CARBON CYCLE RESPONSES OF SEMI-ARID ECOSYSTEMS TO POSITIVE ASYMMETRY IN RAINFALL

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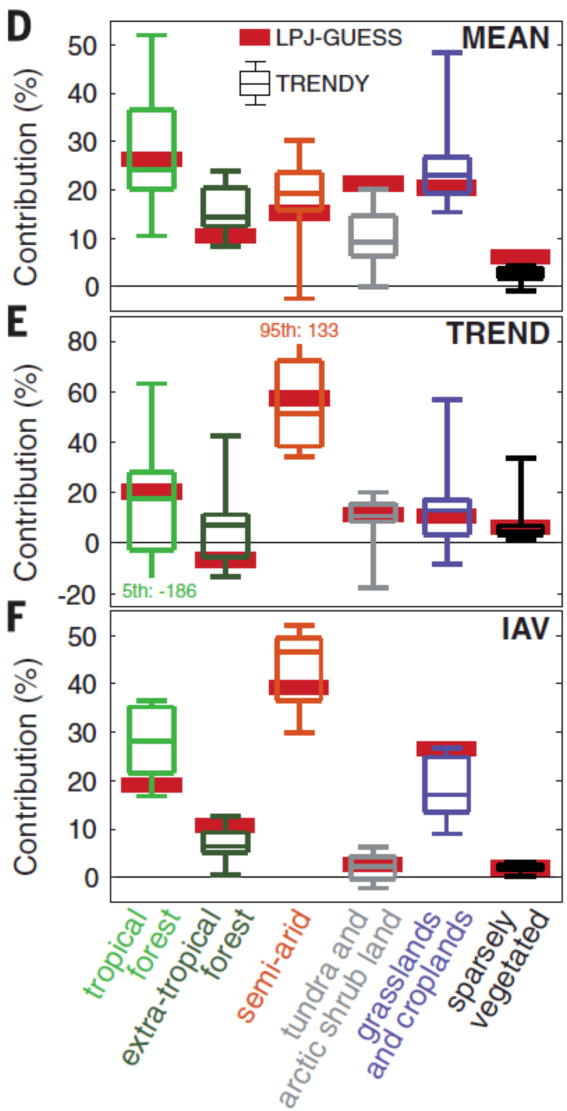
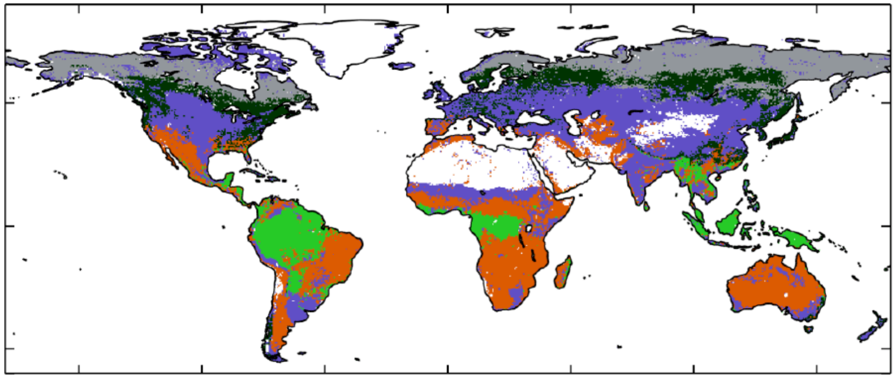
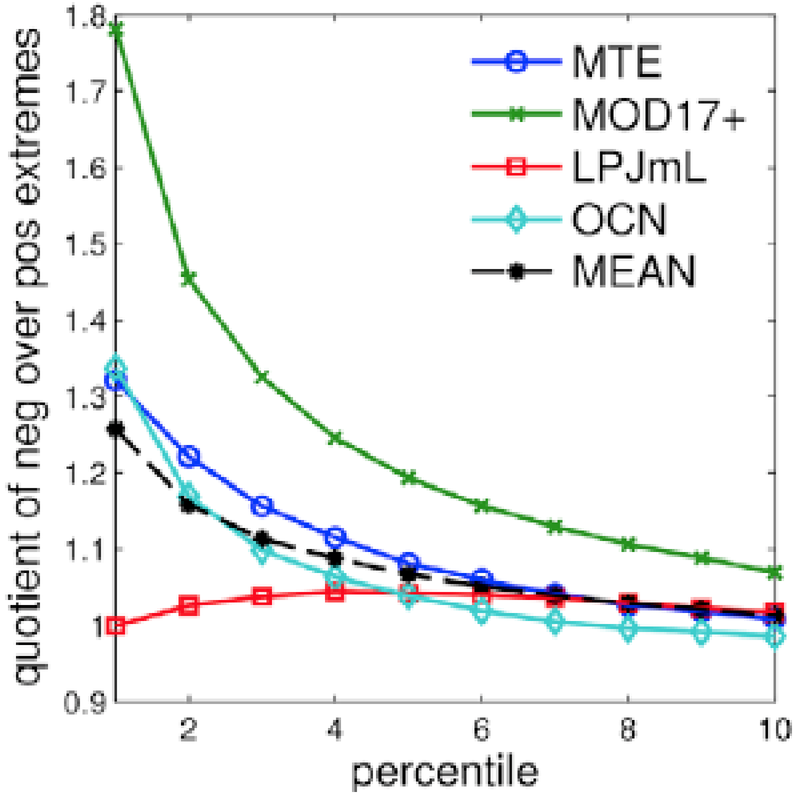
The dominant role of semi-arid ecosystems in the trend and variability of the land CO_2 sink.





Ahlström, A. *et al. Science* 348, 895-899 (2015)

Previous studies point to a substantial influence of negative GPP anomalies on global carbon uptake

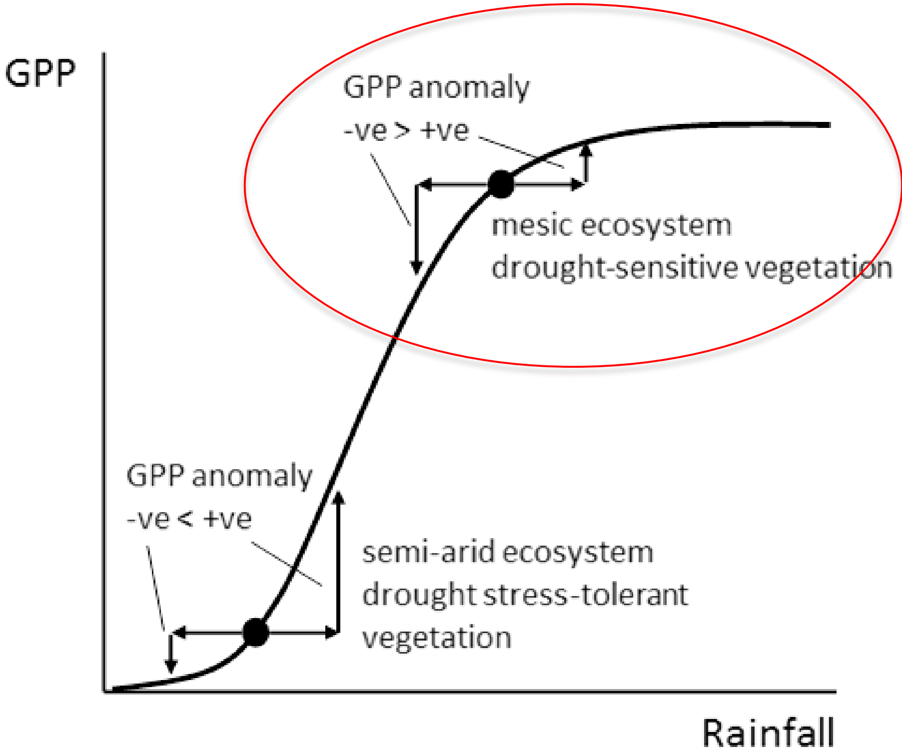


Relative impacts of negative and positive extreme GPP events on global GPP .

Zscheischler et al., Environ. Res. Lett. 9 (2014) 035001

Negative GPP anomalies influence global carbon uptake more than positive ones: possible explanations.

