi Moraes, Rachel Moseley, Caitlin French, Riley DeMattos, Makalani Spina, etc.
  – Students: Darcey Iwashita, Lori Bothwell, Jeremy Albano, Joey Quitan, Olivia Schubert, Sue Pierre, etc.

Climate Change in the Tropics

• Climate is already changing in Hawaii, and throughout the tropics

Giambelluca et al. 2008
Elison Timm et al. 2015
• Evidence exists that rising MAT will alter ecosystem C cycling and storage
  – C input ↑
  – C output ↑
  – Ecosystem C storage ↔
    • Shift from soil to vegetation
  – Cross-site syntheses & elevation transects provide valuable insights
    • Typically confounded by changes in vegetation, substrate, H₂O availability, disturbance, etc.

• Impact of rising MAT for tropical forest C flux & storage?
  – One of the biggest unknowns regarding climate change & terrestrial ecosystems (Wood et al. 2012)
    • Positive feedback/forcing to climate change?
    • "Notable lack of data...to resolve this issue with certainty"
    • Particularly poor understanding of belowground dynamics
    • In situ manipulations; long-term experiments; incorporating scales & diversity
  – Environmental gradients provide valuable insights (Malhi et al. 2010)
    • Long-term integrated response to MAT
Tropical Forest C Cycling with rising MAT

- Hawaiian tropical montane wet forests as a model study system to quantify the impacts of rising MAT on tropical forest C cycling
  - How will the input, partitioning, loss and storage of C respond to rising MAT in tropical forests?

Tropical Forest C Cycling with rising MAT

- 5.2°C MAT gradient (13-18.2°C; 800-1600 m.a.s.l.)
  - C budgets in intact, closed-canopy tropical montane wet forests (n=9)
    - C input, partitioning, loss, & storage

- Model study system
  - Constant:
    - Vegetation
    - Disturbance history
    - Substrate type & age
    - Soil water availability
Hawaiian Islands as a model study system

- Characteristics of Hawaii as a model study system (from P. Vitousek, Fall 2014 NREM Seminar Series)
  - "Ideal compromise between complexity and tractability"
    - Relative simplicity (basalt origin; vegetation)
    - Continuous gradients (substrate; temperature/elevation; precipitation)
    - Distinct rock chemistry (isotopic signal distinct from ocean & crust)

Tropical Forest C Cycling with rising MAT

- A model study system
  - Constant species composition
    - ~85% of total basal area in *M. polymorpha* (overstory) & *C. trigynum* (mid-story)
Tropical Forest C Cycling with rising MAT

- A model study system
  - Maximum aboveground biomass for a given elevation
  - Constant disturbance history (moderately aggrading mature forest)

- A model study system
  - Constant substrate type and age
  - 20k yr tephra-derived Acrudoxic Hydrudands
Tropical Forest C Cycling with rising MAT

• A model study system
  • Constant plant available water
    • MAP varies from 3000 to 4000 mm, but higher MAP at lower elevations where ET is higher
    • Soil VWC high & constant year-round

• Hypothesis 1
  – The flux of C into and out of tropical montane forests increases with rising temperature
    • H₂O is not limiting; No change in disturbance regime

(Litton & Giardina, 2008) (Bond-Lamberty & Thomson, 2010)
Tropical Forest C Cycling with rising MAT

• Aboveground C fluxes increase with MAT
  – Litterfall & ANPP increase with rising MAT
  – GPP increases with rising MAT
    • Agrees well with global relationship (Litton & Giardina 2008)

![Graphs showing relationships between MAT and Litterfall, ANPP, and GPP](Giardina et al., 2014) (Litton et al., unpublished data) (Litton et al., unpublished data)

Tropical Forest C Cycling with rising MAT

• Belowground C fluxes increase with MAT
  – Both C flux out of & into soil increase with rising MAT

![Graphs showing relationships between MAT and Soil CO2 Efflux and TBCF](Litton et al., 2011) (Giardina et al., 2014)
Tropical Forest C Cycling with rising MAT

• **Hypothesis 2**
  – Ecosystem carbon storage will remain constant with temperature
  – Fraction of ecosystem C in live biomass will increase with temperature

- Live Biomass C storage
  – No relationship with MAT
  – Highest live biomass at ~16.5°C (Larjavaara & Muller-Landau 2011)

(Raich et al., 2006)

(Selmants et al., 2014)
Tropical Forest C Cycling with rising MAT

- Detrital C storage
  - SOC constant with MAT
  - CWD and forest floor C ↓ with MAT

(Selmants et al. 2014)

Tropical Forest C Cycling with rising MAT

- Detrital C storage
  - Total detrital C ↓ with MAT
  - Fraction of detrital C in SOC ↑ with MAT

(Selmants et al., 2014)
Tropical Forest C Cycling with rising MAT

- Ecosystem C storage
  - Total ecosystem C ↔ with MAT
  - No shift between C in soil vs. live vegetation

Tropical Forest C Cycling with rising MAT

- In tropical wet forests, increasing MAT will:
  - Increase ecosystem C cycling (i.e., C flux into and out of above- and belowground components)
  - Not change ecosystem C storage
    - Increased loss of C with rising MAT is simply a result of increased input of C
    - No trade-off between live and detrital C with MAT

(Selmants et al., 2014)