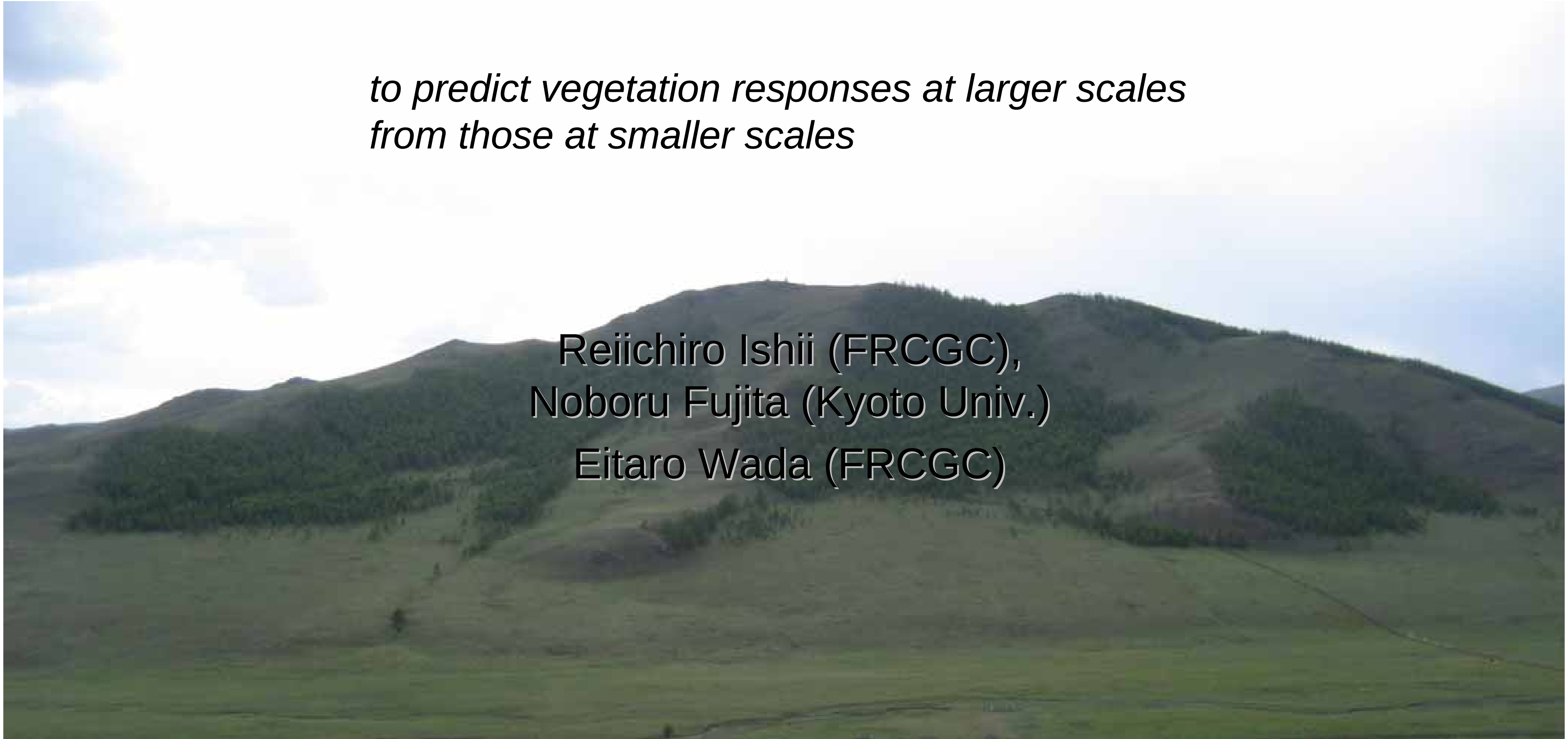
A vegetation transition model at the topographical scale and its application to the Mongolian Forest-Steppe ecotone



to predict vegetation responses at larger scales from those at smaller scales

Reiichiro Ishii (FRCGC),
Noboru Fujita (Kyoto Univ.)
Eitaro Wada (FRCGC)

As we saw,

Vegetation shows different spatial distribution patterns depending on the spatial scales, reflecting the scale-specific mechanisms even the principal factor to be identical: Water.