- Positive skewness of ENSO
  - El Niño stronger than La Niña
  - Southern hemisphere droughts contribute strongly to reductions in global GPP
- Large contribution of mesic ecosystems (eg tropical forests) to global GPP.
  - High rainfall episodes: productivity or saturates or declines as other resources are limiting.
  - Low rainfall episodes: larger negative response.
- Regeneration may be slow compared with drought response ('slow in rapid out principle')

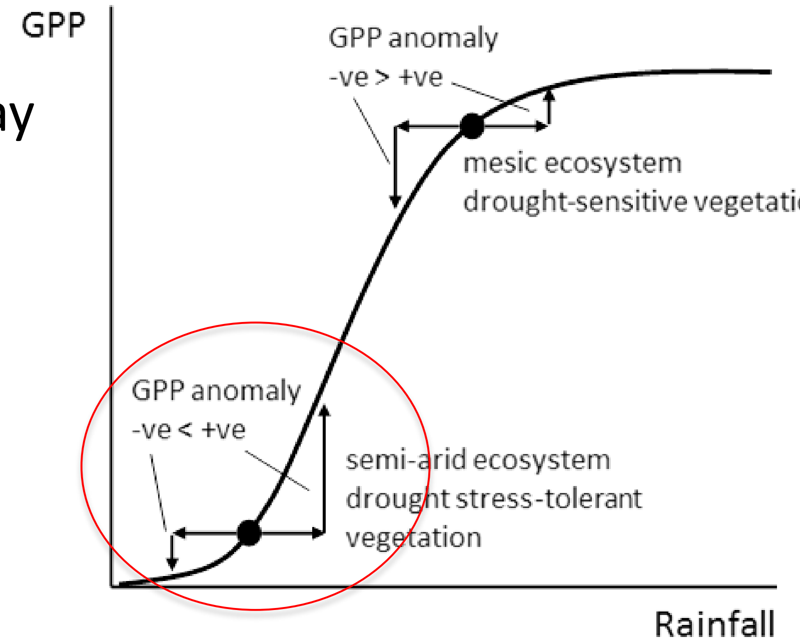


Haverd et al. *Global Change Biology*, doi: 10.1111/gcb.13412, 2016.

These may not apply to semi-arid regions, where we may expect a dominance of positive GPP anomalies.

Positive asymmetry in GPP of semi-arid ecosystems?

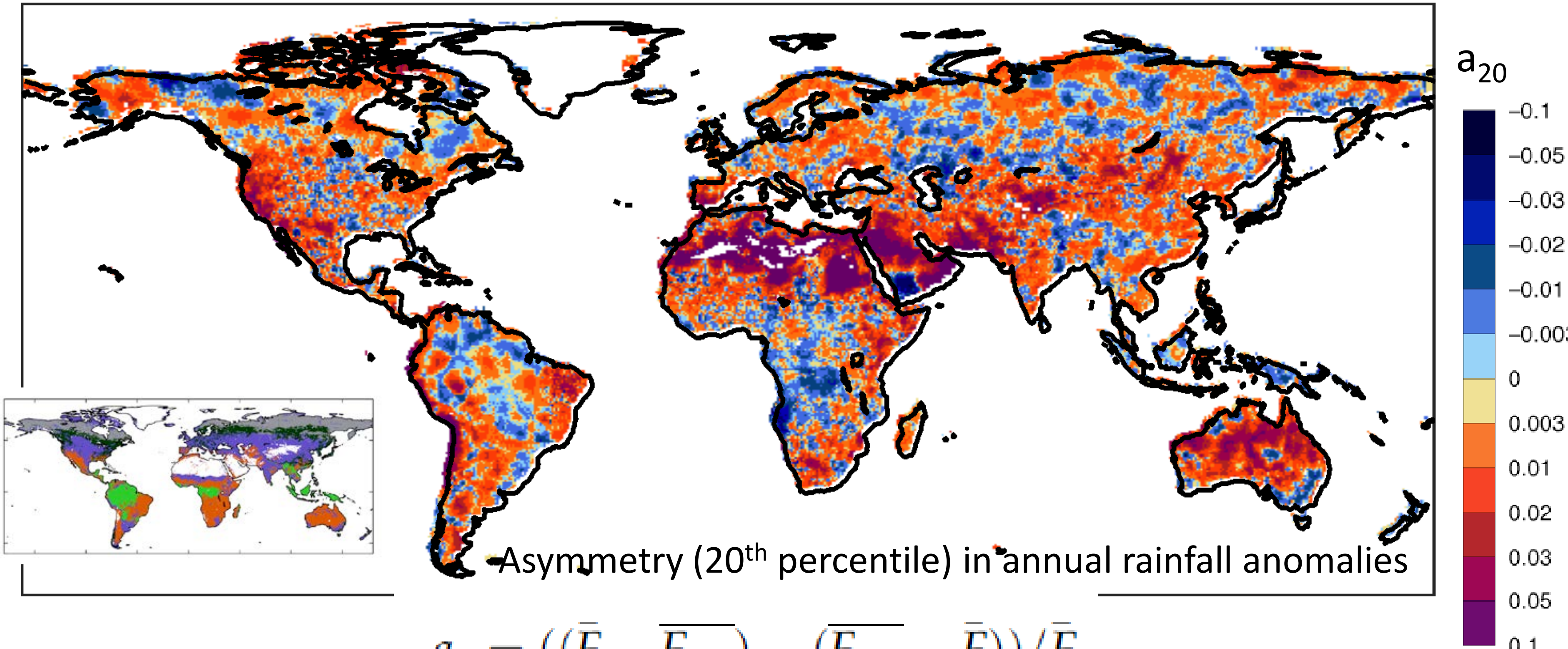
- Positive asymmetry in annual rainfall anomalies
- Drought-adapted biota of these regions may exhibit a rapid growth response during occasional high-rainfall episodes, whereas during inter-pulse periods, little or no production takes place.



Hypothesis

Differential sensitivity of biota to positive anomalies inducing growth flush vs. negative anomalies triggering stress responses to drought will contribute additional, positive, asymmetry to the dependency of GPP on rainfall.

Annual rainfall anomalies normally exhibit positive asymmetry, with skewness increasing with interannual variability.



Asymmetry (20th percentile) in annual rainfall anomalies

$$a_p = ((\bar{F} - \overline{F_{+p}}) - (\overline{F_{-p}} - \bar{F}))/\bar{F}$$

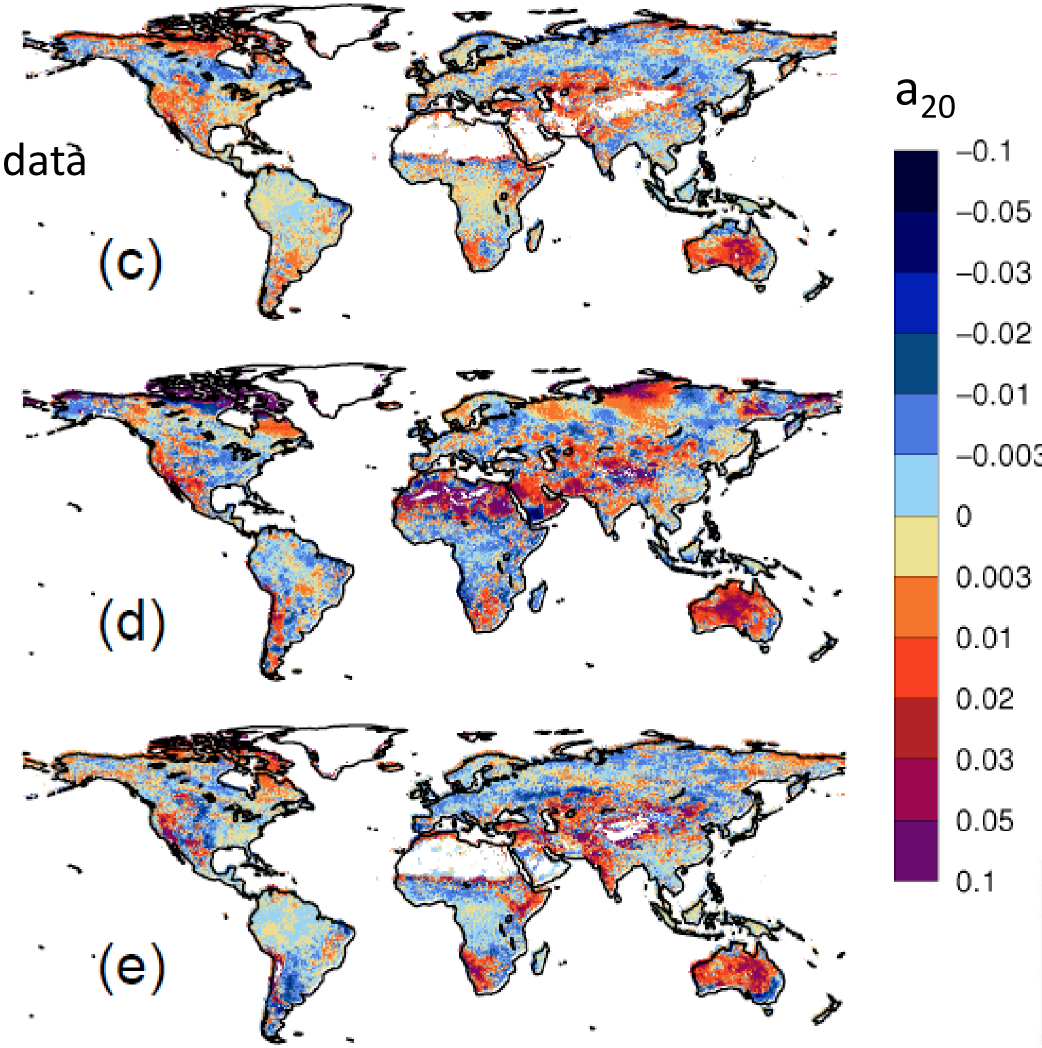
Asymmetry index: relative difference between enhancement of mean flux due to positive anomalies and reduction in mean flux due to negative anomalies. (F_{+p} is the flux time series with p^{th} percentile anomalies replaced my median values)

