A network approach to determine ecosystem vulnerability

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Introduction

Ecosystems are complex networks of interacting variables within the soil, canopy, and atmosphere. In an ecohydrologic process network, we consider nodes to be time series variables related to radiation, vegetation, and energy and water fluxes. Links between nodes are information theory measures that identify different components of time dependencies, namely strength, time scale, redundancy, and stability over time.

Strength
How dominant is a link between two nodes?
peak I_τ

$$I(X_{t-\tau};Y_t)=\sum p(x_{t-\tau},y_t)\log_2\frac{p(x_{t-\tau},y_t)}{p(x_{t-\tau})p(y_t)}$$

units: bits/bit

Time Scale
Is the interaction on a fast or slow timescale?
τ of peak I_τ

$$\tau=\arg\max_{\tau}\left[I(X_{t-\tau};Y_t)\right]$$

units: time

Redundancy
Is the link unique, or redundant due to other links?
T/I

$$\frac{T}{I}(X_{s1}\rightarrow X_{tar})=\min_{X_{s2}}\left[\frac{I(X_{tar};X_{s1}|X_{s2})}{I(X_{tar};X_{s1},X_{s2})}\right]$$

units: bits/bit

Stability
How does the interaction (link) vary over time?
H_L

$$H_L(L)=-\sum p(l)\log_2 p(l)$$

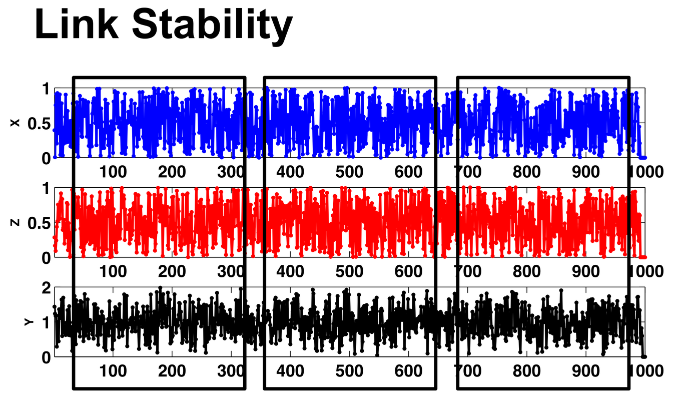
(L= I_τ, τ, T/I, etc)
units: bits

Goals

- Test methods using chaotic coupled logistic maps: *how does network topology impact information flow measures?*
- Form ecohydrologic networks from measured and simulated data: *how do networks respond to weather variations, sampling intervals, or seasons?*

