Testing early-warning signals for the transition of ecological network properties in wetland complex

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Highlights

- Wetlands are one of the world's most productive ecosystems which provide various ecosystem services (e.g., biodiversity conservation, water purification, flood protection, biogeochemical processes, and etc.)
- Wetlands do not function in isolation but they function as *dynamic, complex habitats with connections all around* (Amezaga et al. 2002; Van meter and Basu, 2015).
- It is hard to predict such critical transitions, though, it now appears that certain generic symptoms may occur in systems as they approach a critical point (Scheffer et al., 2009).
- Detect the occurrences of catastrophic transition in the ecological network by change of external conditions (seasonal climate conditions)
- Identify early-warning signals that approaching to tipping point in the time-series data

Methods for wetland hydrology

1. Representation of a wetland bathymetry and its hydrologic dynamics

① A-h and W- h relations (Hayashi and van der Kamp, 2000) (left) and simplification of the relationship (Park et al., 2014) (right)

$$W_{max} = \frac{A_{max} h_{max}}{1 + 2/p}$$

$(p: parameter\ (basin\ shape))$

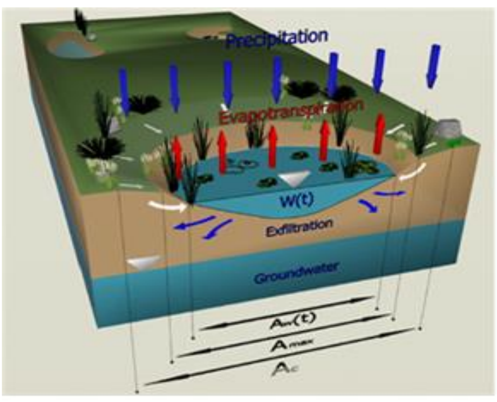
$$A = A_{max}(W^*)^{\beta}$$
$$W^* = W/W_{max}$$

$\beta: Wetland\ profile\ coefficient\ (= 2/(2+p))$

② p and h_{max} are random variables(Hayashi and van der Kamp, 2000; Brooks and Hayashi, 2002)

- $\log p$: correlated with $\log A$
- h_{max}: lognormal pdf

③ Hydrologic model framework for an individual wetland (Park et al., 2014)



$$\frac{dW}{dt} = P * A_{max} - E_1 * A - E_2 * S_w$$

$P: Precipitation\ (mm/day)$

$E_1: Evapotranspiration\ rate (mm/day)$

$E_2: Exfiltration\ \ rate (mm/day)$

Fig 1. Schematic representation of a wetland hydrological mode (Park et al., 2014)

④ Study site

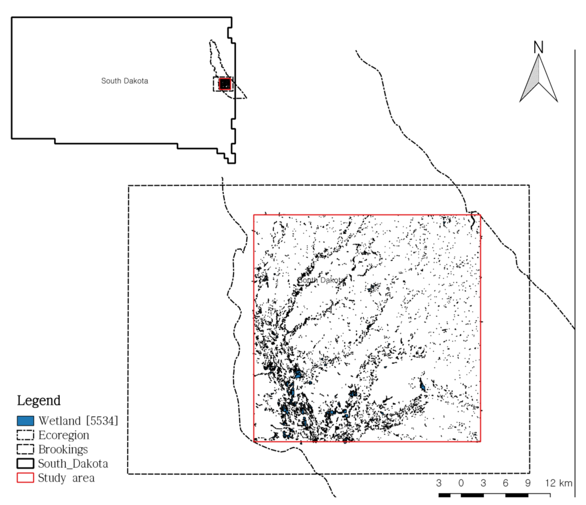


Fig 2. Study site

- **Location**: Big Sioux Basin Ecoregion (Level IV) in South Dakota, USA
- **Simulation Area**: 42.5 km X 42.5 km
- **Wetland Data**: 5,534 wetlands (US Fish & Wildlife Service, 2017. 10.01)
- **Hydro-climate Data**: 2010.1 ~ 2011.12 (NOAA)
  - Precipitation: from 11 observatories
  - Temperature: from 7 (2010) and 8 (2011) observatories
- **Soil data**: Pre-reported in USDA (The most widely distributed in the study site)
  - Soil Ⅰ: $9.17 \times 10^{-4}\ cm/sec$
  - Soil Ⅱ: $2.7 \times 10^{-4}\ cm/sec$
- **Simulation order**
  Winter(S1) – Spring(S2) – Summer(S3) – Fall(S4)