Global distribution of asymmetry in annual GPP and maximum FAPAR annual anomalies: Australia is a hot-spot.

GPP: upscaled flux data

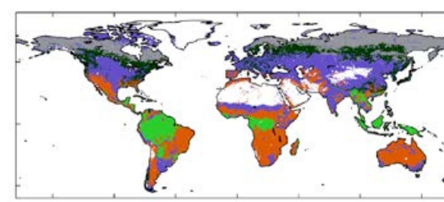
GPP: LPJ-GUESS

Maximum annual GIMMS-3g FAPAR

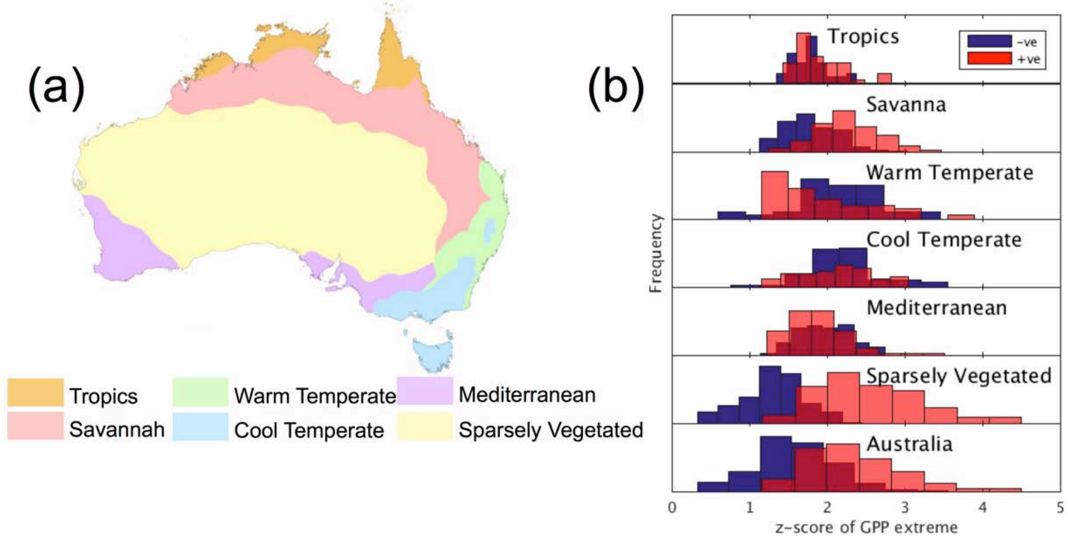


Regions with positive asymmetry account for 42% global GPP

74% of Australian land surface is characterised by positive GPP asymmetry



Frequency distribution of z-score of most extreme positive and negative year in GPP* time-series (1900-2013): positive extremes larger in Savanna and Sparsely vegetated regions.



*Australian carbon balance from regional CABLE simulations, constrained by multiple observation types:

- Haverd, V. *et al.* Multiple observation types reduce uncertainty in Australia's terrestrial carbon and water cycles. *Biogeosciences* **10**, 2011-2040 (2013).
- Trudinger, C. M., Haverd, V., Briggs, P. R. & Canadell, J. G. Interannual variability in Australia's terrestrial carbon cycle constrained by multiple observation types. *Biogeosciences* **13**, 6363-6383 (2016).

Regional CABLE carbon-water cycle assessment for Australia

C. M. Trudinger et al.: Interannual variability in Australia's terrestrial carbon cycle 6

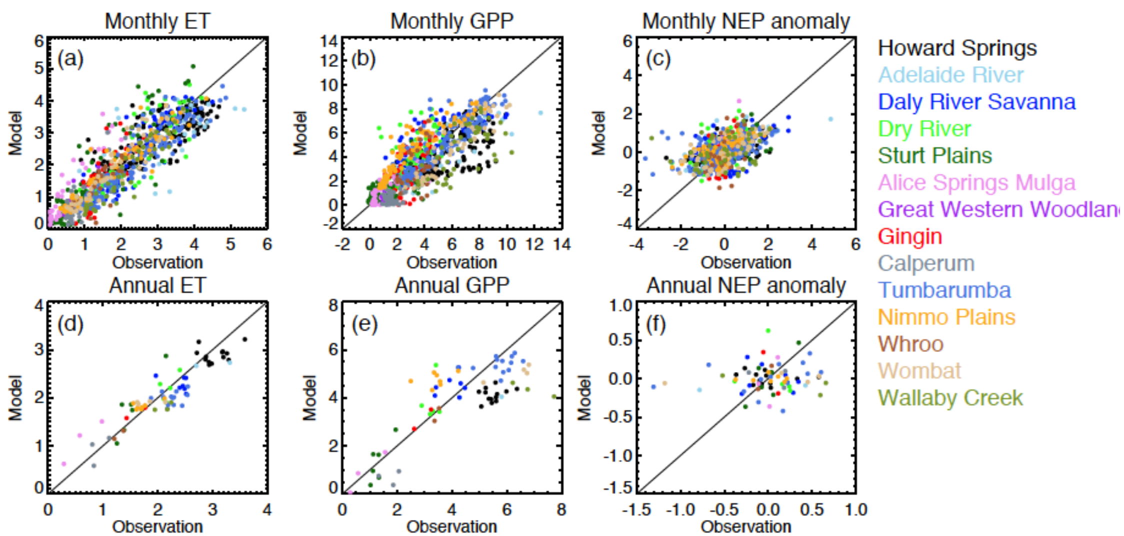
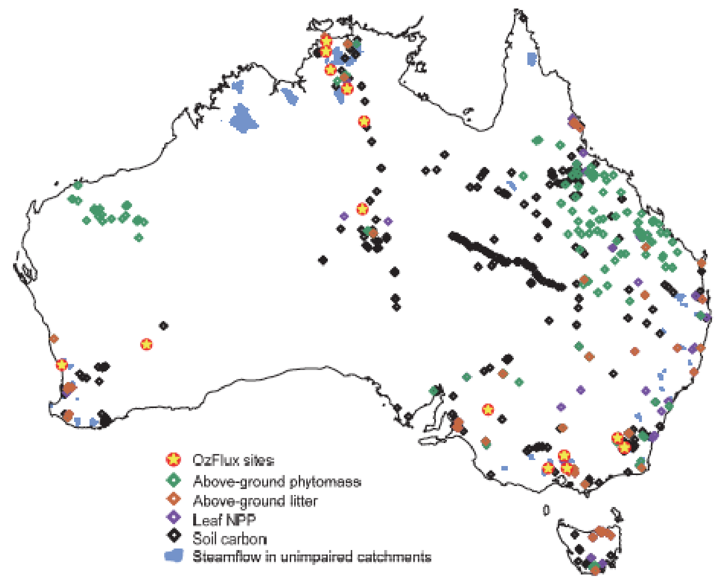


Figure 5. Scatter plots of modelled vs. observed (best case) monthly and annual ET (mm d^{-1}), GPP (gC m^{-2} d^{-1}) and NEP (gC m^{-2} d^{-1}) at 14 OzFlux sites. Symbols are colour-coded according to site.



