Patterns and processes of carbon and water budgets across northern Australian landscapes: From point to region

Importance of the savanna land surface in the earth system

- Local savanna surface water and heat balance influences regional climate through biophysics (heat, moisture, energy)
- Regional to global coupling
- Coupled to global climate through biogeochemical cycles (C, N, P, etc.)
- Changes in climate inherently influence global circulation
- So savanna land surface and Carbon cycle are important

Savanna ecosystem carbon fluxes and pools

GPP = 14.0 t.C.ha$^{-1}$.y$^{-1}$ (Photosynthesis)

$R_e = 9.7$ t.C.ha$^{-1}.y^{-1}$ (Respiration)

NEP = GPP – $R_e = 4.3$

NBP = GPP – $R_e$ - dist = 2.0

Gains
- Woody increment – 1.2 (28%)
- Shrub increment – 0.5 (11%)
- Unknown – 0.3 (7%)

Losses
- Indirect fire – 0.7 (16%)
- Coarse fuel – 0.5 (11%)
- Fine fuel – 1.1 (25%)

Biomass$_{bg}$ 17 t ha$^{-1}$

Biomass$_{ag}$ 34 t ha$^{-1}$

SOC 140 t ha$^{-1}$

Courtesy Hutley, Chen, Beringer, et al.
Spatial variability of Land surface fluxes

- Savanna region heterogeneous vegetation
- Strong rainfall gradient
- North Australian Tropic Transect
- Issues land clearing, fire, aerosols, trace gas emissions
- Need to understand and quantify spatial variability
Spatial variability of Land surface fluxes

- Savanna region heterogeneous vegetation
- Strong rainfall gradient
- North Australian Tropic Transect
- Issues land clearing, fire, aerosols, trace gas emissions
- Need to understand and quantify spatial variability
Overall Research approach

- Predict the responses of savannas to environmental change and provide options for sustainable ecosystem management at local to regional scales.
- Integrated multidisciplinary research program that will evaluate carbon and water budgets as indices of sustainable ecosystem services and health.

**Observations and Processes**: Flux towers, aircraft, satellite. Concentrations. Other trace gases. Land surface, land cover, vegetation properties, physical and biological variables. Transects and gradients

**Models**: SVAT, ecological, bioclimatic, physiological, hydrological, biogeochemical. Net fluxes (comparisons tower). Response processes

**Data Assimilation/Fusion**: Assimilate diverse information

**Regional scaling**: Carbon and water budgets using aircraft and regional models.

**Ecosystem response** to climate and human activities

**Predictive Models**: Carbon and water source/sink projections, response to policy scenarios, verification of outcomes

Specific Objectives

- What is the spatial variability of carbon, water and energy exchanges across important ecosystem types in the top-end and what are the key ecosystems characteristics that drive variability?
- Can fluxes of carbon, water and heat derived from different techniques be used to develop constrained estimates over the top-end?
- Can a coupled mesoscale/carbon model replicate the spatial budgets?
- How can we use remote sensing to inform models and regional budgets?
Measurement overview

- Aircraft
  - Boundary layer
  - Flux transects (transects and grids)
  - RS transects
    - Lidar
    - Hyperspectral
    - PLMR (soil moisture)
- Ground based
  - Remote sensing (ASD, CWD, Cover, etc)
  - Structural (DBH, height, species, GPS)
  - Leaf water and leaf morphology
  - Leaf Area Index (LAI2000 and hemi photos)
  - Physiology (Aci and light use curves)
  - Soil water and physical properties
  - Biomass (live, dead, litter)
- Flux Tower Observations
Remote sensing (ASD, CWD, Cover, etc)
Structural (DBH, height, species, GPS)
Structural (DBH, height, species, GPS)
Leaf water and leaf morphology
Leaf Area Index (LAI2000 and hemi photos)
Physiology (Aci and light use curves)

SPECIES

$V_{m\text{normalz}}$ at $25^\circ C$ ($\mu\text{mol m}^{-2}\text{s}^{-1}$)

- C. laifolia
- E. aparrenin
- E. cornball
- E. miniata
- E. pruinosa
- E. tectifica
- E. terminali
- E. tetrodon

Graph showing normalized $V_m$ values for different species at $25^\circ C$.
Soil water and physical properties
Biomass (live, dead, litter)
We would like to thank the Australian Research Council for funding this project (DP0344744 and DP0772981). We are indebted to the indigenous people of NT and private landholders. We are grateful to several students who have made this project possible including Andrew Coutts, Andrew Kerley, Chris Wendt, Jenny Randle, Chloe Tame, Kasturi Kanniah, Stephen Wood, Carol Hensley and Reza Amiri.
<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
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<tr>
<td>Howard Springs</td>
<td>-12.4942</td>
<td>131.1525</td>
<td>Savanna dominated by <em>Eucalyptus miniata</em> and <em>Erythrophleum chlorostachys</em> Wetland</td>
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<tr>
<td>Fogg Dam</td>
<td>12.559</td>
<td>131.307</td>
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<tr>
<td>Adelaide River</td>
<td>-13.0769</td>
<td>131.1178</td>
<td>Savanna dominated by <em>Eucalyptus tectifica</em> and <em>Planchonia careya</em></td>
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<tr>
<td>Daly Uncleared</td>
<td>-14.1592</td>
<td>131.3881</td>
<td>Savanna dominated by <em>Terminalia grandiflora</em> and <em>Eucalyptus tetradonta</em></td>
</tr>
<tr>
<td>Daly 5yr</td>
<td>-14.1306</td>
<td>131.3828</td>
<td>Savanna 5 year old regrowth dominated by <em>Eucalyptus miniata</em> and <em>Eucalyptus tetradonta</em></td>
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<tr>
<td>Daly 25yr</td>
<td>-14.0633</td>
<td>131.3181</td>
<td>Improved pasture</td>
</tr>
<tr>
<td>Dry Creek</td>
<td>-15.2588</td>
<td>132.3706</td>
<td>Savanna dominated by <em>Eucalyptus tetradonta, Eucalyptus terminalis</em> and <em>Eucalyptus dichromophloia</em></td>
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<tr>
<td>Sturt Plains tower</td>
<td>-17.1508</td>
<td>133.3503</td>
<td>Tussock grassland</td>
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<tr>
<td>Sturt Plains shrubland</td>
<td>-17.1829</td>
<td>133.3526</td>
<td>Shrubland dominated by <em>Eucalyptus pruinosa</em> and <em>Lysophyllum cunninghamii</em></td>
</tr>
<tr>
<td>Sturt Plains woodland</td>
<td>-17.1829</td>
<td>133.3526</td>
<td>dominated by <em>Acacia cowleana</em> and <em>Eucalyptus dichromophloia</em></td>
</tr>
</tbody>
</table>
Howard Springs (12.494S 131.153E)
Site Summary: Howard Springs