Network Metrics

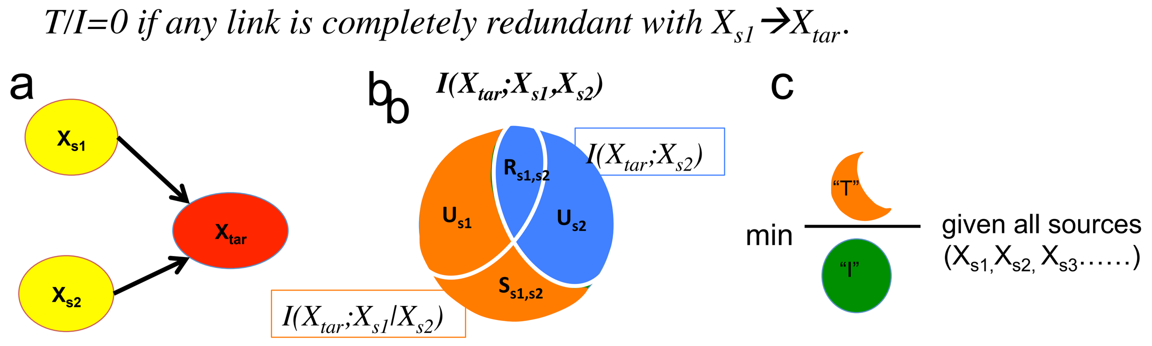
Link Stability



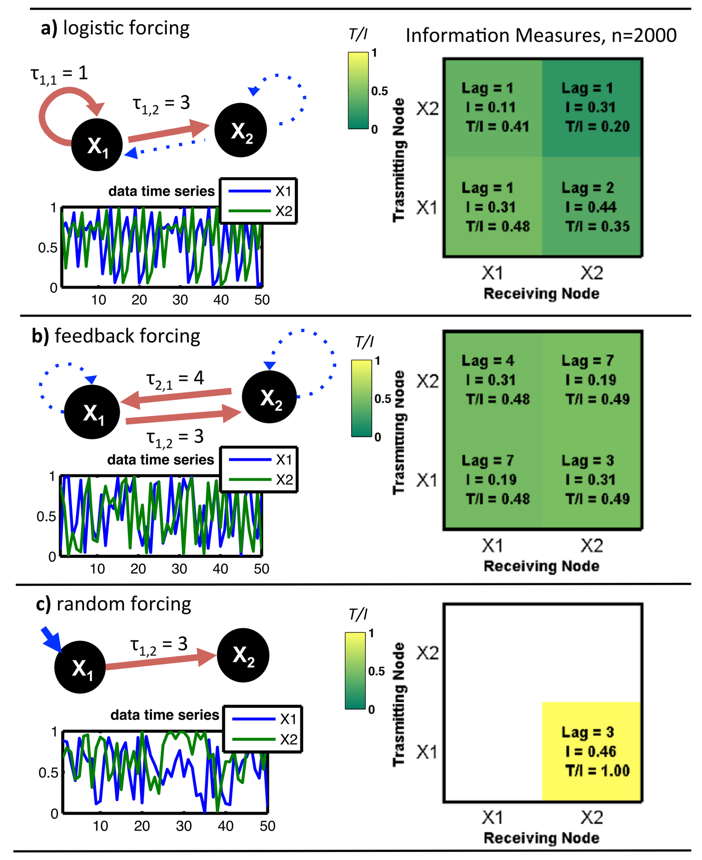
For long time series data, we segment into shorter intervals (as few as n=200 data points) and compute I_τ for a range of time lags. If we have many time windows, the entropy of a link property L (H(L)) represents "link stability"

Information Decomposition

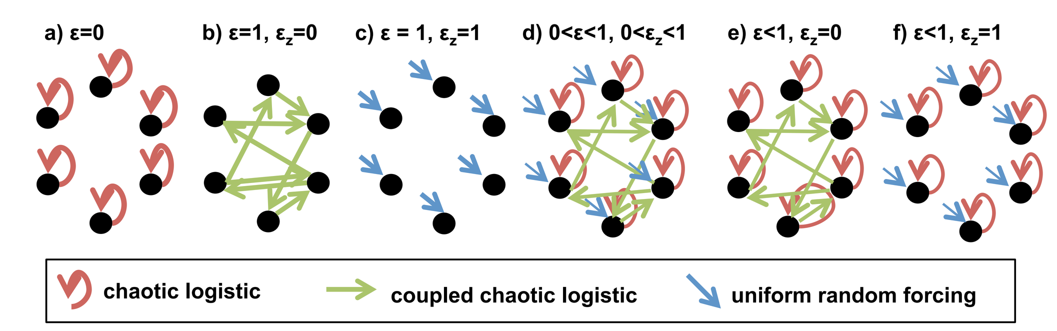
*In the case of 2 detected source links to a target node (**a**), total shared information $I(X_{tar};X_{s1},X_{s2})$ can be decomposed into (**b**) unique (U), redundant (R), and synergistic (S) components. For any detected link $X_{s1}\rightarrow X_{tar}$, we define T/I as the minimum value of conditional over total shared information (**c**). T/I is a conservative measure of relative synergy + uniqueness in that T/I=0 if any link is completely redundant with $X_{s1}\rightarrow X_{tar}$.*