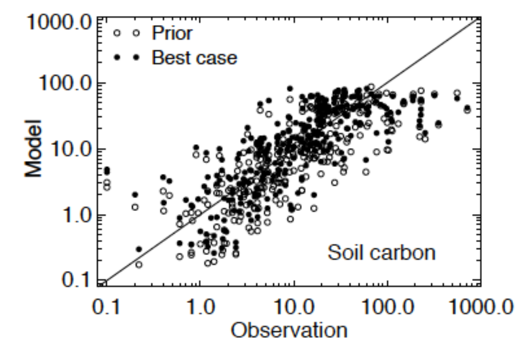
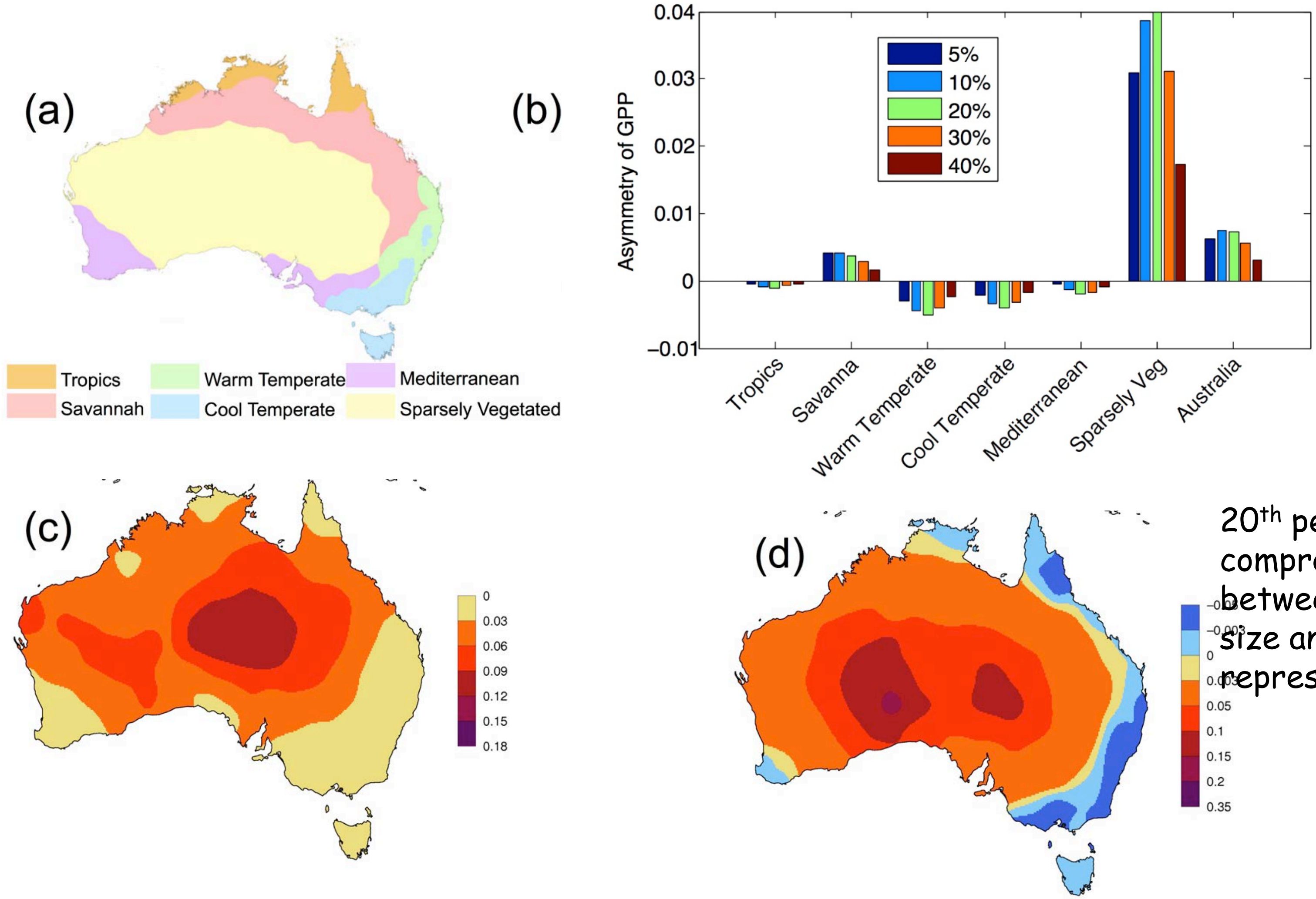


Figure 6. Scatter plot of modelled vs. observed (prior and best case) long-term-averaged soil carbon density in the top 15 cm.

Trudinger, C. M., Haverd, V., Briggs, P. R. & Canadell, J. G. Interannual variability in Australia's terrestrial carbon cycle constrained by multiple observation types. *Biogeosciences* 13, 6363-6383 (2016)

Qualitatively similar asymmetry across wide range of percentiles.



20th percentile a compromise between sample size and representativeness

Asymmetry of outer 20th percentile precip

Asymmetry of outer 20th percentile precip

Mechanisms for effects of rainfall asymmetry on GPP and NEP

- "Extrinsic Forcing": enhancing effect of larger positive extremes (big wets) on GPP because they increase mean rainfall.
- "Intrinsic (non-linear) Response": differential responses of ecosystems to increased vs decreased water availability.

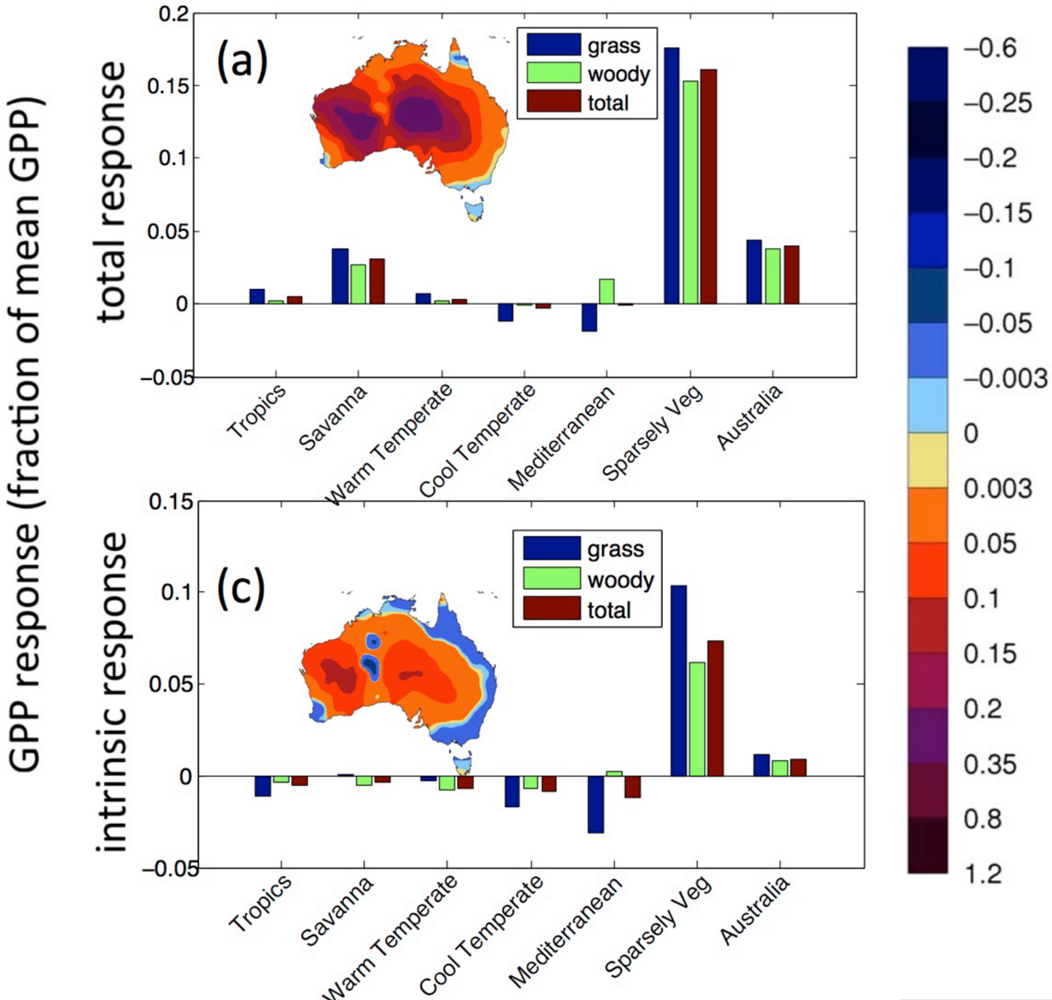
- Define total (extrinsic plus intrinsic) response asymmetry as flux difference imparted by positive precip anomalies, minus flux difference imparted by negative precip anomalies.