Latitude: 12°29'39.12"S
Longitude: 131°09'09"E
Site dimensions: 1ha (5x5 grid of 20x20m boxes).
Description: Eucalypt open forest savanna with woollybutt, stringybark and a sorghum tall grass understory.
Species:
- *Eucalyptus miniata* (212)
- *Erythrophleum chlorostachys* (120)
- *Terminalia ferdinandiana* (105)
- *Terminalia* (61)
- *Eucalyptus tetradonta* (53)
- *Eucalyptus terminalis* (31)
- *Eucalyptus porrecta* (23)
- Cycad (19)
- *Corymbia bleeseri* (18)
- *Eucalyptus clavigera* (10)
- *Buchanania obovata* (2)
- *Eucalyptus confertiflora* (2)
- *Persosnia falcata* (2)
- *Planchonia careya* (2)
- *Livistona humilis* (1)

Stem density: 661 stems/ha (total stems 684 stems/ha)
Basal area: 9.66 m²/ha
Average tree height: 8.87m
LAI - Total: 0.79
  - Overstorey: 0.60
  - Understorey: 0.19
Biomass Harvest - mean live biomass: 66.25 gm⁻² (standard error: 22.29)
  - mean standing dead biomass: 20.54 gm⁻² (standard error: 8.34)
  - mean litter biomass: 297.75 gm⁻² (standard error: 33.31)
  - total mean biomass: 384.54 gm⁻² (standard error: 37.09)

Soil:
- Clay: 4.10% (volume <1μm)
- Silt: 37.90% (volume <1μm)
- Sand: 57.93% (volume <1μm)
- Sand (>1 μm): 7.45% (total weight)
Fogg Dam (12.559S 131.307E)
Adelaide River (13.077S, 131.118E)
Site Summary: Adelaide River

Latitude: 13°04'36.84"S
Longitude: 131°07'04.08"E

Site dimensions: 1ha (5x5 grid of 20x20m boxes).

Species:
- *Eucalyptus tectifica* (114)
- *Planchonia careya* (102)
- *Buchanania obovata* (41)
- *Cochlospremum fraseri* (2)
- *Eucalyptus clavigera* (39)
- *Eucalyptus latifolia* (31)
- Sp. B (12)
- *Eucalyptus terminalis* (11)
- *Eucalyptus confertifolia* (4)
- *Terminalis ferdinandiana* (2)
- *Eucalyptus grandifolia* (1)
- *Eucalyptus tetradonta* (1)
- *Gardenia megasperma* (1)

Stem density: 365 stems/ha (total stems 457 stems/ha)

Basal area: 5.13 m²/ha

Average tree height: 7.01m

LAI- Total: 0.75
Overstorey: 0.75

Biomass Harvest - mean live biomass: 1.28 gm⁻² (standard error: 0.76)
mean standing dead biomass: 0.00 gm⁻² (standard error: 0.00)
mean litter biomass: 98.32 gm⁻² (standard error: 42.15)
total mean biomass: 99.60 gm⁻² (standard error: 42.11)

Soil- Clay: 9.13% (volume <1μm)
Silt: 64.67% (volume <1μm)
Sand: 26.2% (volume <1μm)
Sand (>1 μm): 18.11% (total weight)
Daly River savanna uncleared
(14.159S, 131.388E)
### Site Summary: Daly River Uncleared

**Latitude:**  14°09’33.12”S  
**Longitude:**  131°23’17.16”E  
**Description:**  Eucalypt woodland/grassland savanna  
**Site dimensions:**  1ha (5x5 grid of 20x20m boxes).  
**Species:**  
- *Terminalia grandiflora* (94)  
- *Eucalyptus tetradonta* (47)  
- *Eucalyptus latifolia* (18)  
- *Erythrophleum chlorostachys* (29)  
- *Planchonia careya* (14)  
- *Eucalyptus miniata* (12)  
- *Petalostigma pubescens* (8)  
- *Petalostigma* (6)  
- *Brachychiton paradoxium* (5)  
- *Buchanania obovata* (5)  
- *Owenia vermicosa* (4)  
- *Brachychiton diversifolia* (3)  
- *Pandanus spiralus* (2)  
- *Ficus oposita* (1)  
- *Lysophylum cunninghamii* (1)  
- *Persosnia falcata* (1)  
- Dead stems (41)  
**Stem density:**  292 stems/ha (total stems 330 stems/ha)  
**Basal area:**  9.38 m²/ha  
**Average tree height:**  8.23m  
**LAI**  
<table>
<thead>
<tr>
<th>Total</th>
<th>Overstorey</th>
<th>Understorey</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.72</td>
<td>0.41</td>
<td>0.31</td>
</tr>
</tbody>
</table>

**Biomass Harvest** -  
- **mean live biomass:** 11.21 gm⁻² (standard error: 4.13)  
- **mean standing dead biomass:** 113.26 gm⁻² (standard error: 16.52)  
- **mean litter biomass:** 349.32 gm⁻² (standard error: 32.93)  
- **total mean biomass:** 473.79 gm⁻² (standard error: 35.06)

**Soil**  
- **Clay:** 3.63% (volume <1μm)  
- **Silt:** 31.34% (volume <1μm)  
- **Sand:** 63.46% (volume <1μm)  
- **Sand (>1 μm):** 0.79% (total weight)
Daly River savanna 5yo cleared

(14°07′50.16″S, 131°22′58.08″E)
Daly River savanna 5yo cleared
Site Summary: Daly River Uncleared

Latitude: 14°07'50.16"S
Longitude: 131°22'58.08"E

Site dimensions: 1ha (5x5 grid of 20x20m boxes).