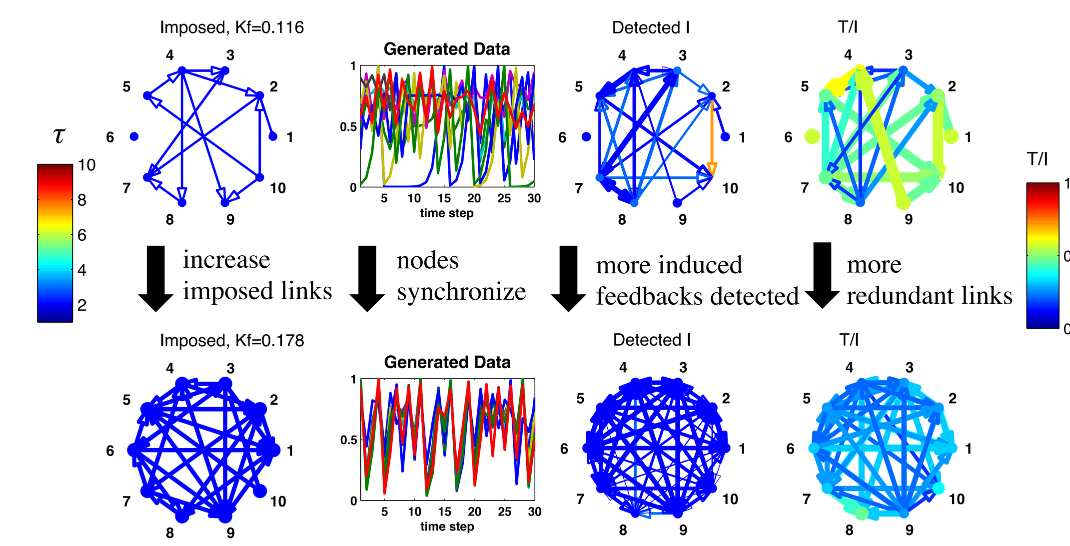
Analysis of Generated Networks



We generate several 2-node cases where $X_2(t) = f(X_1(t-3)) = 4X_1(t-3)[1-X_1(t-3)]$ and X_1 is established by (a) $f(X_1(t-1))$, (b) $f(X_2(t-4))$, and (c) as a uniform random variable. For each case, we generate time series, compute I_τ, and the associated T/I for each link. We see that cases with multiple time dependencies result in completely connected networks due to feedbacks induced by the imposed links. This also leads to high redundancy (low T/I) between links compared to the randomly driven case.

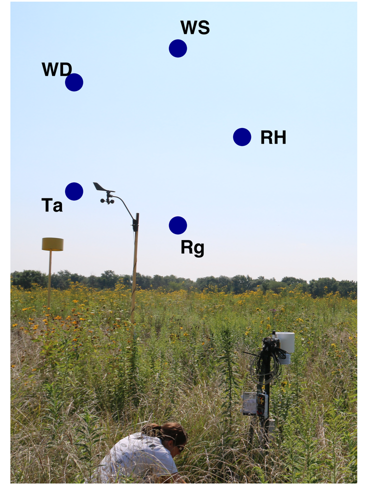


Larger chaotic logistic networks with different forcing structures and connectivities (top) reveal patterns of synchronization (bottom) that depend on imposed and induced feedbacks.