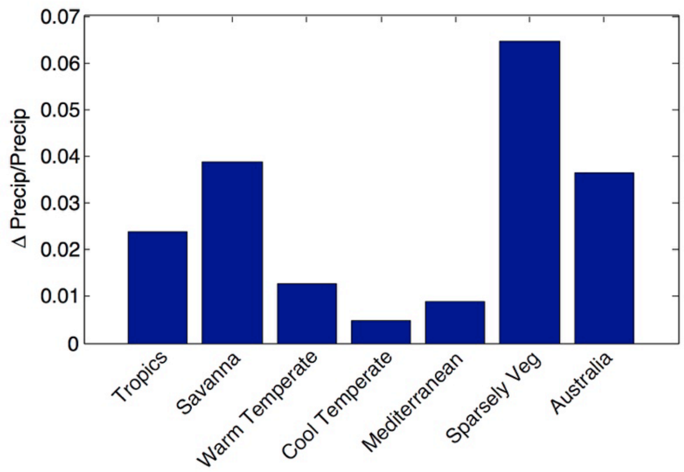
$$r_p = ((\overline{f(x)} - \overline{f(x_{+p})}) - (\overline{f(x_{-p})} - \overline{f(x)}))$$

- Define intrinsic (non-linear) response asymmetry as flux difference imparted by positive precip anomalies (mean precip preserved), minus flux difference imparted by negative precip anomalies (mean precip preserved).

$$r_{p,\mathrm{nonlinear}} = ((\overline{f(x)} - \overline{f(x_{+p,mp})}) - (\overline{f(x_{-p,mp})} - \overline{f(x)}))$$

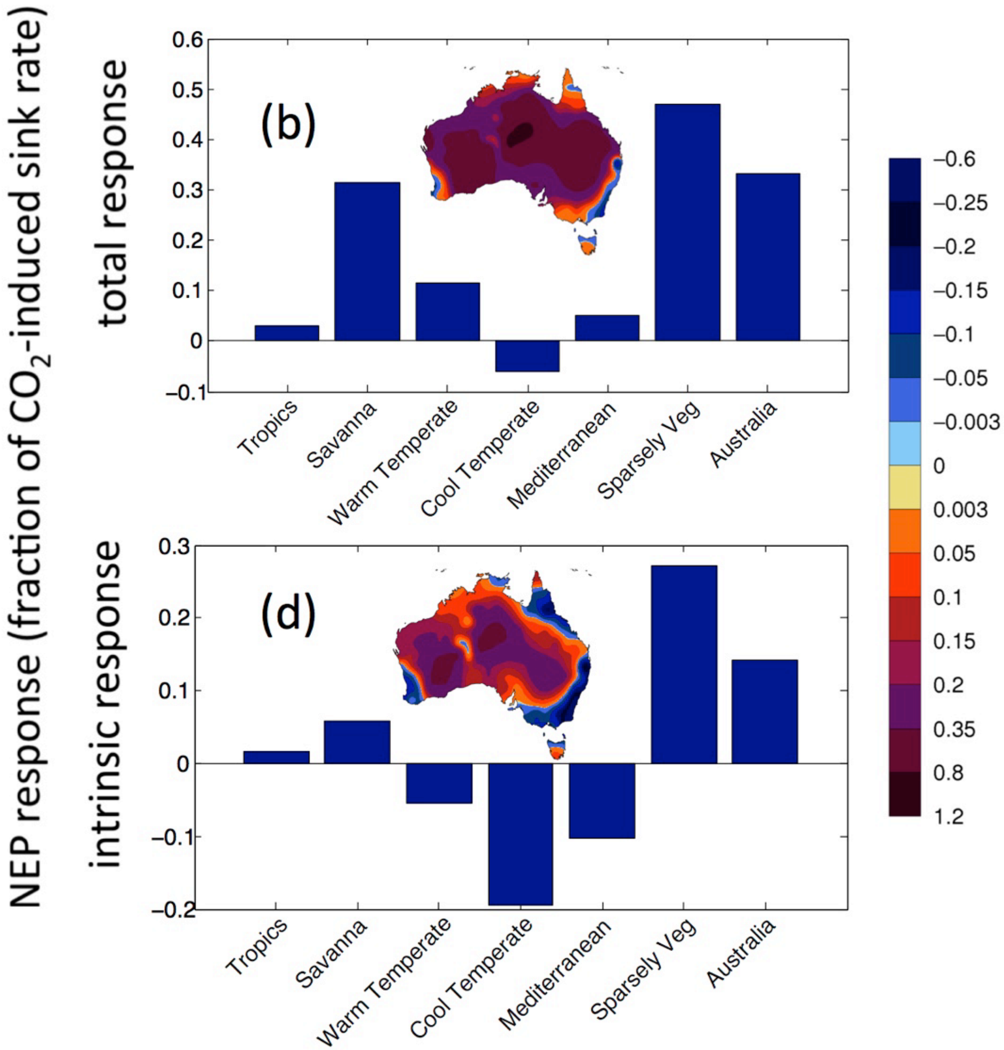
GPP response asymmetry to precipitation





Long-term spatially averaged GPP in semi-arid ecosystems is 9% higher than it would be in the absence of asymmetry in 20th percentile rainfall anomalies.

NEP response asymmetry to precip



In semi-arid regions, asymmetry in precip imparts an NEP flux increase (4.0 g Cm^{-2} yr^{-1}) equivalent to 42% of the present-day (1990–2013) averaged CO_2 fertilization-induced sink rate over Australia (9.5 g Cm^{-2} yr^{-1})

Increasing precipitation extremes may be implicated in increasing net carbon uptake in semi-arid ecosystems.

Summary and Conclusions

- Australia stands out as a hotspot for asymmetry in annual rainfall
- Australian semi-arid ecosystems respond positively to asymmetry in rainfall due to ***both extrinsic forcing and intrinsic response mechanisms***.
- Increasing precipitation extremes may provide ***an additional explanation for greening trends*** in semi-arid ecosystems globally.
- An implication of the significant asymmetric semi-arid ecosystem response is that predictive ecosystem models used to study drought-effects need to incorporate representations of plant and ecosystem mechanisms of ***stress response and recovery***, for example ***stress-related mortality*** and the ***use of nonstructural carbohydrate storage as a buffering mechanism*** against periods of low productivity.

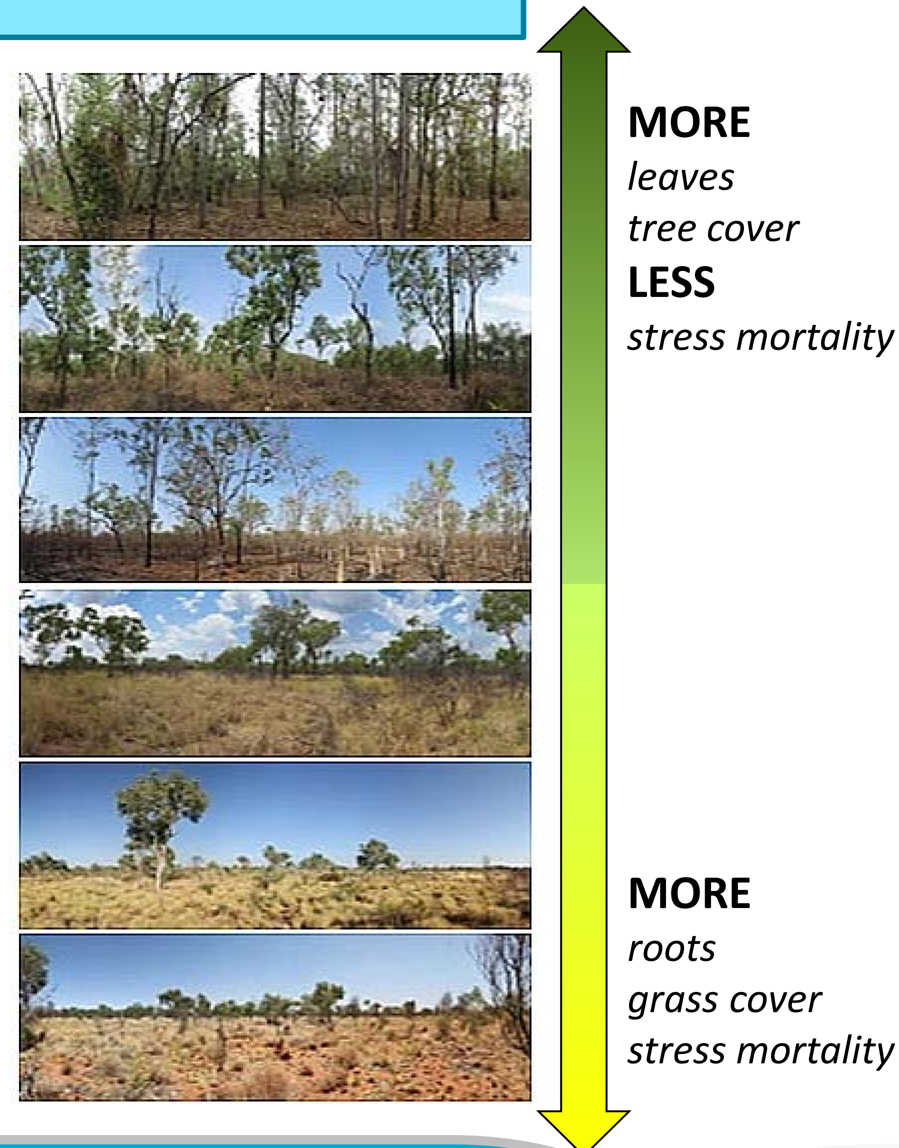
HAVANA (Hydrology, Allocation and Vegetation-dynamics Algorithm for Northern Australia) land surface model