Species:
- *Eucalyptus miniata* (162)
- *Eucalyptus tetradonta* (113)
- *Petalostigma pubescens* (49)
- *Terminalia grandiflora* (28)
- *Planchonia careya* (24)
- *Denhamia obscura* (16)
- *Buchanania obovata* (4)
- *Erythrophleum chlorostachys* (2)
- *Ficus oposita* (2)
- *Persosnia falcata* (1)
- *Terminalia ferdinandiana* (1)
- Dead stems (4)

Stem density: 410 stems/ha (total stems 992 stems/ha)
Basal area: 1.26 m²/ha
Average tree height: 3.31 m

LAI-
- Total: 0.34
- Overstorey: 0.30
- Understorey: 0.05

Biomass Harvest -
- Mean live biomass: 49.33 gm⁻² (standard error: 18.35)
- Mean standing dead biomass: 171.09 gm⁻² (standard error: 59.25)
- Mean litter biomass: 325.19 gm⁻² (standard error: 39.94)
- Total mean biomass: 545.61 gm⁻² (standard error: 99.02)

Soil-
- Clay: 2.7% (volume <1µm)
- Silt: 27.57% (volume <1µm)
- Sand: 78.9% (volume <1µm)
- Sand (>1 µm): 2.03% (total weight)
Daly 25 yr cleared
Dry Creek

(15°15′31.62″, 132°22′14.04″E)
Site Summary: Dry Creek

Latitude: 15°15’31.62"S
Longitude: 132°22’14.04"E

Site dimensions: 1ha (5x5 grid of 20x20m boxes).

Species:
- *Eucalyptus tetradonta* (182)
- *Eucalyptus terminalis* (177)
- *Eucalyptus dichromophloia* (125)
- *Eucalyptus miniata* (41)
  Sp. A (16)
  *Gardenia megasperma* (11)
  *Planchonia careya* (16)
  *Acacia cowleana* (8)
  Sp. B (2)
  Sp. C (1)
  Dead stems (3)

Stem density: 582 stems/ha (total stems 709 stems/ha)
Basal area: 5.42 m²/ha
Average tree height: 6.12 m

LAI:
- Total: 0.52
- Overstorey: 0.48
- Understorey: 0.04

Biomass Harvest:
- mean live biomass: 14.9 gm⁻² (standard error: 7.24)
- mean standing dead biomass: 64.03 gm⁻² (standard error: 14.52)
- mean litter biomass: 494.62 gm⁻² (standard error: 61.17)
- total mean biomass: 573.55 gm⁻² (standard error: 66.65)

Soil:
- Clay: 5.74% (volume <1μm)
- Silt: 47.42% (volume <1μm)
- Sand: 46.83% (volume <1μm)
- Sand (>1 μm): 20.31% (total weight)
Sturt Plains Grassland Tower
*(17°09′2.76″S, 133°21′1.14″E)*
Sturt Plains Grassland Tower
Site Summary: Sturt Plains Grassland Tower

<table>
<thead>
<tr>
<th>Site Summary: Sturt Plains Grassland Tower</th>
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<tbody>
<tr>
<td>Latitude: 17°09'2.76&quot;S</td>
</tr>
<tr>
<td>Longitude: 133°21'1.14&quot;E</td>
</tr>
<tr>
<td>Site dimensions: no grid</td>
</tr>
<tr>
<td>Species: Mitchell grass (genus Astrebla)</td>
</tr>
</tbody>
</table>

### Biomass Harvest -

- **mean live biomass:** 0.00 gm⁻² (standard error: 0.00)
- **mean standing dead biomass:** 163.42 gm⁻² (standard error: 16.73)
- **mean litter biomass:** 148.99 gm⁻² (standard error: 21.32)
- **total mean biomass:** 312.40 gm⁻² (standard error: 30.80)

### Soil -

- **Clay:** 14.47% (volume <1μm)
- **Silt:** 51.23% (volume <1μm)
- **Sand:** 34.30% (volume <1μm)
- **Sand (>1 μm):** 1.02% (total weight)
Sturt Plains Shrubland (?)
Sturt Plains Shrubland
Site Summary: Sturt Plains Shrubland

Latitude:
Longitude:

Site dimensions: 4/25 ha (2x2 grid of 20x20m boxes).