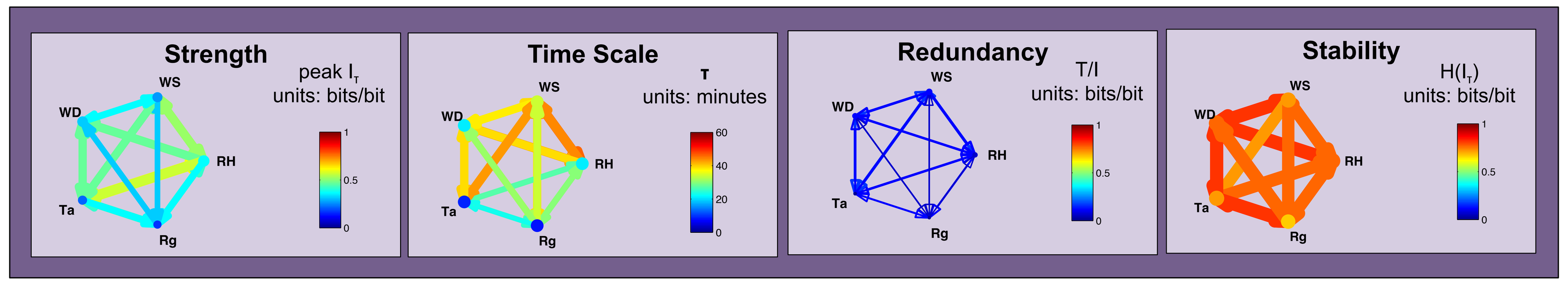
Ecohydrologic Data Networks

Generated Networks		**Real World Networks**
Questions: Do metrics capture imposed links?		**Questions:** What are imposed links? How does network shift due to stress?
Challenges: development and Interpretation of measures		**Challenges:** noise, gaps, intervals of data, nodes represent different types of variables
Findings: Measures capture imposed links and induced feedbacks	➡	**Findings**: inferences about ecohydrologic system behavior