Key Features

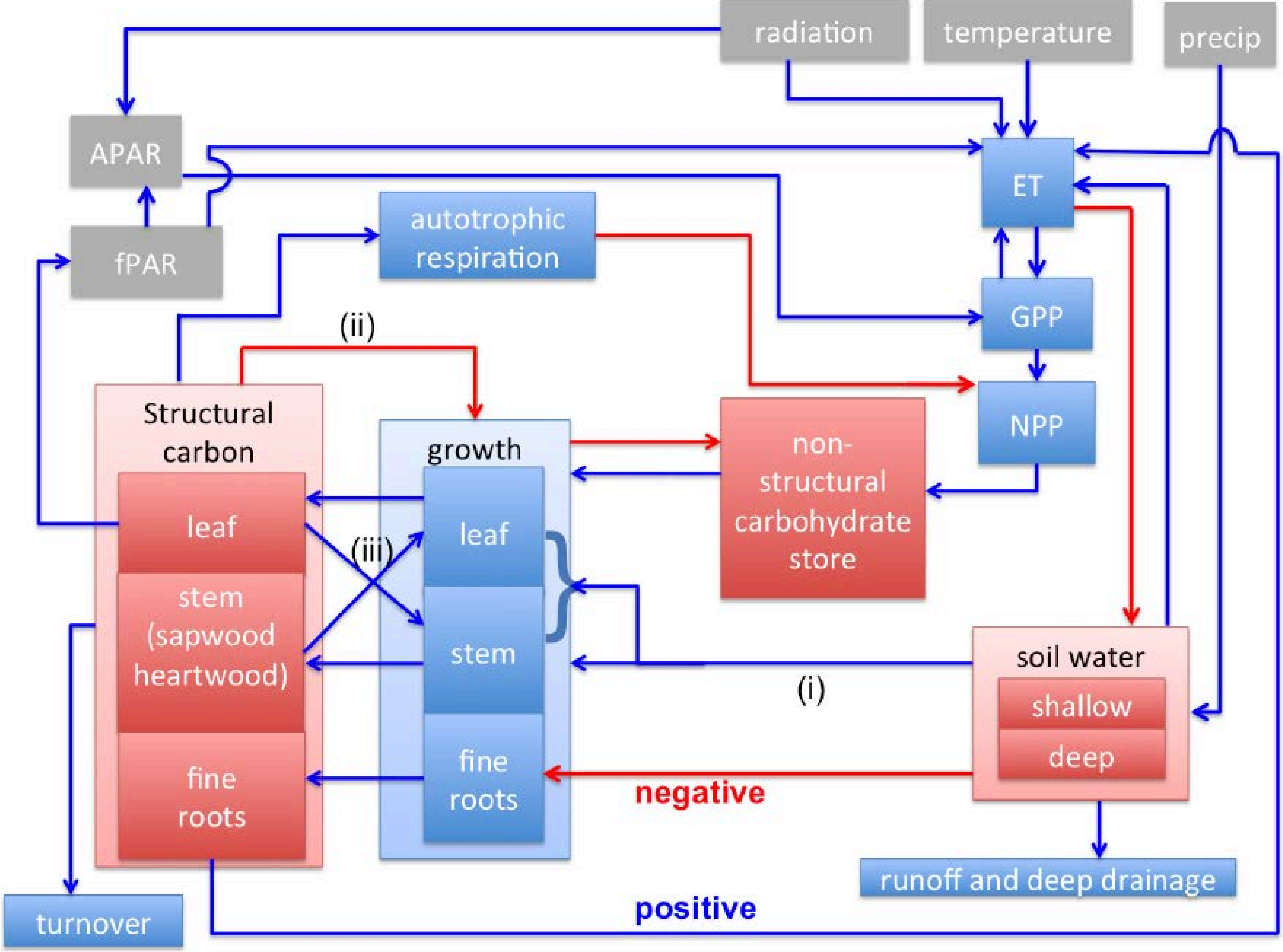
- Root/shoot C-allocation varies in time to maximise the total carbon gain, i.e. the long-term integral of NPP
- Growth decoupled from production
- Storage to buffer stress
- Tree-grass competition
- Emergent leaf and root phenology

Structure➔Function feedbacks

- Mortality ➔ biomass turnover
- Sapwood area ➔ leaf/wood C-allocation (pipe model)
- Sapwood biomass ➔autotrophic respiration
- Clumping index ➔light interception