Species:
- *Eucalyptus pruinosa* (14)
- *Lysophylum cunninghamii* (10)
- *Acacia holicericia* (3)
- *Acacia lysopholia* (3)
- L. Bush (3)
- *Wrightia saligna* (2)
- Ghostgum (1)
- Dead stems (22)

Stem density: 362.5 stems/ha (total stems 1625 stems/ha)

Basal area: 4.86 m²/ha

Average tree height: 3.74 m
Sturt Plains Woodland
(17°10′58.53″S, 133°21′09.39″E)
## Site Summary: Sturt Plains Woodland

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<th>Parameter</th>
<th>Details</th>
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<tr>
<td>Latitude</td>
<td>17°10'58.53&quot;S</td>
</tr>
<tr>
<td>Longitude</td>
<td>133°21'09.39&quot;E</td>
</tr>
<tr>
<td>Site dimensions</td>
<td>4/25 ha (2x2 grid of 20x20m boxes).</td>
</tr>
<tr>
<td>Species</td>
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</tr>
<tr>
<td>Acacia cowleana</td>
<td>(27)</td>
</tr>
<tr>
<td>Eucalyptus dichromophloia</td>
<td>(18)</td>
</tr>
<tr>
<td>Eucalyptus ferruginia</td>
<td>(15)</td>
</tr>
<tr>
<td>Eucalyptus chlorostachys</td>
<td>(6)</td>
</tr>
<tr>
<td>Lysophylum cunninghamii</td>
<td>(4)</td>
</tr>
<tr>
<td>Stem density</td>
<td>427.5 stems/ha (total stems 675 stems/ha)</td>
</tr>
<tr>
<td>Basal area</td>
<td>5.19 m²/ha</td>
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<tr>
<td>Average tree height</td>
<td>5.87 m</td>
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Sturt Plains - Woodland
Darwin Harbor (12.499S 130.886E)
Preliminary data
Ongoing Projects

- Tropical savanna carbon budgets
- GPP and role of smoke aerosols
- Daly River Catchment water balance
- Flux inhomogeneity (Fluxtower, aircraft, etc.)
- Remote sensing (carbon and water)
- Ecosystem/Land surface modeling (CABLE, ACASA, LPJ)
- Regional carbon/water modeling
- Isotopes
- Trace gas measurements (auto chambers / EC)
- Opportunities for collaboration? (SMOZ, FRE and savanna fire emissions etc?)
OSU Boundary Layer Model

Unburned

Burned

3.0°C warmer

http://blg.coas.oregonstate.edu/1.d.model/
Influence of landscape scale fires on the region

- Given fires cover 30% of landscape could this influence regional climate
- Heat-lows and linking of the troughs drives ITCZ onto continent
- Fire on large scales could have an influence

Figure 7.32 Ten-year average of the January 0000 UTC mean sea-level pressure field across Australia. The positions of the east and west coast troughs are indicated (after Fandry & Leslie 1984).

Sturman and Tapper (2005)
Global climate modelling

- CCAM: Conformal cubic atmosphere model, CSIRO
- 60 km spatial resolution over Australia
- Far-field nudging: winds, sea surface temperature
- Implemented fire and regrowth scheme
- Ran model from 1979-1999

Görgen K., et al. (2006)
C-CAM Fire / Re-Growth Scheme

- Fire / re-growth implementation: abrupt changes in prescribed temporal evolution of vegetation properties by forcing perturbations
  - Intensity, area, timing, length of re-growth period
- C-CAM variables modified by fire intensity
  - Leaf area index, albedo, roughness length, vegetation coverage
- Re-growth described via non-linear function, back to vegetation state in seasonal cycle without fires
- Constrained setup
  - Fire event (80% area burnt and 80% intensity, 2 months no-regrowth, 1 month regrowth)
  - No fire-vegetation feedbacks
  - Constant forcing perturbations and yearly fires per experiment
Climatological Impacts Single Scenario, Regional Impacts

Longterm (1979 to 1999) means, averaged over fire-affected area
Scenario: intensity=80%, area=80%, timing=10 October, re-growth length=90 d
Regional Impacts

- Overall intensification of boundary layer processes
- Increased sensible and latent heat fluxes
- Stronger convection
- Increased precipitation, which in a positive feedback loop further enhances this process

Scenario minus control, vertical profiles of longterm means
Continent-Wide Impacts

- Intensification of heat low
- Significant precip. increase
Conclusions

- Step change in albedo, energy and carbon fluxes after fire
- Demonstrated influence on Boundary Layer
- Burning on large scales may influence regional climate by strengthening heat low and strengthening the monsoon
- Next sensitivity study to look at 90 realizations of the same run varying parameters.
- Generate reduced statistical model
- Part of the equation for sustainable fire management practices
Fire / re-growth sensitivity test

Boundary layer penetration of impacts
(1979-1999 means, dots indicate significant at 90%)

Görgen K., et al. (2006)
Boundary layer penetration of impacts (1979-1999 means, dots indicate significant at 90%)

Vertical motion (fire - control)

Görgen K., et al. (2006)
Boundary layer penetration of impacts (1979-1999 means, dots indicate significant at 90%)
Fire / re-growth sensitivity test

Circulation shift in November (850 mb): strongest easterlies and ITCZ shifted south

Görgen K., et al. (2006)
Annual Energy Fluxes

- Step change in fluxes following fire
- Strong seasonal changes

Year 2001-2002
Rainfall 1699 mm.year\(^{-1}\)
Total ET 978 mm.year\(^{-1}\)

Year 2002-2003
Rainfall 1486.8 mm.year\(^{-1}\)
Total ET 892 mm.year\(^{-1}\)

Net Biome Productivity

- Measurements indicate net sink of -0.7 and -2.6 tC.ha\(^{-1}\).yr\(^{-1}\) for each annual period.
- But fire results in emission of ~+1.5 and +2.9 tC.ha\(^{-1}\).yr\(^{-1}\) based on fuel loads.
- NEP for year including fire ~ +0.8 and + 0.3 tC.ha\(^{-1}\).yr\(^{-1}\).
- True NBP?
## Summary results

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<td>+17</td>
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<td>-20.8</td>
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<td>Fire losses</td>
<td>+1.5</td>
<td>+2.9</td>
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<tr>
<td>NEP-fire</td>
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<tr>
<td>NBP</td>
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<td>-0.6</td>
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</table>

* Indicates impacts of a fire event in that year excluding emissions.
Future work

Alterations in savanna energy exchange following fire are likely to have important impacts on atmospheric circulation and water balance

