Theoretical Bridging of Socio-Economics and Ecology:
Process Network Approach to Understanding How Forest Ecosystems Adapt to Change

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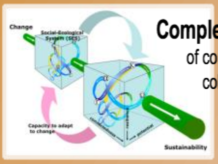
Social-Ecological Systems

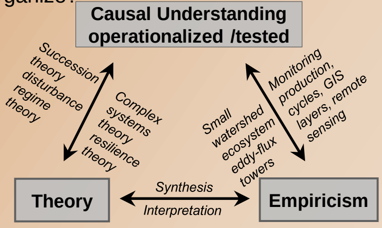
SES: A combined system of social and ecological components and drivers that interact and give rise to results, which cannot be understood based on social or ecological considerations alone. A pivotal hinge to connect these two different systems in dimensionality & complexity is needed (e.g. thermodynamics)



Complex system: Large networks of components give rise to complex collective behavior, sophisticated information processing, and adaptation via learning *[Kim and Oki, 2011]*

Resilience Thinking

Resilience theory treats biophysical & socioeconomic elements of a region as components of a single SES and emphasizes (1) the capacity of SES to continue delivering services and (2) the trade-offs associated with being in different regimes [Walker and Salt, 2006]. **Key questions**: (1) How to define the state of a complex system? (2) How to identify subsystems? (3) How are the observed variables connected to one another? (4) Do the subsystems self-organize?



Capturing Key Couplings, Time Scales, and System States

The entropy (H) is a measure of uncertainty [e.g., Shannon,1948];

$$H(X_t) = -\sum p(x_t)\log p(x_t)$$

Mutual information (I) measures the reduction in uncertainty due to the knowledge of another variable [Guiasu, 1977]:

$$I(X_t, Y_t) = \sum_{x_t, y_t} p(x_t, y_t)\log\frac{p(x_t, y_t)}{p(x_t)p(y_t)}$$

Transfer entropy (T) measures the reduction in the uncertainty of the current state of Y_t that is gained from a block length history of X_t that is not present in a block length history of Y_t itself [Schreiber, 2000]:

$$T(X_t > Y_t, \tau) = \sum_{y_t, y_{t-\Delta t}, x_{t-\tau\Delta t}} p(y_t, y_{t-\Delta t}, x_{t-\tau\Delta t}) \cdot \log\frac{p(y_t | y_{t-\Delta t}, x_{t-\tau\Delta t})}{p(y_t | y_{t-\Delta t})}$$

T is estimated at a lag at which transfer of information takes place from X_t to Y_t in comparison to the single point immediate history of Y_t (Ruddell & Kumar, 2009). We analyzed the time series data of 15 variables of ecohydrologic systems in Gwangneung deciduous forest in 2008.

15 variables: atmospheric pressure (PA), precipitation (Precip), net radiation (Rg), latent heat flux (LE), sensible heat flux (H), CO2 flux (NEE), gross primary productivity (GPP), ecosystem respiration (RE), air temperature (T), canopy temperature (Tc), vapor pressure deficit (VPD), soil temperature (Ts), soil water content (SWC), wind speed (WS), and wind direction (WD).

Logical Criterion for Coupling Type Classification

	T>Δ(T)	I>Δ(I)	T>I
Type 1. Synchronization dominated	F[a]	T	F
Type 2. Feedback dominated	T	T	F
Type 3. Forcing dominated	T	-	T
Type 4. Uncoupled	F	F	-

* T is true; F is fail (Ruddell and Kumar, 2009)

Each demonstrates one of the six observed canonical types of coupling. Tz shows the information flow coupling (the ratio of T to zero-lag I). Dotted lines are significance thresholds (Δ), above which Tz is statistically significant.