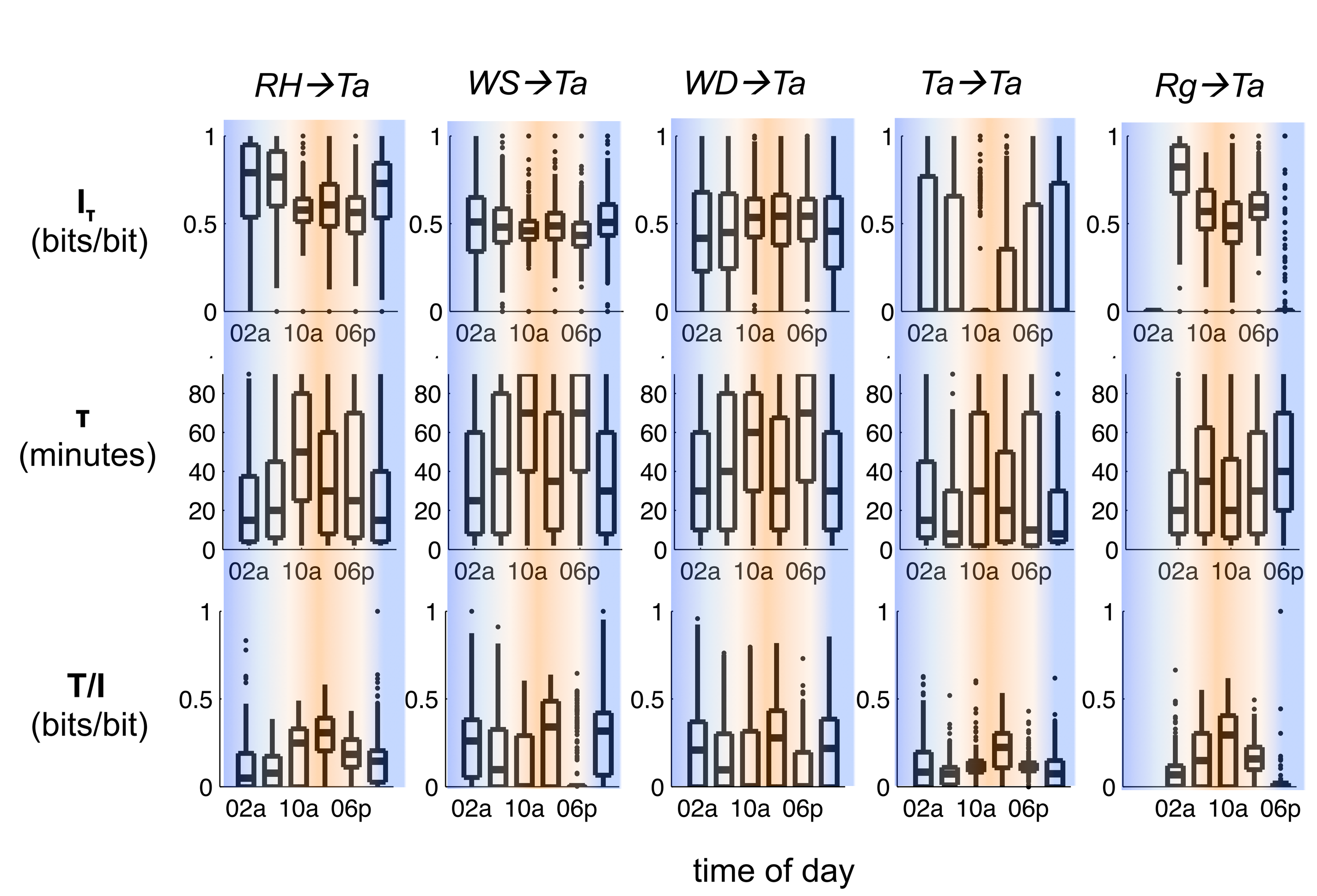


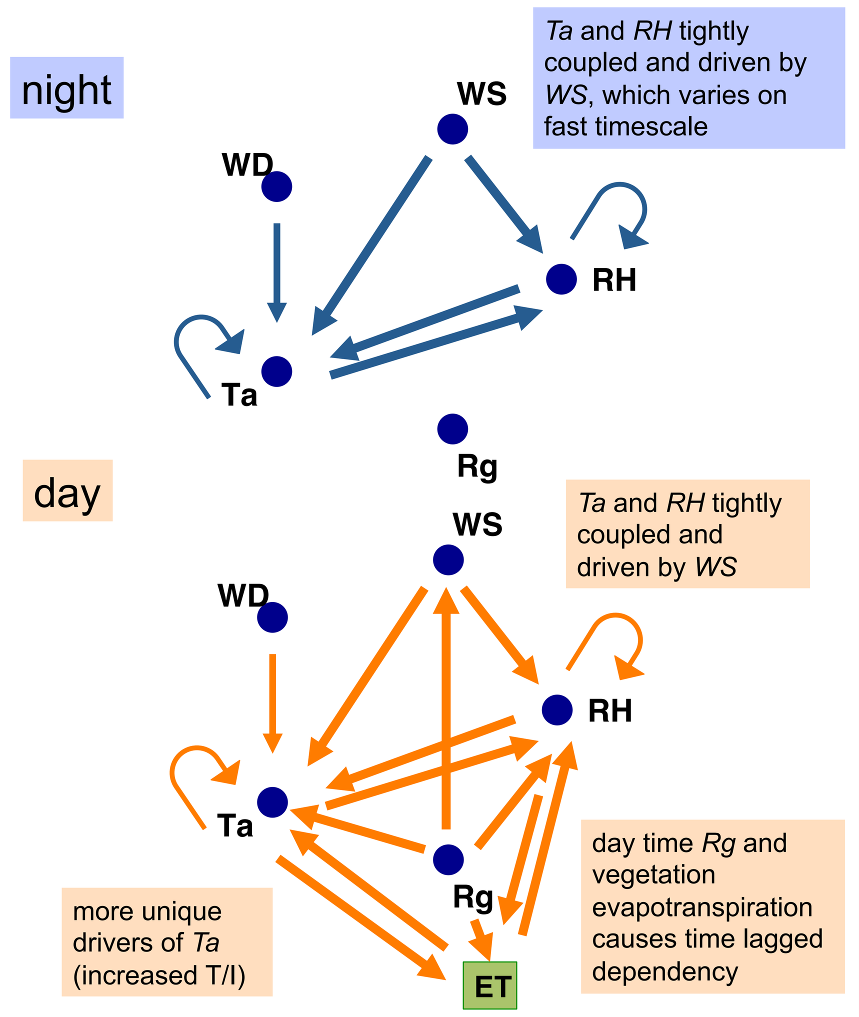
Study Site:
Sangamon Forest Preserve
Weather Station (IML-CZO)
Nodes: radiation (*Rg*), windspeed (*WS*), direction (*WD*), temperature (*Ta*), relative humidity (*RH*) (precipitation and leaf wetness not shown)
Dates: June-Nov 2014,March-Nov 2015
Temporal Resolution: 1 minute
Network Window: 4 hours (240 mins)

