Local heterogeneity and scaled dependence of eco-hydrological process in mire

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1. Introduction - Background & objective
2. Model description of NICE
3. Improvement in hydro-geomorphic & vegetation succession processes
4. Nonlinear interaction between geomorphology & eco-hydrology
5. Preliminary conclusions and way forward
Landcover change in the study area (Kushiro Mire in Japan)

- **Kushiro mire (177 km²)**
- **Kushiro main river**
- **Kucyoro river**
- **Study area for vegetation succession**

**Legend**
- Forest
- Farm
- Mire (Reed-sedge)
- Alder
- Bare
- Urban
- River & Lake
- Other land

**NIES Survey Station**
- ◯ Water Flow Depth (5 Points)
- △ Groundwater level (10 Points)
- ▽ Water Sampler & Turbidity Sensor (1 Point)

**Hokkaido Development Bureau**
- ◇ Water Flow Depth (1 Point)

**AMeDAS**
- ◇ Meteorological data (1 Point)

**1976**

**1997**

**Hokkaido**

**Kushiro District**

**Alnus japonica (Thunb.) Steud.**

**River channelization**

**Study area for vegetation succession**

**Kushiro main river**

**Kucyoro river**

**Legend**

- Forest
- Farm
- Mire (Reed-sedge)
- Alder
- Bare
- Urban
- River & Lake
- Other land
Nature restoration project to restore/recover mire ecosystem
(http://www.ks.hkd.mlit.go.jp/kasen/kentou/teigen03_05.html)

- Kushiro Mire Conservation Plan -

Detailed strategies;
(i) Restoration of meandering river channel about 1.3 km in the Kushiro River (Kayanuma District) within 5 years.
   - Hororo River
   - Setsuri River
   - Numaoro River
   - Osobetsu River
(ii) In order to prevent sediment inflowing into the mire, possible mitigation measures are needed in addition to restore meandering river channel.
(iii) It is very important to predict the impact of the restoration project on the hydro-geomorphic change and vegetation succession in the surrounding areas.

Plan of river restoration
(Ministry of land infrastructure & transport)
What is a role of inland water in biogeochemical cycle?

Common knowledge?: Terrestrial biosphere is assumed to take up most of carbon on land.

Inland waters process large amounts of organic carbon and must be considered in strategies to mitigate climate change!

(Battin et al., 2009)

Aufdenkampe et al., 2009
National Integrated Catchment-based Eco-hydrology (NICE) model

Atmospheric boundary-layer ↔ Land surface
Downward radiation flux, temp., humidity, wind, pressure, prec.
Upward radiation flux, momentum, sensible&latent heat-flux

Assimilation with satellite data

Atmospheric model

Surface & Intermediate flows

Natural area
Agricultural area
Urban area

Urban canopy model

Surface & Intermediate flows

Surface flow
Unsaturated layers
Intermediate flow
Groundwater flow

Surface ↔ Land surface

Unsaturated ↔ Saturated layers

Mass transport model
Vegetation succession model

Land

Atmosphere

Surface

Unsaturated layer

Saturated layer

Groundwater flow

Surface flow

Seawater intrusion

Lake

River ↔ Lake

B.C.; Ocean tide

Drain
Sewerage

Overflow

Manhole

Agricultural area

Natural area

Urban area

Drain
Sewerage

Overflow

Manhole

Agricultural area

Natural area

Urban area
Modeling vegetation succession in the Kushiro Mire

<Dominant species>
Alder (Alnus japonica) : 4,924 ha (29.4%)
Reed (Phragmites australis) : 1,314 ha (7.9%)
Moss (Polytrichum spp., Sphagnum spp.) : 1,352 ha (8.1%)
Sedge (Carex lasiocarpa, Carex lyngbyei) : 9,122 ha (54.6%)

<Others>
Willow (Salix spp.)
Japanese ash (Fraxinus mandshurica var. japonica)
Meadow sweet (Spiraea salicifolia)

<Assumption>
Horizontal homogeneity

Different type of zonation & vegetation growth of alder thickets
(i) Natural river area: germinated alder thicket, similar height & DBH
(ii) Improved river area: alder thicket raised of seed, different height & DBH

Simulate the competition of only two species in mire between alder & native vegetations (reed, sedge, et al.)
Extension of gap model by adding growth reduction factor

Tree diameter growth - logistic curve -
\[
\frac{dD}{dt} = \frac{GD(1 - DH / D_{\text{max}} H_{\text{max}})}{(274 + 3b_2 D - 4b_3 D^2)}
\]

Growth rate scalar
\[
G = G_{\text{max}} \left[ r(Q_h) r(F) r(M) r(T) r(S_D) \right]^{1/3}
\]