⑤ Seasonal Dryness Index (SDI)

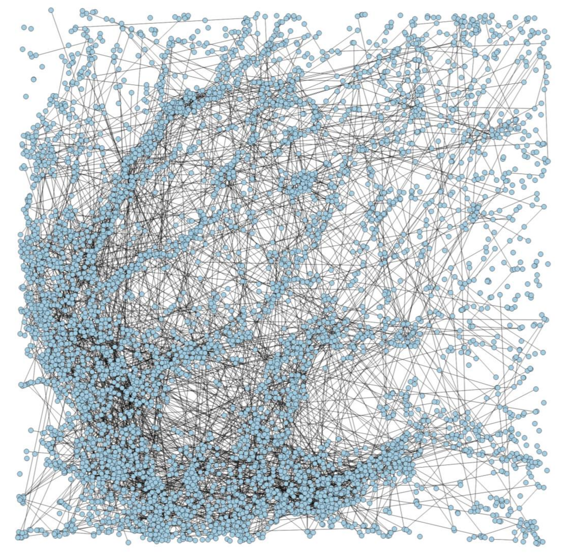
$$SDI = \frac{(Evapotranspiration\ rate + Exfiltration\ rate)}{(Precipitation * Frequency)}$$

2010	Rainfall intensity, I [mm]	Rainfall frequency, λ [day^{-1}]	PET [mm/day]	SDI Soil Ⅰ	SDI Soil Ⅱ
S1	2.77	0.33	0	859.3	252.8
S2	4.33	0.34	1.41	544.4	160.8
S3	12.43	0.47	4.18	137.0	40.8
S4	9.32	0.29	1.19	297.9	88.0
Total precipitation : 881.60 mm					

2011	Rainfall intensity, I [mm]	Rainfall frequency, λ [day^{-1}]	PET [mm/day]	SDI Soil Ⅰ	SDI Soil Ⅱ
S1	2.82	0.26	0	1100.6	323.8
S2	4.90	0.52	1.05	310.3	91.6
S3	7.62	0.37	4.20	282.9	84.3
S4	1.29	0.16	1.27	3743.0	1105.4
Total precipitation : 589.23 mm					

Methods for ecological network

1. Ecological network of wetland
: Heavy-tailed dispersal model (probabilistic)



$$p(l) = kl^{-\gamma}, 1 < \gamma \leq 3$$

$$P(l) = \int_l^{\infty} kl^{-\gamma} dl = \frac{k}{\gamma - 1} l^{-(\gamma-1)}$$

$l: step\ length$

$\gamma: power\ law\ exponent$

Fig 3. Wetland network by heavy-tailed dispersal model (β=3).