- Heating contrasts between burned and unburned areas could generate local scale circulations and convection.
- On landscape scales this may modify patterns of precipitation and potentially affect the strength of the Australian monsoon.
- Boundary layer profiles and mesoscale climate modelling will be employed to address these questions.
Location of study site
Regional Transport – TOMS Aerosol Loading in Australian Region, 6 October 2000

Wain, Tapper and Mills, 2001
Biophysical ecosystem changes

- Changes in energy balance follow fire.
- Energy balance helps determine overlying boundary layer and climate

\[ Q^* = Q_G + Q_H + Q_E \]

- \( Q^* \) = Net radiation
- \( Q_G \) = Ground heat flux
- \( Q_H \) = Sensible heat flux
- \( Q_E \) = Latent heat flux
Effects of Fire:

- Carbon dioxide released through biomass burning
- Decreased albedo
- Scorching of the leaves
- Trees shut down and do not photosynthesise
Emissions from N.T. biomass burning in 1992

29.5 x 10^6 tonnes of biomass consumed; emissions were:

- 11.3 Tg carbon as carbon dioxide
- 1.02 Tg carbon as carbon monoxide
- 0.005 Tg carbon as particulate matter
- 0.026 Tg nitrogen as nitrous oxides

[NB. 1 Tg (teragram) = 10^{12} grams]

(Beringer, Packham and Tapper, 1995)
Soil respiration

Soil respiration

\[ y = 0.35x - 5.26 \]

\[ R^2 = 0.55 \]

Soil temperature (°C)

Fcs (μmol m⁻² s⁻¹)

- Wet soil
- Dry soil

\[ R^2 = 0.079 \]

Soil temperature (°C)
Stem respiration

[Graph showing CO₂ flux with data points for E. miniata, E. tetradonta, and E. chlorostachys]
Seasonality – Leaf Area Index

The graph shows the variation in leaf area index (LAI) over the course of a year, distinguishing between understorey and overstorey vegetation. The dry season is indicated by a horizontal bar at the bottom of the graph.

Key:
- Understorey
- Overstorey

The LAI values range from 0.0 to 2.0, with the highest LAI values occurring in March and April, indicating peak leaf development in these months. The lowest LAI values occur during the dry season, as indicated by the horizontal bar.
Annual Bowen Ratio

Daily Bowen ratio and rainfall

Year and day of year

Bowen Ratio (H/LE)

Bowen Ratio (L)

Daily rainfall totals (mm.day⁻¹)

Preburn
Heat and Moisture Fluxes before and after the burn

The diagram shows the fluxes of sensible heat (H) and latent heat (LE) over a period from 5-Aug-01 to 8-Aug-01. There is a significant increase in fluxes on 7-Aug-01, which is marked as Fire.
\[ \sim 40 \text{ gC.m}^{-2} \]

\[ = 0.4 \text{ tC.ha}^{-1} \]
Seasonality – Leaf Area Index

Howard Springs

Understorey

Overstorey
Hypothesis 3

*Future climate change will alter the north Australian fire regime, with consequent feedbacks to vegetation and climate*

The climate associated with a projected doubling of CO₂ will lead to a more extreme fire regime for northern Australia and a likely increase in area burnt each fire season. This will lead to dynamic changes in vegetation and climate in a series of complicated feedbacks.
Eddy covariance sites - FluxNet

Few tropical sites
Conclusions

- Fire is an integral part of Tropical Australia
- Emissions from fire contributes to the enhanced greenhouse
- Fire alters the heat and moisture balance
- This may in turn influence local to regional climate
- Changes in the carbon balance are also important
NT Savannas - NBP estimate

- Assume NEP 1.5 t ha\(^{-1}\) y\(^{-1}\)
- Area 400 000 km\(^2\)
- Savanna sink strength 60 Mt C y\(^{-1}\)
- Fire emission
  - low fire year (9 Mt C y\(^{-1}\)) Beringer et al. (1995)
  - high fire year (20 Mt C y\(^{-1}\))
- Fire consumes between 15-35% sequestered C
- Approximation only
Grasses 45% of annual NEP estimate
Grass ‘carbon neutral’ over 2-3 y period
What is woody sink strength?

<table>
<thead>
<tr>
<th></th>
<th>Wet</th>
<th>Dry</th>
<th>Late Dry</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree</td>
<td>0.48</td>
<td>0.65</td>
<td>0.40</td>
<td>1.53</td>
</tr>
<tr>
<td>Understorey</td>
<td>1.13</td>
<td>0.16</td>
<td>0.00</td>
<td>1.29</td>
</tr>
<tr>
<td>Total</td>
<td>1.61</td>
<td>0.81</td>
<td>0.40</td>
<td>2.82</td>
</tr>
</tbody>
</table>
NT Savannas - NBP estimate for tree component

- Assume 0.75 t ha\(^{-1}\) all Eucalypt savanna
- Area 400 000 km\(^2\)
- Tree carbon sink strength 30 Mt C \(y^{-1}\)
- Equivalent to fire emissions
  - Biomass consumed
    - 29.5 Mt \(y^{-1}\) (Beringer et al. 1995)
    - 23 Mt \(y^{-1}\) (Russell-Smith et al., submitted)
<table>
<thead>
<tr>
<th>Community</th>
<th>NEP $\text{ (t C ha}^{-1} \text{ y}^{-1})$</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical savanna (NT)</td>
<td>2.8</td>
<td>Eamus et al. (2001)</td>
</tr>
<tr>
<td>Sahelian savanna</td>
<td>0.32</td>
<td>Hanan et al. 1998</td>
</tr>
<tr>
<td>Amazonian forest (mature)</td>
<td>1</td>
<td>Grace et al. 1996</td>
</tr>
<tr>
<td>Amazonian forest (young)</td>
<td>5.5</td>
<td>Malhi et al. 1998</td>
</tr>
<tr>
<td>Temperate deciduous forest</td>
<td>2-5</td>
<td>Goulden et al. 1996</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Greco and Baldocchi 1996</td>
</tr>
</tbody>
</table>
Vegetation and the carbon cycle