At the *Topographic scale*,

Forest-Steppe Ecotone exisbits a Slope direction- dependent discontinuous vegetation pattern:

South slopes: Grassland

North slopes: Larch forest

Questions:

Why the transition is so discontinuous and how did the pattern emerge?

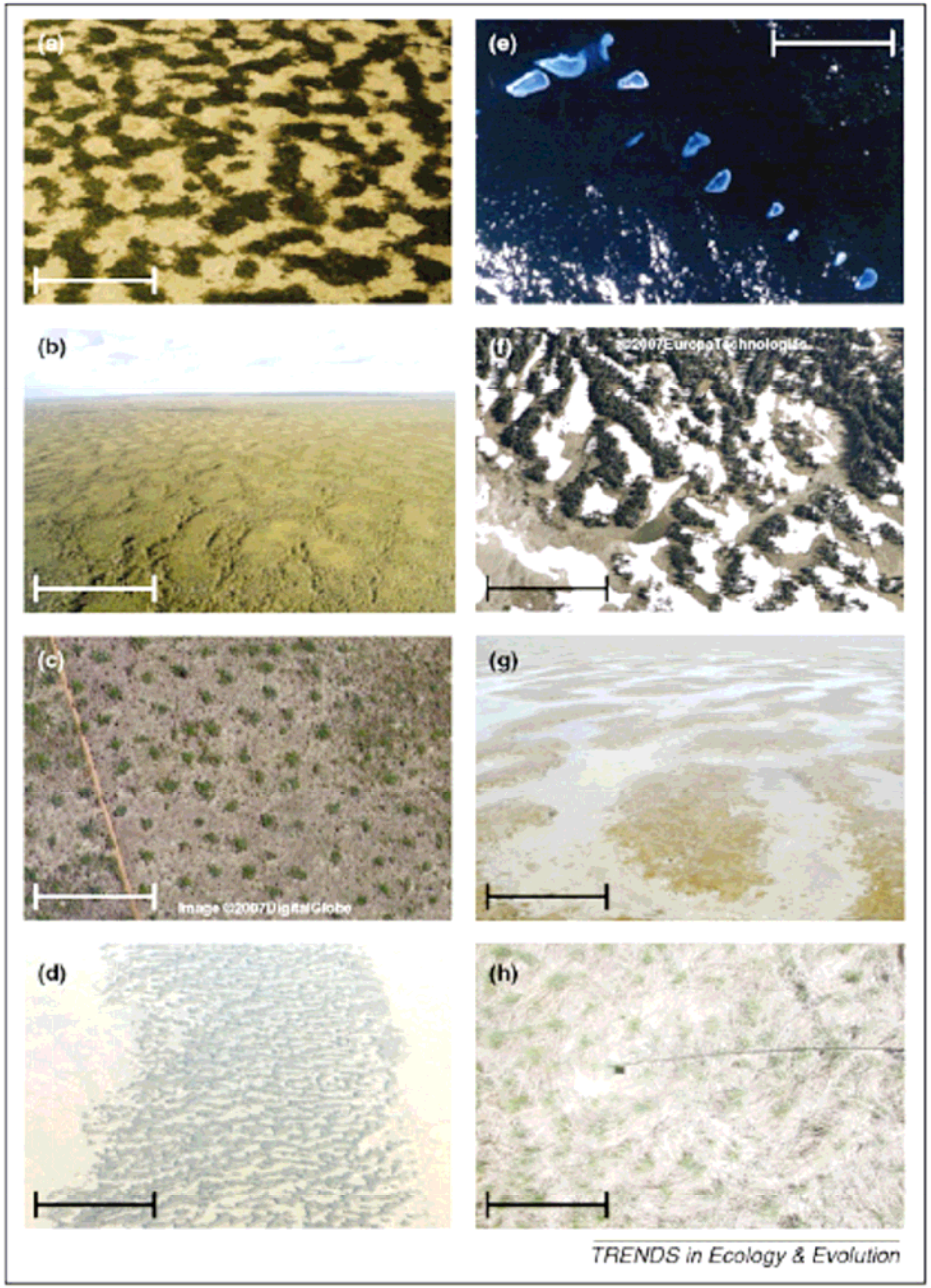
Why this pattern are not seen everywhere with the similar climatic conditions?