Average network measures for over 2000 generated networks. Links are on average strong, short timescale (< 1 hour), highly redundant (low T/I), and vary over time (high H(I)).



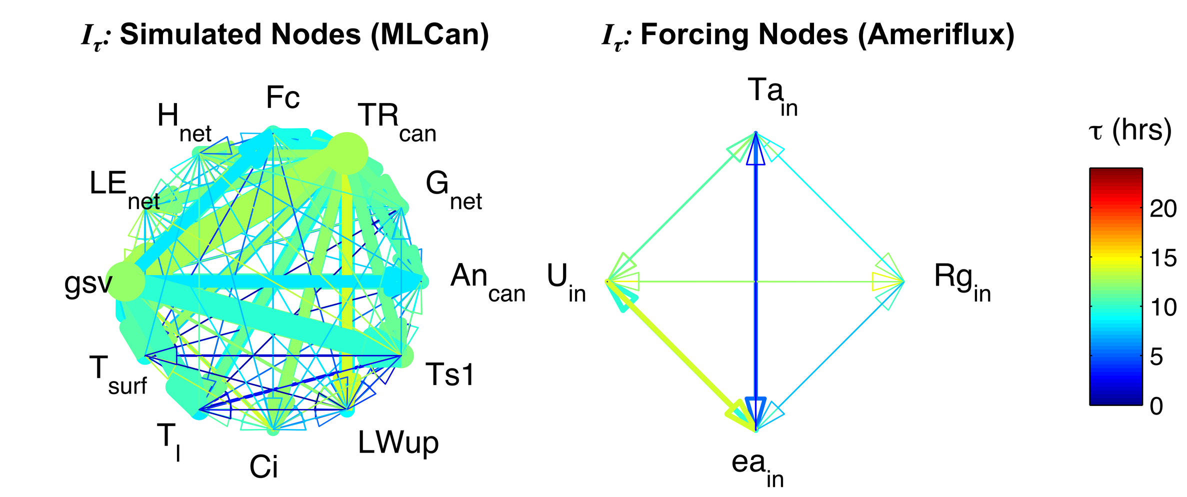
Below: network measures for links to air temperature (Ta) of strength (I_τ), timescale (τ), and redundancy (T/I) for all networks summarized based on time of day (6 4-hour networks per day). We observe that day time networks (orange shading) have slightly weaker links, but longer timescale and higher T/I than night networks (blue shading).