2. Topological analysis
- Metrics used: Mean degree (<k>)

3. Initial state of simulation
- Ac = 46% (Ac with highest frequency of area change during 1000 time-series)

$$A_c(\%) = \sum A_{current} * 100 / \sum A_{max}$$

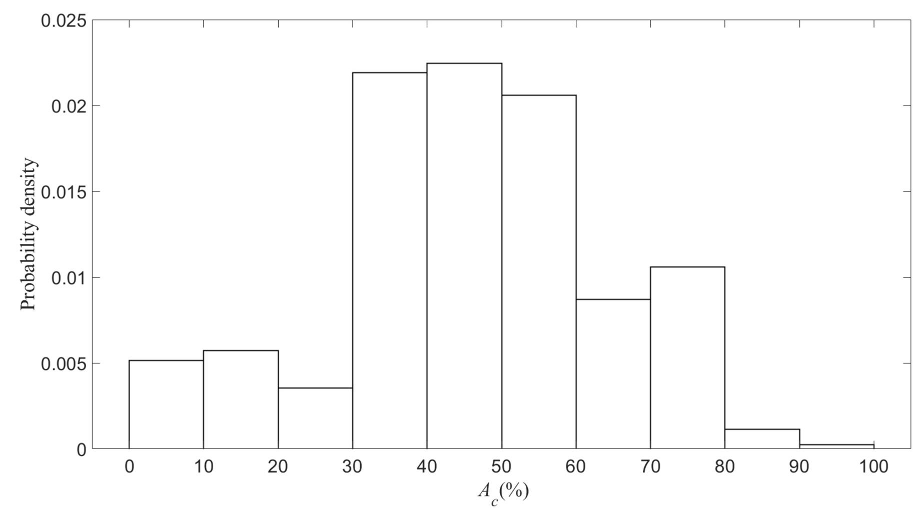


Fig 4. *Probability density function of A_c*

Results of network topology

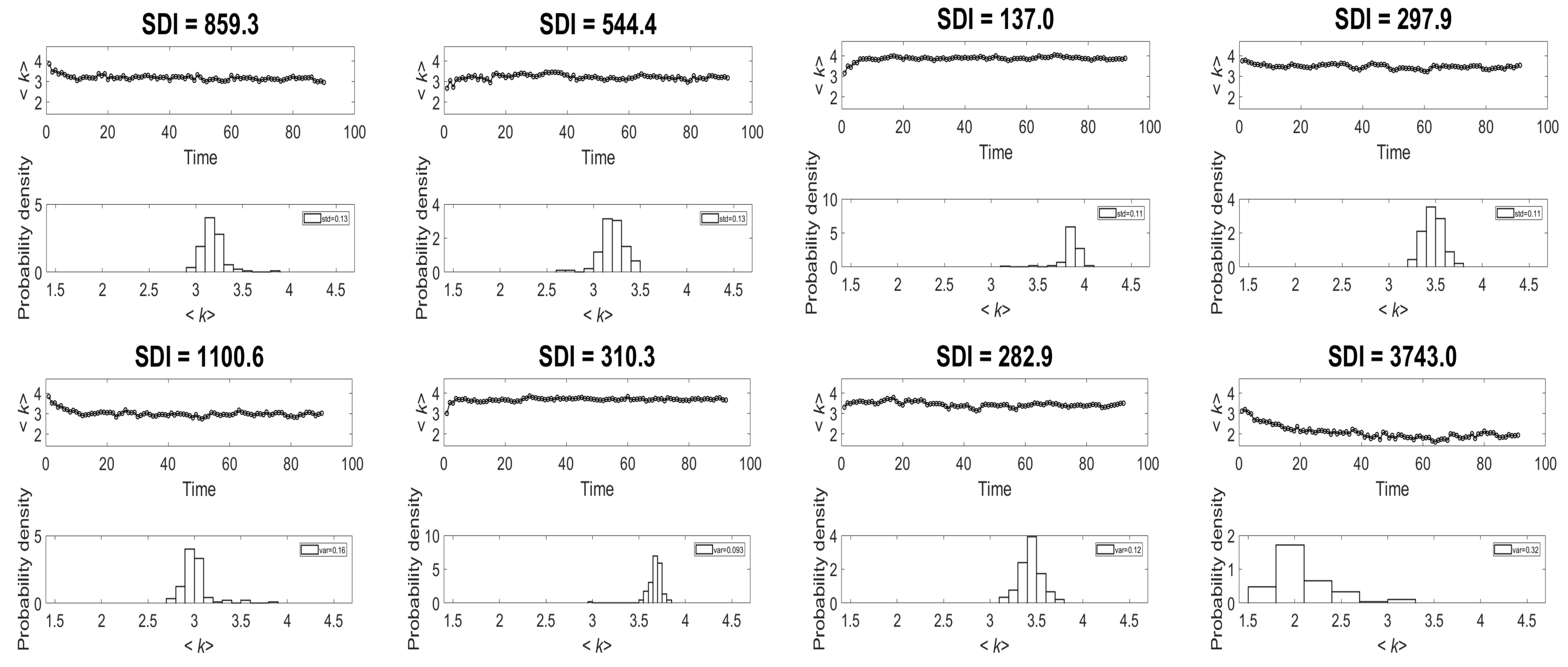


Fig 5. Standard deviation of <k> for Soil Ⅰ in 2010 (upper) and 2011 (lower)