Hint: we know that

In fine scale, where topography is negligible,

Vegetation often exibits discontinuous spatial distribution, reflecting complex interaction among individuals over Water utilization.

Positive feedback is essential for such Self-organization

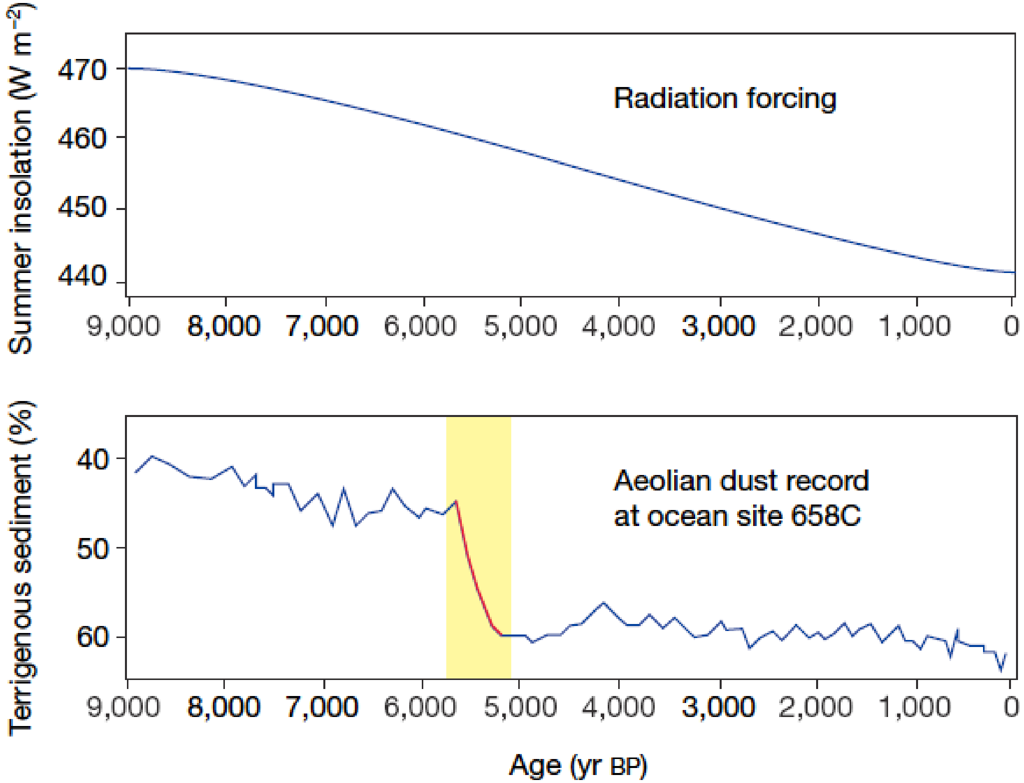


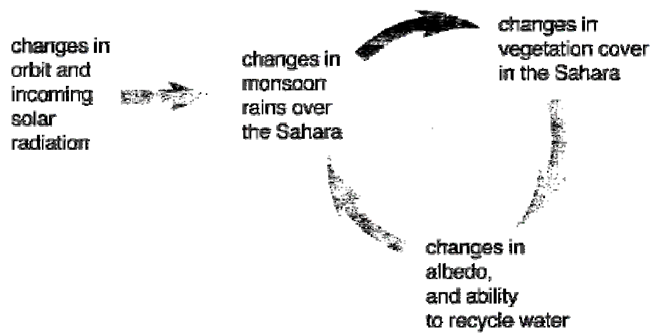
Rietkerk and van de Koppel 2008

Even at Continental Scale,

Non-Linear biological response amplifies the gradual environmental change.