Ecohydrologic Model Networks

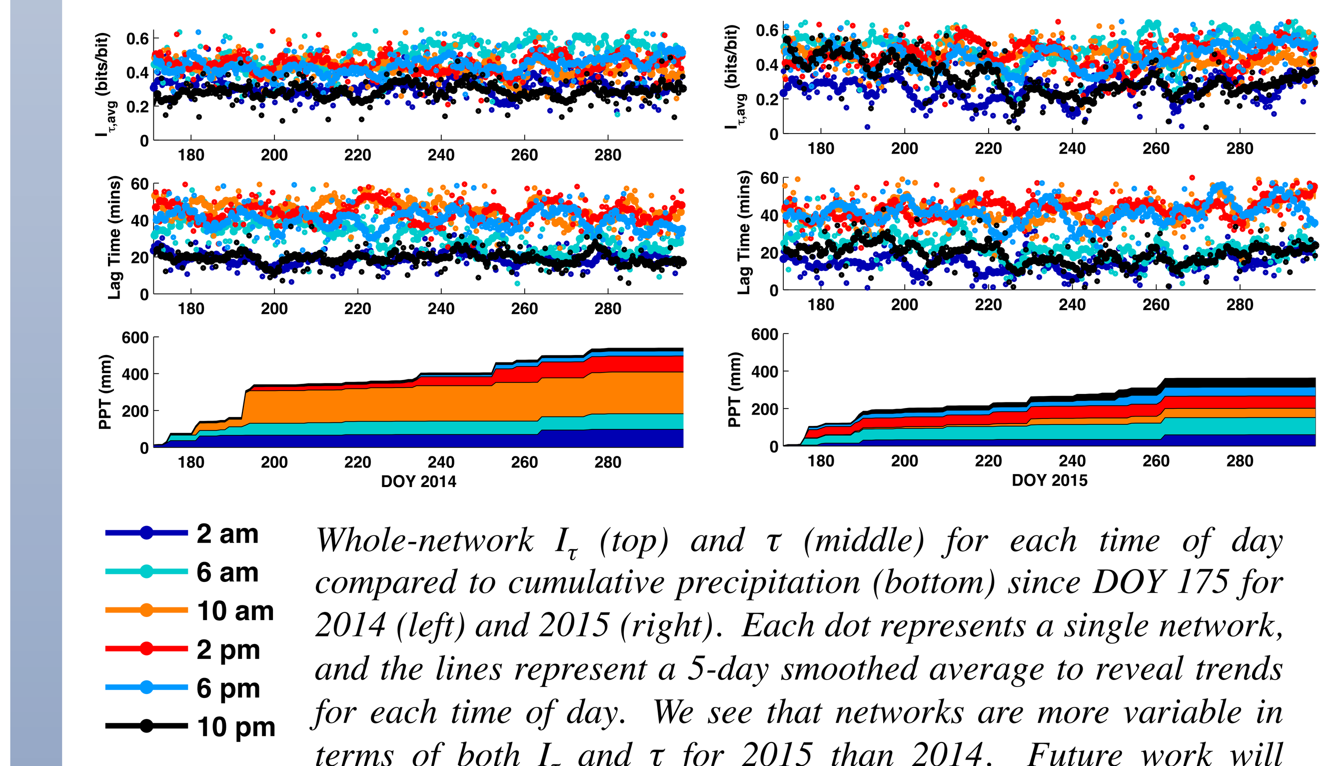
Time series nodes such as *Rg*, *WS*, and *Ta* are used as forcing for ecohydrological models that simulate leaf, root/soil, and ecosystem fluxes of carbon, water, energy, and nutrients. Model results and their associated process networks can help us understand vegetation responses to weather variability.



MLCan was used to simulate vegetation and ecosystem fluxes for the Bondville, IL Ameriflux tower site during the growing season of 2005. Simulated network (left) is more strongly connected than forcing data network (right) (I_τ indicated by line width, τ by color), but links are also more redundant.

Future Work

- how do sampling interval and data source impact network structure?
- assess network responses to weather variability and seasonality of perturbations



Whole-network I_τ (top) and τ (middle) for each time of day compared to cumulative precipitation (bottom) since DOY 175 for 2014 (left) and 2015 (right). Each dot represents a single network, and the lines represent a 5-day smoothed average to reveal trends for each time of day. We see that networks are more variable in terms of both I_τ and τ for 2015 than 2014. Future work will involve assessing ecosystem and network response to individual and accumulating weather events.

Acknowledgments

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Chaotic logistic network analysis section can be found in: *Entropy* 2015,17(11), doi: 10.3390/e17117468