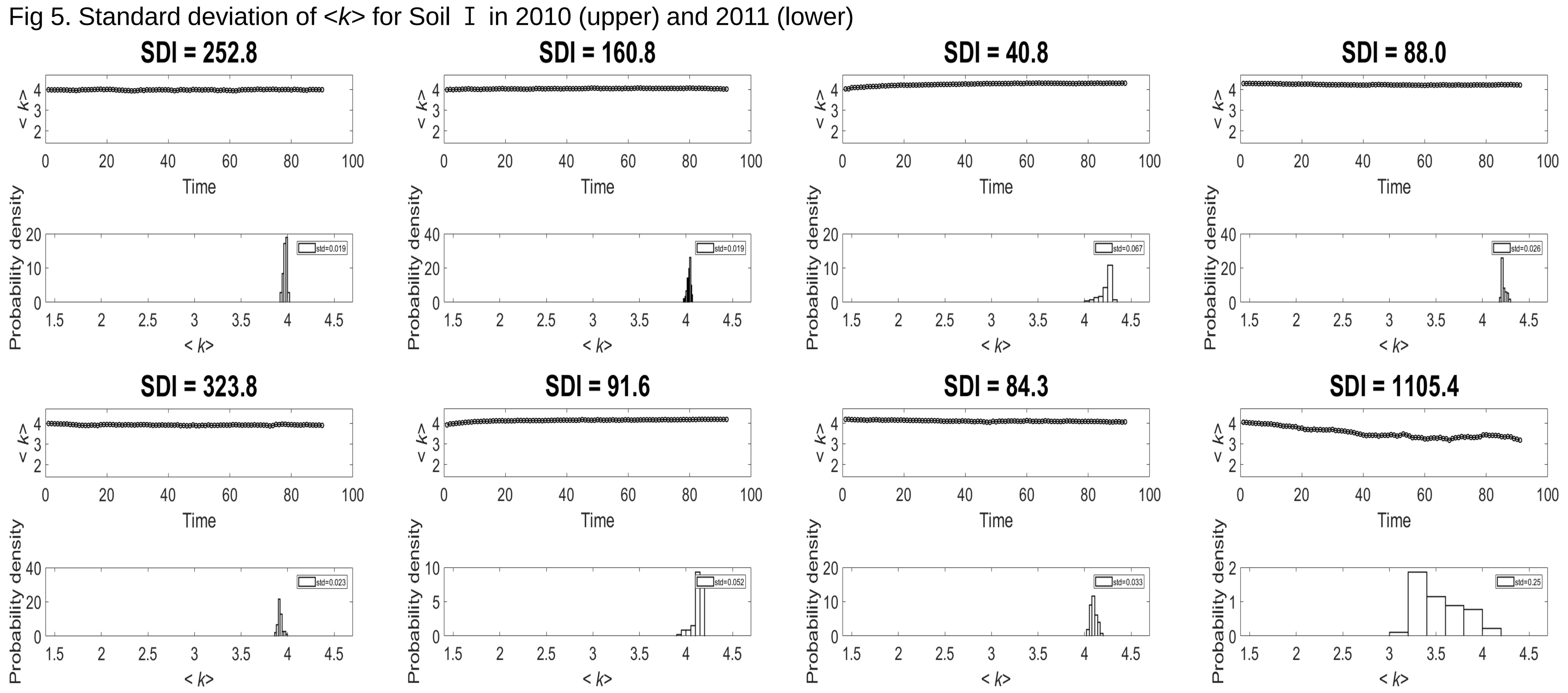


Fig 6. Standard deviation of <k> for Soil Ⅱ in 2010 (upper) and 2011 (lower)

- Topology of ecological network changes depending on the area variation of wetlands (Network topology recovery in wetter season as area re-filled the waterbody).
- In the highest SDI season (S4 of 2011, Z160A(SDI = 3743.0)) observation value of functional characteristics (<*k*>, *E* and *cc*) are completely different (significant decrease).
- Different variance is observed in the time series data with different external conditions (SDI) (Fig. 5~6).

Method for steady-state of wetland complex

1. Method for finding steady-state of wetland complex
- Results that seems to be a early warning signals were observed, but grasp the steady-state of the wetland complex for each external conditions is needed for clearly finding the early-warning signal and tipping-point.
- Check the effect from difference of initial area: three different initial area(A_c=58.6%, 94.9% and 9.8%)
- Check the effect of precipitation patterns
- Consider the exchange with groundwater as a feedback action to maintain the steady state of the wetland complex.