Carbon cycle - fluxes and pools

- **GPP** - Gross primary productivity
  - carbon assimilated via photosynthesis
- **NPP** - Net primary production
  - fraction of GPP allocated to growth minus respiration from vegetation ($R_a$)
- **NEP** - Net ecosystem production
  - losses from soil respiration ($R_h$)
- **NBP** - Net biome production
  - losses from disturbance
Savanna carbon cycle

Tree and grass components

- **Tree**
  - C3
  - Long lived
  - long term carbon pool

- **Grass**
  - C4
  - Short lived
  - short term carbon pool
Post fire recovery - Evaporative fraction weeks 5-8 post fire

- Mean pre fire
- Weeks 5-6
- Weeks 7-8
Post fire recovery - Daily flux of $G$ 5-8 weeks post fire

<table>
<thead>
<tr>
<th>Date</th>
<th>Energy flux density (MJ.m$^{-2}$.day$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-Sep-01</td>
<td>0.2</td>
</tr>
<tr>
<td>8-Sep-01</td>
<td>0.0</td>
</tr>
<tr>
<td>9-Sep-01</td>
<td>0.2</td>
</tr>
<tr>
<td>10-Sep-01</td>
<td>0.4</td>
</tr>
<tr>
<td>11-Sep-01</td>
<td>0.8</td>
</tr>
<tr>
<td>12-Sep-01</td>
<td>1.0</td>
</tr>
<tr>
<td>13-Sep-01</td>
<td>1.2</td>
</tr>
<tr>
<td>14-Sep-01</td>
<td>1.0</td>
</tr>
<tr>
<td>15-Sep-01</td>
<td>0.8</td>
</tr>
<tr>
<td>16-Sep-01</td>
<td>0.6</td>
</tr>
<tr>
<td>17-Sep-01</td>
<td>0.4</td>
</tr>
<tr>
<td>18-Sep-01</td>
<td>0.2</td>
</tr>
<tr>
<td>19-Sep-01</td>
<td>0.0</td>
</tr>
<tr>
<td>20-Sep-01</td>
<td>0.2</td>
</tr>
<tr>
<td>21-Sep-01</td>
<td>0.4</td>
</tr>
<tr>
<td>22-Sep-01</td>
<td>0.8</td>
</tr>
<tr>
<td>23-Sep-01</td>
<td>1.0</td>
</tr>
<tr>
<td>24-Sep-01</td>
<td>1.2</td>
</tr>
<tr>
<td>25-Sep-01</td>
<td>1.0</td>
</tr>
<tr>
<td>26-Sep-01</td>
<td>0.8</td>
</tr>
<tr>
<td>27-Sep-01</td>
<td>0.6</td>
</tr>
<tr>
<td>28-Sep-01</td>
<td>0.4</td>
</tr>
<tr>
<td>29-Sep-01</td>
<td>0.2</td>
</tr>
<tr>
<td>30-Sep-01</td>
<td>0.0</td>
</tr>
<tr>
<td>1-Oct-01</td>
<td>0.2</td>
</tr>
<tr>
<td>2-Oct-01</td>
<td>0.4</td>
</tr>
<tr>
<td>3-Oct-01</td>
<td>0.8</td>
</tr>
<tr>
<td>4-Oct-01</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Mean pre fire daily $G$

Weeks 5-6

Weeks 7-8
Ensemble average of Energy balance components 1-2 weeks post fire Site A

- **Energy flux density (W.m\(^{-2}\))**
  - Sensible heat flux \(H\)
  - Net radiation \(R_n\)
  - Soil heat flux \(G\)
  - Latent heat flux \(LE\)

---

Ensemble average of energy balance components pre-fire at Site A.

- **Energy flux density (W.m\(^{-2}\))**
  - Sensible heat flux \(H\)
  - Latent heat flux \(LE\)
Table 5.2 Char height, scorch height, and corresponding fire intensity, using the relationship of Williams et al. (1997) as in figures 4.4 and 4.5. Remaining biomass following each fire is also given.

<table>
<thead>
<tr>
<th></th>
<th>Site A</th>
<th>Site B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Leaf char height (m)</strong></td>
<td>2.01 ± 0.10</td>
<td>0.45 ± 0.03</td>
</tr>
<tr>
<td><strong>Leaf scorch height (m)</strong></td>
<td>13.5 ± 1.5</td>
<td>2.50 ± 0.45</td>
</tr>
<tr>
<td><strong>Average intensity (kW.m⁻¹)</strong></td>
<td>3563 ± 637</td>
<td>607 ± 60</td>
</tr>
<tr>
<td><strong>Total/grass fuel load</strong></td>
<td>6.4/1.6</td>
<td></td>
</tr>
<tr>
<td><strong>Remaining Biomass (t.ha⁻¹)</strong></td>
<td>0.95 ± 0.28</td>
<td>1.1 ± 0.19</td>
</tr>
</tbody>
</table>
Diurnal Energy Fluxes Control and Burn Site

Control Site day 225-235

Burn Site day 260-270

Rn
H
LE

Incr 5-10%
Incr 40-50%
Decr 30-40%
Daily Albedo at Burn and Control (Burn2) Site, August – September 2001

Time Series of average shortwave albedo values at both sites

- Albedo 0.12
- Albedo 0.06

Fire at control site

Albedo 2

0.06
Evapotranspiration Before and After the Fire at the Burn Site

Howard Springs Fire - ET

- Fire

216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232

Julian Day

Daily Evapotranspiration (mm.day⁻¹)
Energy Flux Time Series for the Control (Burn2) Site, August 2001 – January 2002

Daily Energy Flux (MJ m⁻² day⁻¹)

