Effects of extreme weather cycles on ecosystem photosynthesis, respiration and evapotranspiration in semi-arid central Australia

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Precipitation
Climatology

- **Mean:** 318 mm yr$^{-1}$ ([http://www.bom.gov.au](http://www.bom.gov.au))
  - **Semi-arid**
- **Median:** 298 mm yr$^{-1}$
  - **Summer (DJF):** 72%
  - **Monsoon season (Nov–Apr):** 86%
    - Just inside the monsoon tropics (Bowman et al. 2010)
- **Minimum:** 100 mm yr$^{-1}$, 2009
- **Minimum:** 750 mm yr$^{-1}$, 2010

- **Long-term at Alice Springs airport:**
  - **Record:** 2010–2011, 1408 mm (2 yr)$^{-1}$; 50–100 yr recurrence interval (Papalexioou & Koutsoyiannis 2013)
    - Interaction: Australian low and the monsoon depression (Kong & Zhao 2010)
  - Chance of either system being strong in a given year is small (Berry et al. 2011)

- **Hypothesis:** the Mulga ecosystem was expected to range from a strong sink (wet) to a strong source (dry) (Huxman et al., 2004; Baldocchi, 2008; Wohlfahrt et al., 2008; Yan et al., 2011)
Precipitation Extremes

- **First year:** > 200 mm above the long-term average (http://www.bom.gov.au: Territory Grape Farm 1987–2012)
- **Second year:** > 100 mm below normal
- **Extraordinary explosion in grasses, forbs and fauna throughout the region, 2010–Apr 2011**
- **Rainfall concluded by April 2011, after which months of below-average precipitation were common**
- **May–Aug 2012: record period without rainfall**
- **Spatial heterogeneity larger in second year**

Figure 1 Carbon dynamics in central Australia

Cleverly et al., J. Geophys. Res.
Pulse–Response, first year
Evapotranspiration and soil moisture

- Rapid decline in soil moisture after rainfall
- Exponential decline of ET following rainfall
- Exponential increase in inherent water use efficiency as soil dries
- Better fit between IWUE* and soil moisture during wet season

Eamus et al., 2013 Agric. Forest Meteor.
Nocturnal Respiration Responses
Soil moisture & substrate availability

- **Mar–15 Jul 2011**: Very large thermal sensitivity of nocturnal respiration
  - Coincides with cessation of wet period and
  - senescence of understorey growth (Eamus et al. 2013)
  - limited leaf water stress in Mulga (−1.8 MPa) (Eamus et al. 2013)
- **Weak thermal sensitivity during dry periods**
- **Small sample size when soil was very wet resulted in no significant differences between moisture classes**

Cleverly et al., J. Geophys. Res.
Net Photosynthesis
Seasonal sensitivity

- **Mulga:**
  - steep quantum yield (initial slope of light response function)
  - near-zero midday assimilation in dry

- **Ecosystem:**
  - morning net assimilation, midday net respiration
  - Assimilation fails to saturate in full sunlight at the peak of GPP responses (Feb)

Cleverly et al., J. Geophys. Res.

Eamus et al., 2013 Agric. Forest Meteor.
Diurnal Respiration Responses
Temperature & irradiance

- \( GPP = \text{NEP} + R_e \)
- Exterpolation of nocturnal respiration (Arrhenius)
  - \( u^* \) filter leads to substantial over-estimation of \( R_e \) and GPP
    - consistent with double-counting of de-storage fluxes (Aubinet 2008)
  - very close agreement between nocturnal \( R_e \) and light response estimates of \( R_e \)
    - close agreement between nocturnal + storage fluxes and LRF estimates (van Gorsel et al. 2009)
- Low-light and high-light LRFs match below respective temperature optima
- Soil moisture limitations imposed at high temperature

\[ \gamma, E_s < 500 \text{ W m}^{-2} \]
\[ \text{NEE}^{\max}, E_s > 500 \text{ W m}^{-2} \]
\[ \text{Arrhenius, } E_s < 10 \text{ W m}^{-2} \]
\[ \text{Arrhenius, } u^* \text{ filtered} \]
**Partitioning NEE**  
**Gross primary production and ecosystem respiration**

- **Nocturnal \( R_e \):**
  - \( u^* \) filter: unrealistically large \( R_e \)
  - not used for partitioning

- **Diurnal \( R_e \):**
  - **High light:**
    - **Midday positive NEE can be larger than intercept** (Scott et al. 2010)

\[
R_e = \begin{cases} 
  R_{e\text{night}} = \sum \text{NEE} \\
  R_{e\text{night}} = a \exp \left( bT_s \right)_{\theta,\text{date}} \\
  R_{e\text{day}} = \gamma(T) \\
  R_{e\text{day}} = \gamma(T)_{\text{GPP}=0} = \text{NEE}^{\text{max}}(T) 
\end{cases}
\]

- **Nightly sums**
  - Nights with no gaps
  - \( R_{e\text{night}} \): Sum of all nocturnal CO\(_2\) fluxes (points; Fig. 2)
  - Nights with gaps present
  - \( R_{e\text{night}} \): Full night filled with sum from \( Q_0 \) model given average nightly \( T \), soil moisture and date (curves 1–6, Fig. 2)