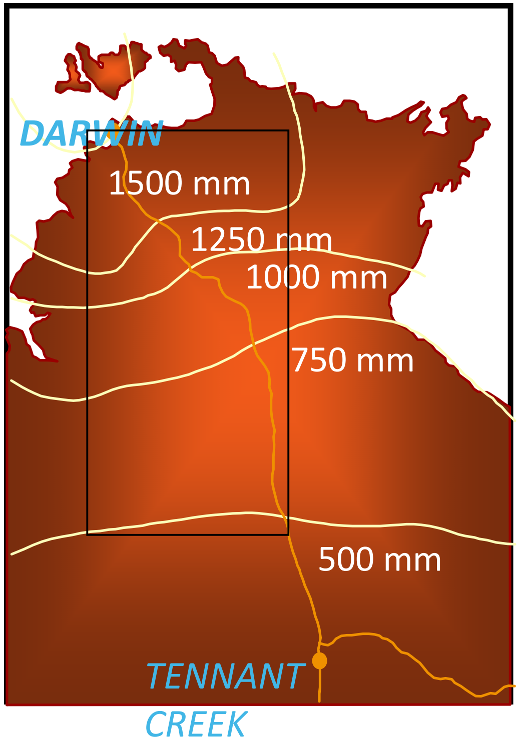


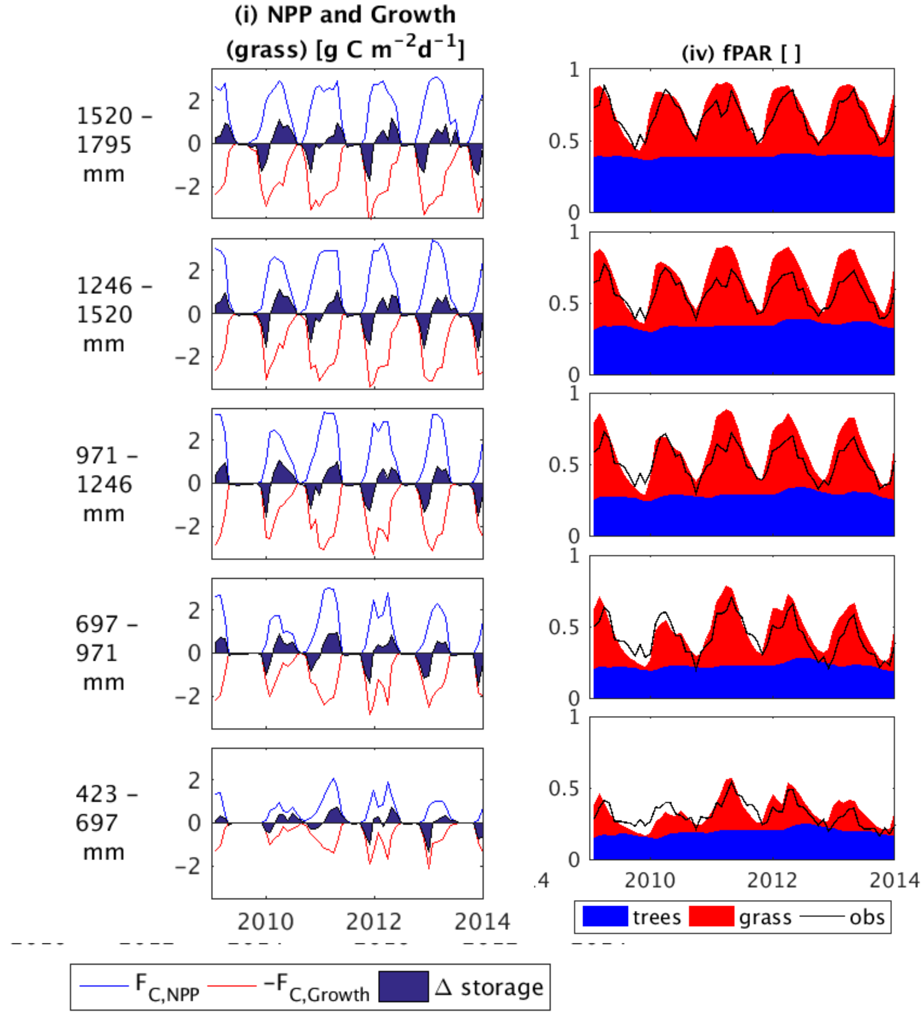
Haverd, V. *et al.* Coupling carbon allocation with leaf and root phenology predicts tree–grass partitioning along a savanna rainfall gradient. *Biogeosciences* **13**, 761-779 (2016)



Haverd, V. *et al.* Coupling carbon allocation with leaf and root phenology predicts tree–grass partitioning along a savanna rainfall gradient. *Biogeosciences* **13**, 761-779, (2016)

Model Dynamics: NPP, Growth and Storage





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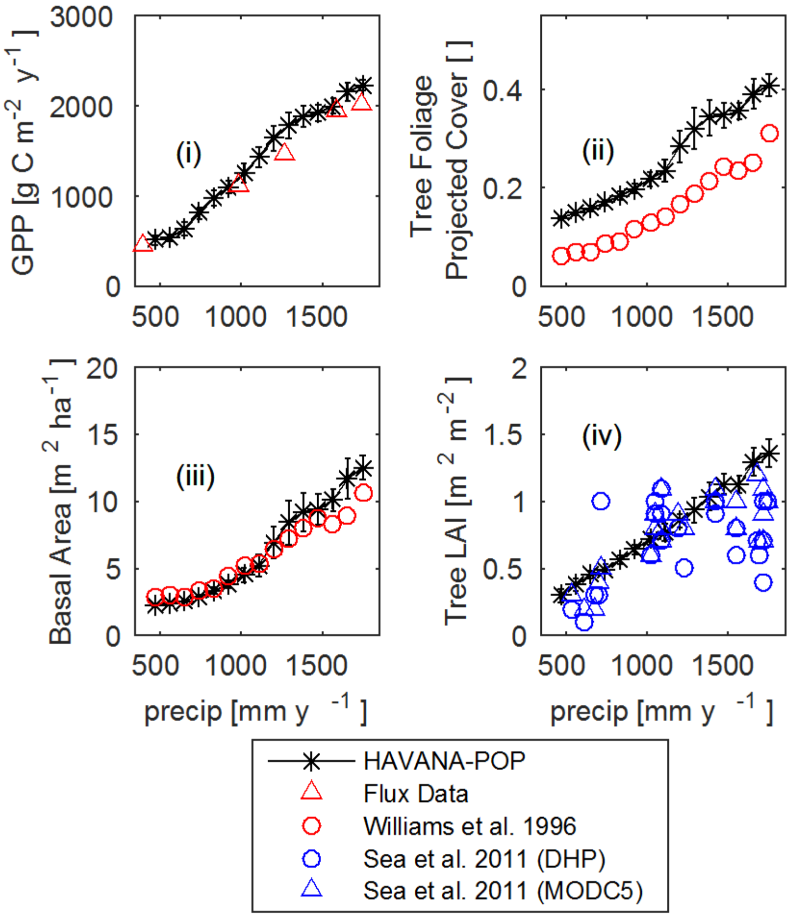
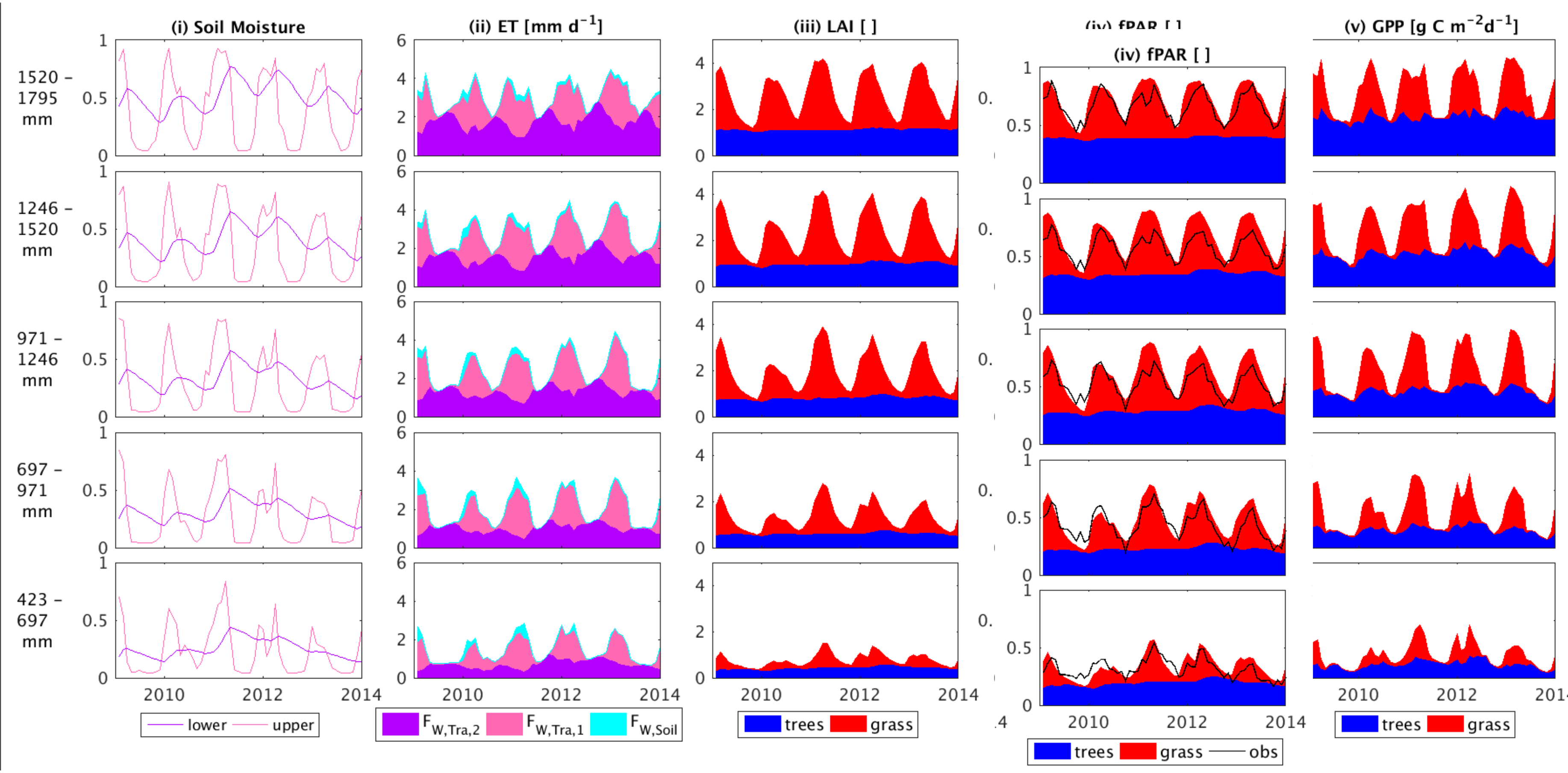
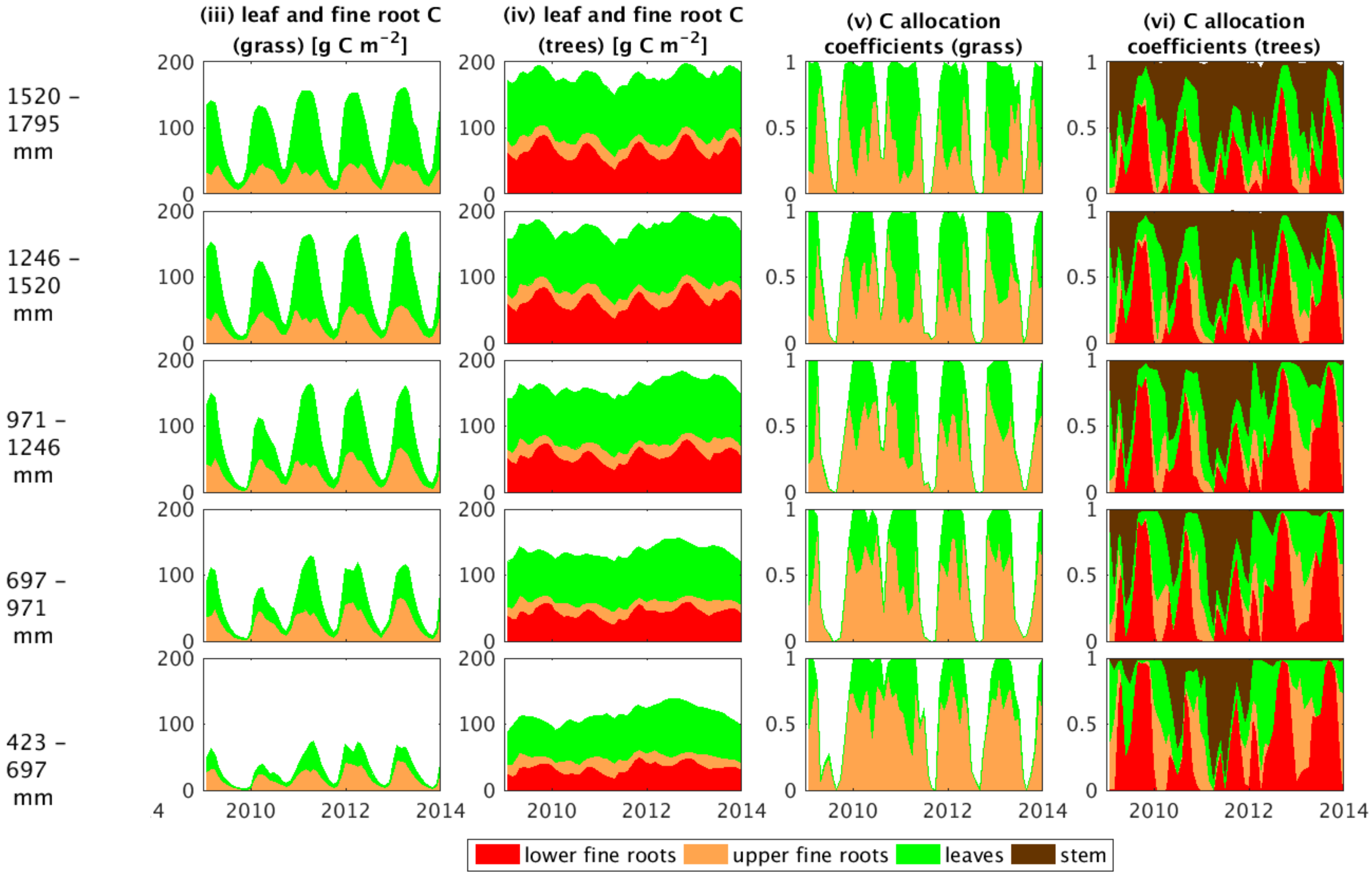
Variation of Structure and Function Along the NATT