- $Q^*$
- $Q_H$
- $Q_E$
- $Q_G$

Fire at control site ~20 days missing data
Concluding Comments

- Fire and fire scars have massive impacts in the Australian tropics where ~30% of the area burns each year.
- We have already documented some of the direct impacts of fire scars on heat, moisture and (as you will see) CO2 fluxes to the atmosphere.
- These impacts on heat and moisture may in turn influence local to regional-scale climate – this is an important area for future research.
- Future collaboration in this area is planned with NTU, CRCTS, NCAR, U. of Colorado (PAOS). Potential funding from ARC, NSF and NCAR.
Savanna carbon fluxes and pools

NEP = 2.8 t ha\(^{-1}\) y\(^{-1}\)

Biomass\(_{ag}\) 34 t ha\(^{-1}\)

Biomass\(_{bg}\) 17 t ha\(^{-1}\)

SOC 140 t ha\(^{-1}\)
Atmospheric CO$_2$

NEP = 2.8 t ha$^{-1}$ y$^{-1}$

GPP

Plant resp

NEP = NEP = 2.8 t ha$^{-1}$ y$^{-1}$

Soil and litter resp

Disturbance

Short term uptake

Medium-term storage

Long-term storage

NPP

NEP

NBP
Net Biome Productivity

• Net biome productivity (NBP) is net ecosystem productivity (NEP) but accounting for disturbance (FIRE!).

• Initial emissions and long term recovery are important.
Longer term carbon balance

August 2001 to January 2002

Daily carbon flux (g CO₂·m⁻²·day⁻¹)

- Net ecosystem production
- Ecosystem respiration
- Gross primary production

Aug01 Day of year Jan02
Effects of Fire:

- Carbon dioxide released through biomass burning
- Decreased albedo
- Scorching of the leaves
- Trees shut down and don’t photosynthesise
FIGURE: CO$_2$ flux with DBH. Red diamonds represent *Erythrophloem chlorostachys*, green diamonds represent *Eucalyptus miniata*, and purple diamonds represent *Eucalyptus tetradonta*. 
FIGURE 5.18: Comparison of average rates of respiration from each of *Eucalyptus miniata*, *Erythrophloem chlorostachys*. Standard error for each species was ± 0.022683, 0.012342 and 0.016029 reading left to right.
Eucalyptus miniata

Erythrophloem chlorostachys

Eucalyptus tetradoonta
**TABLE 5.1:** Flux rates from each collar group

<table>
<thead>
<tr>
<th>Collar group</th>
<th>Mean CO₂ flux (mg CO₂ m⁻² s⁻¹)</th>
<th>Standard error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (C)</td>
<td>0.051242</td>
<td>0.004865</td>
</tr>
<tr>
<td>Wet (W)</td>
<td>0.124797</td>
<td>0.015560</td>
</tr>
<tr>
<td>Saturated (S)</td>
<td>0.102987</td>
<td>0.012404</td>
</tr>
</tbody>
</table>
FIGURE 5.19: Effect of temperature on CO₂ flux from Eucalyptus miniata, Eucalyptus tetradonta and Erythrophloem chlorostachys.
Leaf Respiration rates

FIGURE 5.24: Leaf respiration rates by species groupings
**TABLE 5.4:** Comparison of quantification of respiration components of the northern Australian wet-dry tropical savanna

<table>
<thead>
<tr>
<th>Component</th>
<th>Chen <em>et al.</em> (2002b)</th>
<th>This investigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>2.3 g C m$^{-2}$ day$^{-1}$</td>
<td>1.2 g C m$^{-2}$ day$^{-1}$</td>
</tr>
<tr>
<td>Stem</td>
<td>0.11 g C m$^{-2}$ day$^{-1}$</td>
<td>0.3 g C m$^{-2}$ day$^{-1}$</td>
</tr>
<tr>
<td>Leaf</td>
<td>0.38 g C m$^{-2}$ day$^{-1}$</td>
<td>7.7 g C m$^{-2}$ day$^{-1}$</td>
</tr>
<tr>
<td>Total</td>
<td>2.8 g C m$^{-2}$ day$^{-1}$</td>
<td>9.2 g C m$^{-2}$ day$^{-1}$</td>
</tr>
</tbody>
</table>
FIGURE 5.28: Uncorrected ecosystem carbon flux for the study site
FIGURE 5.29: Ecosystem CO$_2$ flux using $u^*$ > 0.15 correction
**TABLE 5.6:** Comparison of different methods to measure ecosystem respiration

<table>
<thead>
<tr>
<th>Technique used to measure ecosystem flux</th>
<th>Result of technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nighttime eddy covariance (raw)</td>
<td>0.94 g C m(^{-2}) day(^{-1})</td>
</tr>
<tr>
<td>Nighttime eddy covariance (corrected with u* &gt;0.15)</td>
<td>1.4 g C m(^{-2}) day(^{-1})</td>
</tr>
<tr>
<td>Net ecosystem respiration using observations and estimates (this study)</td>
<td>9.2 g C m(^{-2}) day(^{-1})</td>
</tr>
<tr>
<td>Net ecosystem respiration in the dry season Chen <em>et al.</em> (2002b) results</td>
<td>2.8 g C m(^{-2}) day(^{-1})</td>
</tr>
</tbody>
</table>
Evapotranspiration (W m\(^{-2}\))

- **EC1 Unburnt**
- **EC2 Burnt**

**July '97 (Mid-dry)**

- LAI 0.71
- LAI ? (<0.2)
Within-catchment variability

- Two tower sites established (EC1, EC2)
- EC2 fire induced flushing

Mean ET Sep ‘97

<table>
<thead>
<tr>
<th>Site</th>
<th>ET (mm)</th>
<th>LAI</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC1</td>
<td>1.24</td>
<td>0.8</td>
</tr>
<tr>
<td>EC2</td>
<td>1.55</td>
<td>1.0</td>
</tr>
</tbody>
</table>