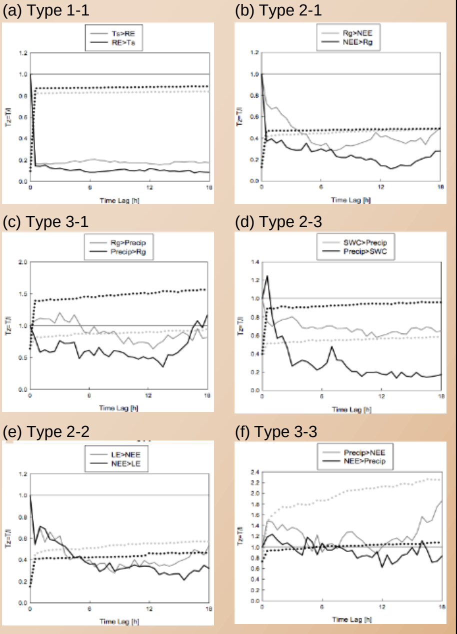


Figure 1. Tz lag plots for May 2008 in Gwangneung Deciduous Forest: (a) soil temperature (Ts) - respiration (RE); (b) net radiation (Rg) - net ecosystem exchange (NEE); (c) precipitation (Precip) - Rg; (d) soil water contents (SWC) - Precip; (e) latent heat flux (LE) - NEE; (f) Precip - NEE

Self-Organizing Network

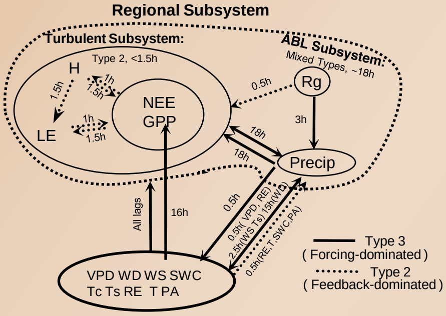


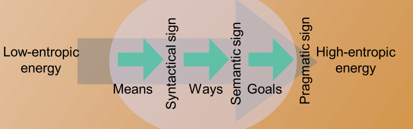
Figure 2. **The process network** of ecohydrological system for May 2008 in Gwangneung deciduous forest, South Korea.

The adjacency matrix for the 15 variables resulted in 210 pairwise couplings, of which 25% were found statistically significant at one or more time lags (ranging from 0.5 to 18 h). A self-organizing "turbulent" subsystems was formed from H, LE, NEE and GPP, which share "feedback" couplings at <1.5 h time scale. A "synoptic" subsystem was formed from PA, VPD, WD, WS, T_c, T, T_s, RE and SWC, which are synchronized, serving as a large-scale forcing to other subsystems.

Summary & Outlook

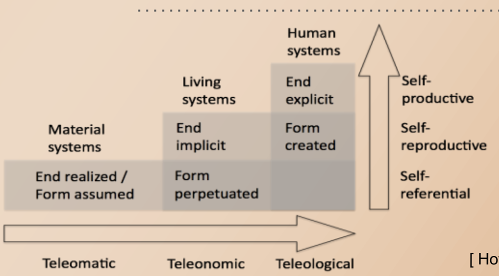
Using information flow statistics, process networks can be delineated from multivariate time series data. 'mutual information (measure of synchronization) and 'transfer entropy' (cause of synchronization) should be considered simultaneously. Process network approach is able to identify the differences between various states of ecohydrological and biogeochemical systems on the basis of variations in the pattern of feedback couplings on the network. Further scrutiny and other applications are currently in progress.

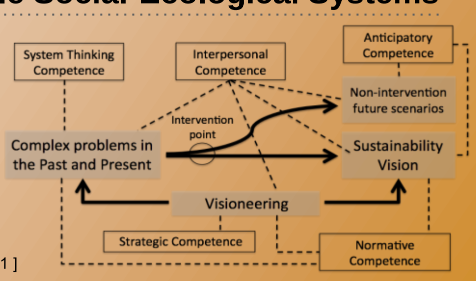
Constitution of Sense as a 3-Level Architecture of Self-Organization



Constitution of Sense [Hofkirchner, 2010]

Research & Education for Sustainable Social-Ecological Systems





[Hofkirchner, 2010; Wiek, 2011]