Results of steady-state of wetland complex

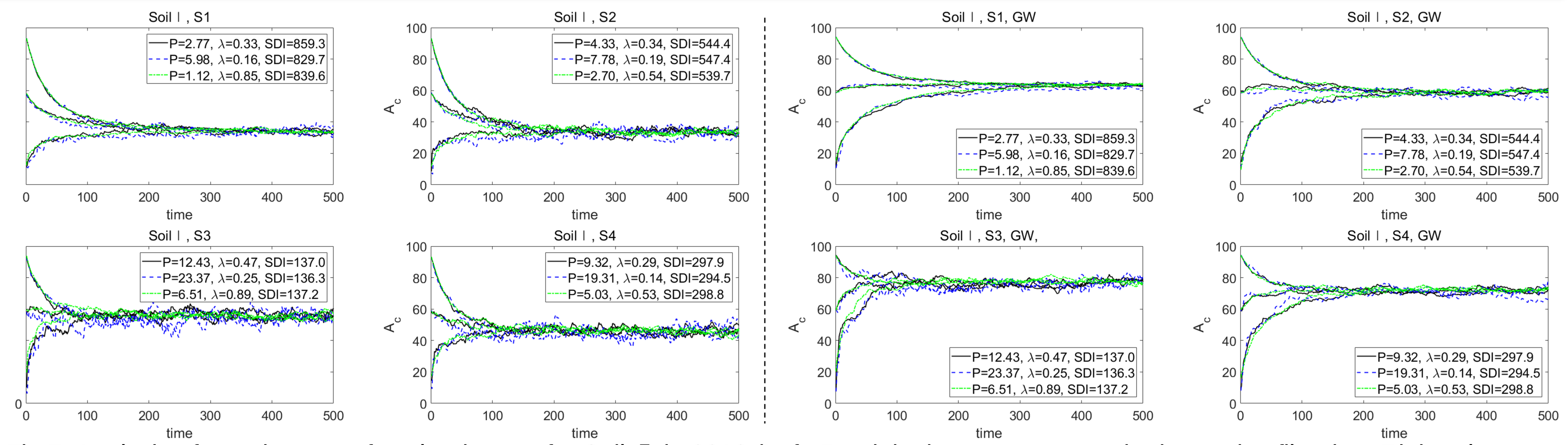


Fig 7. Analysis of steady-state of wetland areas for Soil Ⅰ in 2010 (Left: Precipitation, evapo-transpiration and exfiltration, Right: plus exchange with groundwater)