- **Arrhenius function used to compare to other methods (curve 7, Fig. 2; Fig. 3)**

- **Night: \( u^* \) filter**
  - Arrhenius function used to compare to other methods; application to partitioning results in unrealistically large rates of \( R_e \) (Fig. 3) and GPP

- **Sunlit fluxes: dusk and dawn**
  - \( R_{e\text{day}} \): intercept of light response curve (\( y \)) within each \( T \) class (Fig. 3)

- **Sunlit fluxes: full sunlight**
  - \( R_{e\text{day}} \): \( \text{NEE}^{\text{max}} \) within each \( T \) class (Fig. 3)

\[
\text{GPP} = R_e - \text{NEE} = 0
\]

\[
\text{GPP} = R_e - \text{NEE}
\]

Cleverly et al., J. Geophys. Res.
Carbon responses
Gross primary production and ecosystem respiration

- **Large GPP:**
  - $33 - 66 \text{ mol m}^{-2} \text{ yr}^{-1}$

- **Small–moderate $R_e$:**
  - $34 - 45 \text{ mol m}^{-2} \text{ yr}^{-1}$
  - closely matches LAI
  - decomposition pulse during understorey senescence

- **Wet year:** carbon sink

- **Dry year:** carbon neutral

- **Hypothesis:** rejected (thus far)

Cleverly et al., *J. Geophys. Res.*
Storm pulses
Rainfall and soil moisture

- **Multi-day storm ensembles:**
  - **storm period: 2–5 days**
    - low temperature
    - little irradiance
    - small vapour pressure deficit
  - large surface soil moisture content
  - inter-storm period: 5–10 days

![Graphs showing rainfall, soil moisture, temperature, and energy flux over time.](Cleverly et al., J. Geophys. Res.)
Light & water use efficiency
OzFlux transect

- Convergence on negative exponential across sites
- Alice Springs:
  - Large range in VPD and $T_a$
  - No LUE response to VPD
  - Large WUE response to VPD

\[
LUE = \frac{\sum_{i=1}^{n} GPP_i}{\sum_{i=1}^{n} 0.5(F_{sd})_i}
\]

\[
WUE = \frac{\sum_{i=1}^{n} GPP_i}{\sum_{i=1}^{n} ET_i}
\]

\[WUE_m = \frac{GPP_i}{\sum_{i=1}^{n} 0.5F_{sd}(i)}\]

Shi et al., in preparation
Phenology responses
Gross ecosystem photosynthesis & EVI

- Large variability in seasonal phenology
  - No detectable growing season during dry years
  - Nearly full-year growing season during extraordinarily wet years
  - Start-of-growing season and End-of-growing season vary

Ma et al., Remote Sensing Environ.
Soil
Heavily weathered red kandosol

- Typical of large areas of semi-arid Australia; large potential for drainage (Schmidt et al. 2010, Morton et al. 2011)
- Sandy loam (74/11/15% sand/silt/clay)
- Hardpan commonly formed in the top metre (possibly deeper) (Morton et al. 2011)
- Soil organic matter:
  - 1.1% at surface, 0.7% at 0.1 m depth, 0.5% in hardpan
- Surface bulk density: $1.69 \pm 0.02 \text{ g cm}^{-3}$

Cleverly et al., J. Geophys. Res.
Atmospheric humidity gradients
Penman-Monteith ET

Cleverly et al., J. Hydrometeorol.

Figure 1. Conditional three-circuit, two-layer aerodynamic resistance model. See text for variable descriptions.

Figure 2. Specific humidity ($q$) profiles through the canopy and atmosphere, scaled by layer thickness ($\Delta z$). Subscripts represent the measurement height. a-c: difference between $q$ measured at two heights (subscripts $m$: measurement, $c$: canopy, 2: 2 m). d: Atmospheric $q$ profile (± standard error, se) during the period of maximal gradients in the top layer (22 Dec. 2012 21.00–23.00 LST; squares and broken line) and in the base layer (5 Nov. 2012 1.30–4.00 LST; circles and solid line).
Penman-Monteith Inversion
\( C_E & C_D \)

- **Improved conductance response to vapour pressure deficit**
- **Smaller error during summer**
- **Separation between layers based upon \( D \)**

\[
G_{Sx}^{-1} = r_{ax} \left\{ \left[ \frac{\Delta Q_A + \rho c_p D r_{ax}^{-1}}{\lambda w'q'} - \Delta \right]^{-1} \right\} - 1
\]

\[
r_{am} = \left( UC_D \right)^{-1} \approx \frac{\ln \left[ \left( z_m - z_d \right) / z_{0m} \right]}{k^2 U} \ln \left[ \left( z_m - z_d \right) / z_{0v} \right]
\]

\[
r_{av} = \left( UC_E \right)^{-1} = -\frac{q_a - q_0}{w'q'} \quad (Brutseart 1982, Stull 1988)
\]

Cleverly et al., J. Hydrometeorol.
Thank you