Growth reduction factor \( (r) \)
- Light \( r(Q_h) = c_1 \left[ 1 - \exp \left[ -c_2 (Q_h - c_3) \right] \right] \)
- Nutrient \( r(F) = c_4 + c_5 F - c_6 F^2 \)
- Soil moisture \( r(M) = \left[ \frac{M^* - M}{M^*} \right]^{1/2} \)
- Temperature \( r(T) = \frac{4(T - T_{\text{min}})(T_{\text{max}} - T)}{(T_{\text{max}} - T_{\text{min}})^2} \)
- Submerged depth (Water table depth) \( r(S_D) \)

Crown diameter \( C_D = \exp \left[ \ln(D) b_0 + b_1 \right] \)

\( \cdot \) Multiplicative approach
\( \cdot \) Liebig’s Law of the Minimum

↓ Stepwise procedure (Bugmann, 1996)
Self-organization and positive feedback in wetland ecosystem

(i) Vegetation – water table feedbacks by using two partial differential equations about logistic curve & water table – carrying capacity (Ridolfi et al., 2006)
(ii) Self-organization & vegetation collapse by using equations about biomass & sedimentation (Van de Koppel et al., 2005)
(iii) Regular/cyclic pattern such as string or maze at regular slope or boundary conditions (Rietkerk et al., 2004)
(iv) It is difficult to simulate spatial heterogeneity and succession process in these previous researches!

Microtopographic profile, vegetation, and surface water redistribution on planar hillslope (Saco et al., 2007)

Aerial photographs of maze pattern in western Siberia (Rietkerk et al., 2004)

Simulated vascular plant biomass (left: maze, right: string) (Rietkerk et al., 2004)
Objective of this study

1. Developing process-based model which simulates hydrologic cycle, mass transport, and vegetation succession processes iteratively, by combining with previous researches about effective classification of the characteristics of “invasive alder” and “native mire vegetation”

2. Down-scaling and feedback process in the new simulation system for improvement in local heterogeneity of hydrologic cycle, and accuracy in nonlinear interaction between hydrology, geomorphology, and ecology in the mire

3. Reproducing and quantification of nonlinear relationship between drying phenomena (elevation aggradations, decrease in soil moisture and G.W.L., etc.) and alder invasion during the past decades

4. Improvement in prediction of mire recovery by river restoration, and proposal of more suitable “nature restoration project” through investigation of self-organization, feedback, and hysteresis in ecosystem

5. Improvement in biogeochemical cycle along terrestrial-aquatic continuum for global environmental change
Impact of water-heat-sediment-nutrient transport processes on vegetation succession and possibility of mire recovery (Kushiro Mire)

Distribution of *Alnus japonica* 

Simulated soil moisture 

Simulated alder invasion 

GIS Simulated

Elevation change 

No strategy Restoration

Future forecast 
Nonlinear interaction and feedback of hydrologic cycle, elevation change, and vegetation succession in NICE

Surface & unsaturated water flow model

Groundwater flow model

\[ \frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h_g}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h_g}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h_g}{\partial z} \right) + W = S_s \frac{\partial h_g}{\partial t} \]

Diffusion model for sediment & nutrient

\[ \frac{\partial}{\partial t} \{ D \cdot C \} + \frac{\partial (M \cdot C)}{\partial x} + \frac{\partial (N \cdot C)}{\partial y} = \frac{\partial}{\partial x} \left( K_{xx} D \cdot \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} D \cdot \frac{\partial C}{\partial y} \right) + D \cdot L(C) + q_{su} - w_f \cdot c_b \]

Elevation change model for suspended & bed material loads

\[ \frac{\partial z_B}{\partial t} = -\frac{1}{1-\lambda} \left( q_{su} - w_f c_b + \frac{\partial q_B}{\partial x} \right) \]

\[ q_B = (8 \tau_s - 0.047)^{3/2}, \quad \tau_s = \frac{u_*^2}{(\rho_s/\rho - 1) gd} \]

\[ q_{su} = K \left[ \frac{\alpha_s \rho_s \cdot \Omega}{\rho_s \sqrt{\tau_s}} - \frac{w_f}{\sqrt{s'gd}} \right] \]

Vegetation dynamics & succession model

\[ \frac{dD}{dt} = \frac{GD(1 - DH / D_{max} H_{max})}{(274 + 3b_2 D - 4b_1 D^2)}, \quad G = G_{max} \left[ r(Q_{ai})r(F)r(M)r(T)r(S_p) \right]^{1/3} \]

Characteristic of study area

Shallow groundwater level and sediment deposition/erosion in low elevation area greatly affect heterogeneous vegetation change

Improvement from previous researches

(i) Simulation of one-dimensional head without elevation change (Rietkerk et al., 2004)
(ii) only one-dimensional elevation change without the difference between suspended & bed material load & without diffusion effect (Van de Koppel et al., 2005)