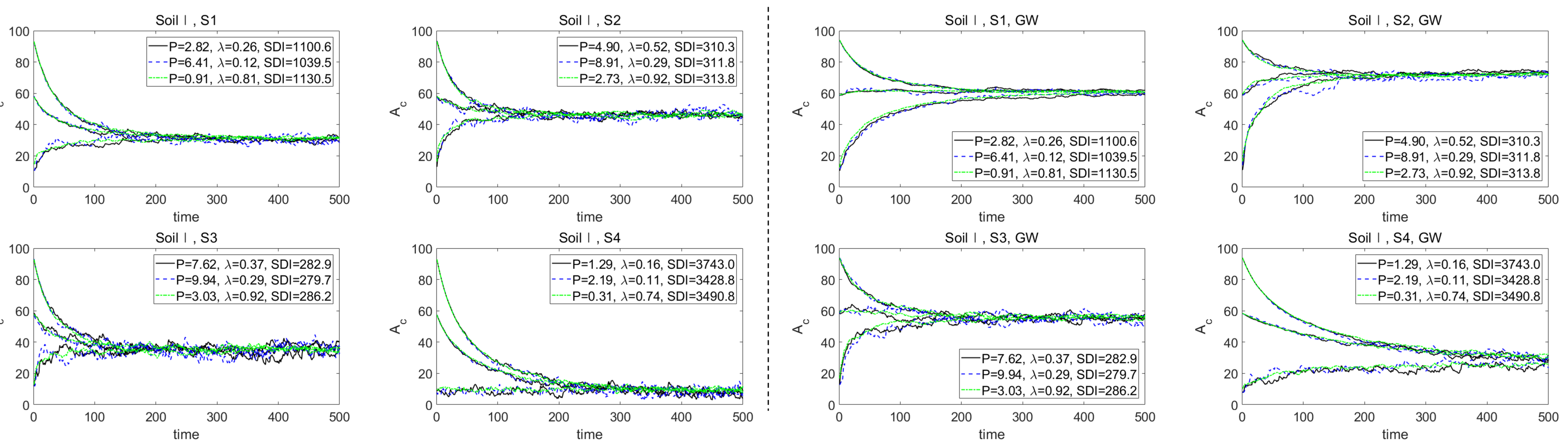


Fig 8. Analysis of steady-state of wetland areas for Soil Ⅰ in 2011 (Left: Precipitation, evapo-transpiration and exfiltration, Right: plus exchange with groundwater)

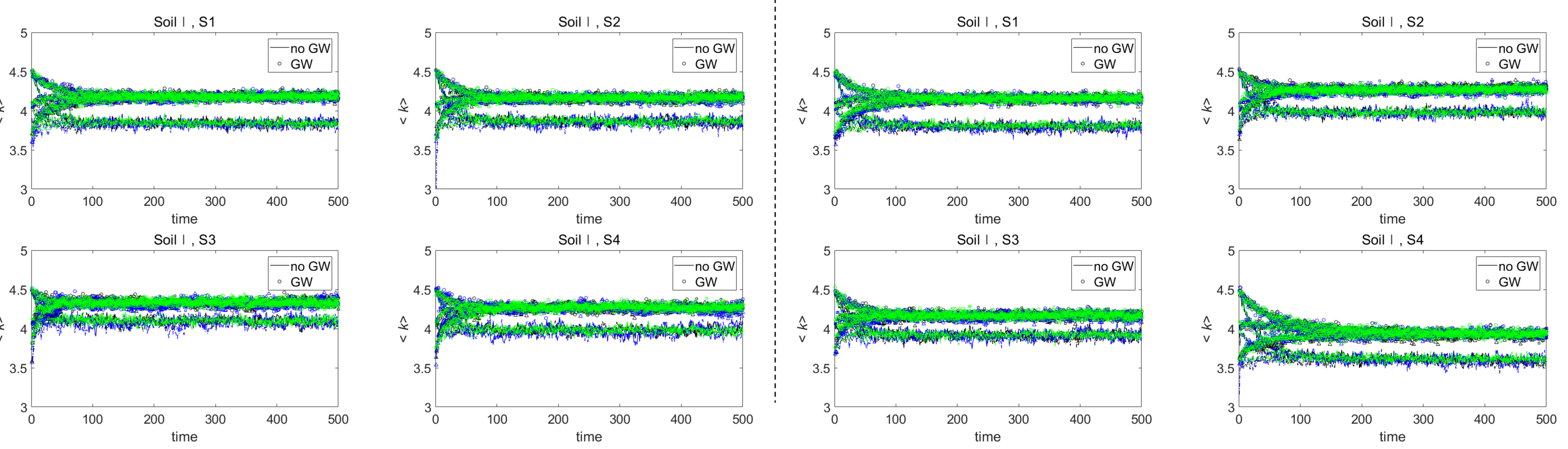


Fig 9. Analysis of steady-state of wetland areas for Soil Ⅰ in 2011 (Left: Precipitation, evapo-transpiration and exfiltration, Right: plus exchange with groundwater)

- Depending on the initial conditions (initial A_c) and external conditions (hydro-climatic pattern), noise of area change(A_c and <k>) occurs, but converges to a steady-state.
- The network topology also converges to a different steady-state according to each external condition.
- We observed that the wetland area was maintained due to the exchange with groundwater, and that the network function was also maintained.

Conclusions

❑ Topology and critical transition of ecological networks
- ✓ The behavior(decrease and recovery) of time-series data of network topology metrics according to external conditions (seasonal hydrological climate conditions) is observed differently.
- ✓ Identify that resilience of ecological network decreases in a high SDI season through an early-warning signal with increasing standard deviation(variance)

❑ Steady-state of wetland complex
- ✓ We observed the steady-state exists for each seasonal hydro-climatic conditions through the analysis of the long-term simulation.
- ✓ The steady-state is similar depending on the SDI, and it is possible to infer the range of disturbance in which no regime shift occurs through the range of noise according to the hydro-climatic condition.

References

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