Model Dynamics: Soil Moisture, GPP, LAI

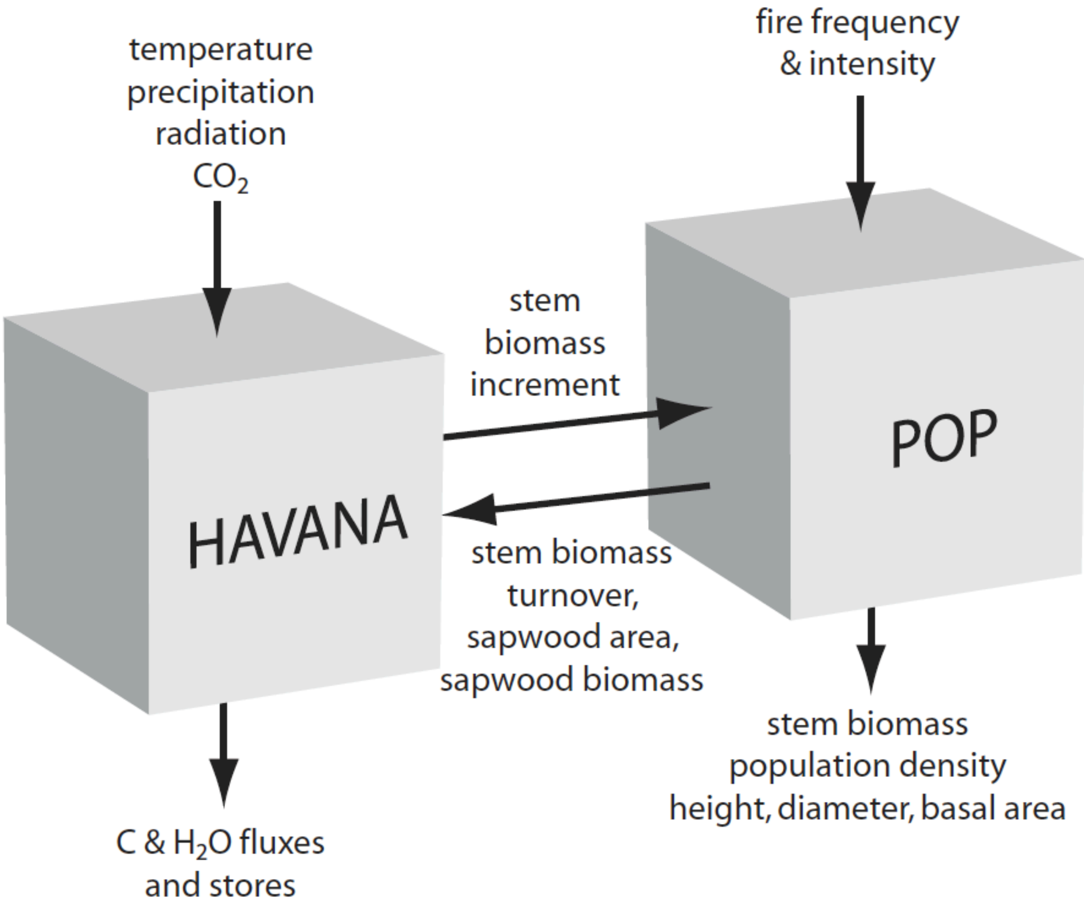


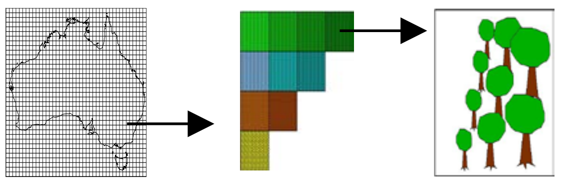
Model Dynamics: Allocation and C Pools



HAVANA – POP Coupling

POP is a module for tree demography and disturbance-mediated landscape heterogeneity.*





Grid-cell (tile) represented by patches distinguished by time since last disturbance

Recruitment, Growth, Mortality in each patch

*Haverd et al. 2013 *Geophysical Research Letters* 40: 5234-5239

Dynamic Allocation: growth allocated to pool with highest marginal gain in NPP

- C dynamics controlled by allocation of growth , and first-order decay, e.g.

$$\frac{dC_{\mathrm{L}}}{dt} = \alpha_L F_{C,Growth} - k_L C_L$$

- Carbon allocation coefficients vary in time to maximise the total carbon gain, i.e. the long-term integral of $F_{C,NPP}$
- Allocation coefficients have “bang-bang” character
  - at each instant *t*, an allocation coefficient of one is assigned to the pool for which the marginal return on invested growth is largest while all the other pools receive zero allocation