(I) NICE includes heterogeneous distribution of roughness coefficient in various vegetation
(II) NICE includes both kinematic & dynamic wave theory in surface flow
(III) NICE includes seedling establishment, mortality, regeneration, succession & competition processes in addition to the mutual interaction between ecology & hydrology (Pastor et al., 2002; Rietkerk et al., 2004; Van de Koppel et al., 2005; Ridolfi et al., 2006; Saco et al., 2007)
(IV) Simulated values of soil moisture (M) & submerged depth (S_p) in NICE are reflected in succession simulation, which unify ecological and hydrological regimes
(V) NICE simulates nonlinearity between hydrologic cycle, sediment deposition, & vegetation succession
Down-scaling and feedback process in the extension of NICE

Regional simulation with $\Delta X \& \Delta Y=500m$

Down-scaling through boundary conditions

$\Delta X & \Delta Y=100m$
220x460x20 meshes

$\Delta T=30min$

NICE model
(water, heat, mass)

$\Delta T=1year$

Change in reed & alder

Vegetation succession model

Feedback process

<Meteorological data>
Temperature
Precipitation
Solar radiation, et al.

<Simulation results>
River discharge
Soil moisture
Soil temperature
Groundwater level
Sediment accumulation
Nutrient loadings(N,P)

$\Delta T=1month$

1month ave.

Around mire:
$\Delta X \& \Delta Y=10m$

Development of Integrated Catchment-based Eco-Hydrology Model applicable to Mire

Extension of Integrated Model to Spring Snowmelt Runoff

Water Purification by Mire Vegetation

Increase of Soil-Moisture & Groundwater Level

Decreased Sediment Quality

Recovery of Mire Ecosystem

Increased Sediment & Nutrients

Drying of Mire Inflow

Excessive Sediments & Nutrients

Mire Inflow

Possibility of Recovery of Mire Ecosystem

Conditions necessary for Formulation/Recovery of Mire Ecosystem

Invasion of Alder

Drying Phenomena

Simulations of before/after Remanerding

Before Remanerding

After Remanerding

Inflow

Outflow

Inflow

Outflow

Inflow

Outflow

Inflow

Outflow
Averaged groundwater-level relative to ground surface in 2001-2002
(Nakayama, Ecol. Model., 2008)

- Observed value
- Simulated value

Elevation

Meandering river (past)
Channelized river (present)
Improvement in hydrologic cycle by using finer resolution in Kushiro Mire

(Top figure; Nakayama & Watanabe, Water Resour. Res. 2004)

Δx=500m

Δx=100m

Downscaling

Effective for improvement in boundless biogeochemical model (CH₄, CO₂)!
Simulated groundwater flow in dry and flood season for evaluating two conceptualizations of peatland hydrology (Reeve et al., 2000)

Dry season (July 2002)

Typhoon season (October 2002)

“Shallow flow” model?

“Ground-water flow” model?
Relation between microtopography and inundated flow (May 2002)
Simulated result of feedback process between geomorphology and eco-hydrology in the mire
Preliminary conclusions and future directions

1. **Down-scaling** in the new simulation system improved local heterogeneity of hydrologic cycle with finer resolution in the mire.

2. **Feedback process** in the new simulation system improved the accuracy in nonlinear interaction between hydrology, geomorphology, and ecology in the mire.

3. The result clarified the interaction between groundwater and inundated flow, and shed light on two conflicting conceptualizations of peatland hydrology, “shallow-flow and groundwater-flow models”.

4. Further improvement in flexibility of feedback (interactive) simulation will clarify hydro-ecological regimes and “chicken and egg” problem.

5. Further model improvement from stochastic to deterministic processes, refinement of nitrogen fixation, and growth process based on carbon balance will be attractive and contribute to better “nature restoration project” in the long-term scale.

6. Feedback and inter-relationship between micro (genetic) – regional levels through “metabolic theory of ecology” and “meta-ecosystems” (spatial scales coupling of local ecosystems including energy, materials and organisms across ecosystem boundaries) are important.
Way forward: Toward improvement in boundless biogeochemical cycles in terrestrial-aquatic ecosystems

1. Contribution of inland waters to continental-scale carbon cycling has remained uncertain due to a paucity of data.

2. Boreal and subarctic peatlands store about 15-30% of the world’s soil carbon as peat and affect the dynamics of greenhouse gases such as methane (Limpens et al., 2008).

3. Rivers may contribute on emitting CO$_2$ up to 10 % of net ecosystem exchange. It may alter carbon balance of terrestrial systems (Butman and Raymond, 2011).

4. Main components needed for analysis are (i) CO$_2$ concentration in surface water, (ii) areal extent of rivers, and (iii) rate of exchange of CO$_2$ between water and atmosphere (Melack et al., 2011).

5. Improvement in local heterogeneity about complex eco-hydrological processes would help to construct the improvement in boundless biogeochemical model with finer resolution (Battin et al., 2009).

6. Necessity for improvement in biogeochemical cycle along terrestrial-aquatic continuum for global environmental change.

7. If this effect is important, the terrestrial CO$_2$ sink may be prove smaller than thought so far.
Question ?