- 20% site difference in LAI
- 20% site difference in ET
Conclusions

- Spatial and temporal variation of surface fluxes may be significant
- Determined by seasonal variation in LAI and soil water - therefore predictable
- Fire effects significant
- LAI and soil water dynamics
  - Part of on-going research activities in P1.2
Tropical savanna of northern Australia

Overstorey LAI
Wet to dry 0.6 - 1
*Eucalyptus* dominated

Understorey LAI
Wet to dry 0.2 - 1.4
*Sorghum* dominated

Rainfall 1700 mm
BA 10-12 m² ha⁻¹
Stems ha⁻¹ 700
Semi-arid savanna of northern Australia

Overstorey LAI
Wet to dry 0.07 - 0.05
*Eucalypt* dominated

Understorey LAI
Wet to dry 0.2 - 0.05
*Acacia* dominated

Rainfall 520 mm
BA 2 m² ha⁻¹
Stems ha⁻¹ 77
Eucalypt Savanna Water Balance

Rainfall (1720 mm)

Evapotranspiration (1110 mm)

Runoff and Shallow Throughflow (410 mm)

Groundwater Recharge (200 mm)

Groundwater Flow to Howard River (180 mm)

Groundwater Surplus 20-70 mm

Error range 0-140 mm

After Cook and Hatton (1998)
Vegetation and the carbon cycle

GPP 120

autotrophic respiration 60

heterotrophic respiration 55

combustion

NPP 60

Animals

DETritus

τ < 10yr

[300]

< 0.1

? to

'INERT' CARBON
τ > 1000yr
[150]

DOC export 0.4

MODIFIED SOIL CARBON
τ = 10 to 1000yr
[1050]

(IPCC TAR WG1 2001)
Impacts of clearing Australia’s native vegetation

Figure 7.9. Energy balance and momentum transfer for a forest.
Vegetation and the energy cycle

Radiation balance

\[ Q^* = (L_{\text{down}} - L_{\text{up}}) \]

\[ + (K_{\text{down}} - K_{\text{up}}) \]

Albedo (\( \alpha \)) = \( \frac{K_{\text{up}}}{K_{\text{down}}} \)

Forest \( \alpha = 0.1 \)

Grass \( \alpha = 0.2 \)
Vegetation and the energy cycle

Net radiation drives exchanges of energy at the surface and is described by an energy balance:

\[ Q^* = Q_G + Q_H + Q_E \]

- \( Q^* \) = Net radiation
- \( Q_G \) = Ground heat flux
- \( Q_H \) = Sensible heat flux
- \( Q_E \) = Latent heat flux
Basics of Climate-Vegetation Interaction
Savanna fluxes

MODIS satellite products to derive GPP and give spatial variations
Wet-dry tropics - Monsoon driven

Cyclone Thelma
Fire Scars Mapped in 1999

1997, 1998 and 1999 ~ 250,000 km² burned in each dry season
Net ecosystem production

- Net ecosystem production (NEP) = GPP – $R_a - R_h$

Chapin III et al. (2002)
Net Biome Production

- Disturbance results in increases C losses
- Defined as Net Biome Productivity (NBP)

\[ \text{NBP} = \text{GPP} - R_a - R_h - \text{disturbance} \]

- Short-term carbon uptake
  - NPP: 60 Gt/yr

- Medium-term carbon storage
  - NEP: 10 Gt/yr

- Long-term carbon storage
  - NBP: 1-2 Gt/yr

- CO2: Plant respiration
- Soil and litter respiration
- Disturbance

IGBP 1998
Figure 6.4. The concentrations and radiative forcing by (a) CO₂, (b) CH₄, and (c) nitrous oxide (N₂O), and (d) the rate of change in their combined radiative forcing over the last 20 kyr reconstructed from Antarctic and Greenland ice and firm data (symbols) and direct atmospheric measurements (red and magenta lines). The grey bars show the reconstructed ranges of natural variability for the past 650 kyr (Siegenthaler et al., 2005a; Spahni et al., 2005). Radiative forcing was computed with the simplified expressions of Chapter 2 (Myhre et al., 1998). The rate of change in radiative forcing (black line) was computed from spline fits (Enting, 1987) of the concentration data (black lines in panels a to c). The width of the age distribution of the bubbles in ice varies from about 20 years for sites with a high accumulation of snow such as Law Dome, Antarctica, to about 200 years for low-accumulation sites such as Dome C, Antarctica. The Law Dome ice and firm data, covering the past two millennia, and recent instrumental data have been splined with a cut-off period of 40 years, with the resulting rate of change in radiative forcing shown by the inset in (d). The arrow shows the peak in the rate of change in radiative forcing after the anthropogenic signals of CO₂, CH₄ and N₂O have been smoothed with a model describing the enclosure process of air in ice (Spahni et al., 2003) applied for conditions at the low accumulation Dome C site for the last glacial transition. The CO₂ data are from Etheridge et al. (1996); Montzka et al. (2001); Montzka et al. (2004); Siegenthaler et al. (2005a); South Pole; Siegenthaler et al. (2005b); Kohler et al. (2005); and MacFarling Meure et al. (2006). The CH₄ data are from Steele et al. (1999); Blunier et al. (1993); Dlugokencky et al. (1994); Blunier et al. (1995); Chappellaz et al. (1997); Montzka et al. (2001); Fröhlich et al. (2002); and Ferretti et al. (2005). The N₂O data are from Machida et al. (1998); Battle et al. (1996); Fröhlich et al. (1999, 2002); and MacFarling Meure et al. (2006). Atmospheric data are from the National Oceanic and Atmospheric Administration’s global air sampling network, representing global average concentrations (dry air mole fraction; Steele et al., 1999; Dlugokencky et al., 1994; Tans and Conway, 2005), and from Mauna Loa, Hawaii (Keeling and Whorf, 2005). The globally averaged data are available from http://www.cmdl.noaa.gov/.