Well known Example: Dry and Wet Sahara

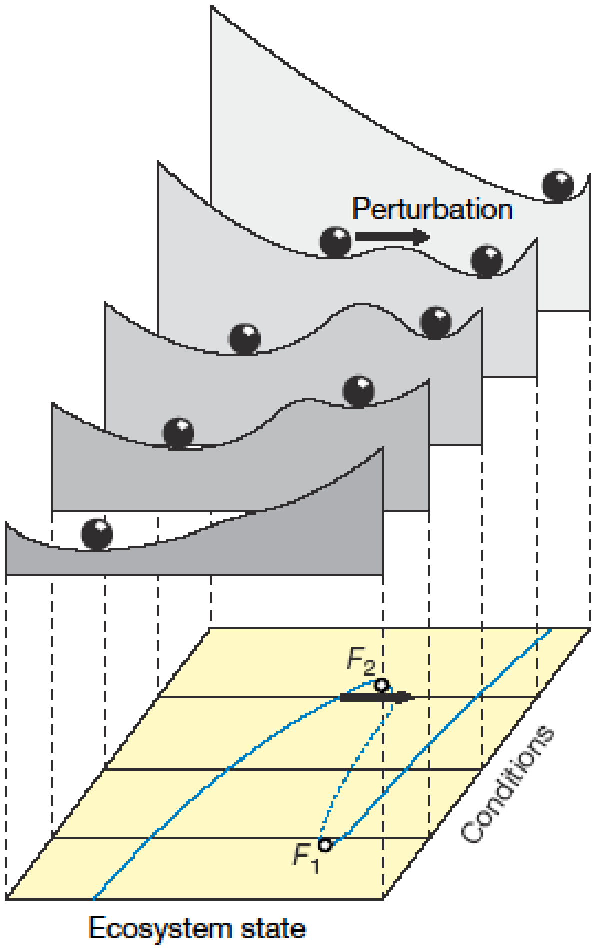




Environment – Organism interaction (feedback)

As we saw, many previous studies have pointed out that ecosystems often exhibit catastrophic and irreversible response (i.e., “Regime-shift”) to gradual change of environment.

Positive feedback → Bistability → "REGIME-SHIFT"



Scheffer et al.(2001)

1. the contrast among states in ecosystems is usually due to a **shift in dominance among organisms with different life forms**.
2. state shifts are usually **triggered by obvious stochastic events** such as pathogen outbreaks, climatic extremes.
3. feedbacks that stabilize different states involve both biological and physical and chemical mechanisms.
4. all models of ecosystems with alternative stable states indicate that **gradual change in environmental conditions**, such as global warming, **may have little apparent effect** on the state of these systems, but still alter the `stability domain' or resilience of the current state and hence the likelihood that a shift to an alternative state will occur in response to natural or human-induced fluctuations.

Main Objective

Discontinuous

Temporal change ⇔ Spatial transition

Difficult to detect *temporal change* in the Continental scale (takes too long).

We often observe *spatial pattern* of *vegetation which exhibit higher contrast than the environmental condition at the finer scales.*

Assuming that the underlying mechanism for temporal and spatial vegetation transition is identical, we might construct a unique model which accounts for both transitions.

By developing a vegetation transition model at topographic scale which can be validated with spatial pattern ,

we might detect some signal of Regime-shift at larger scales in advance.

<u>We need field work to acquire the parameters to get the model quantitative.</u>

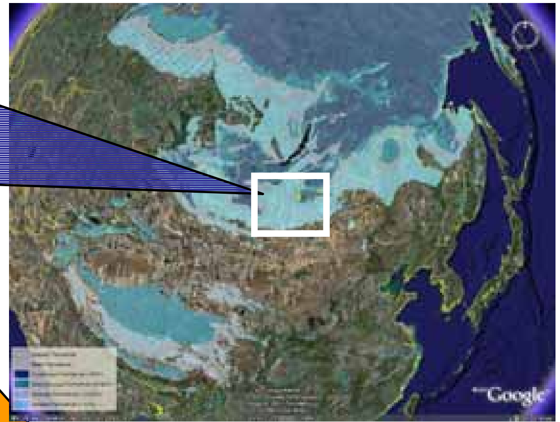
Target area & Sample site

Gachuurt (30km North-East of Ulaanbatar)

Vegetation | *Permafrost Distribution*

Continental Scale

Desert-Steppe-Taiga
Latitude:
Precipitation gradient

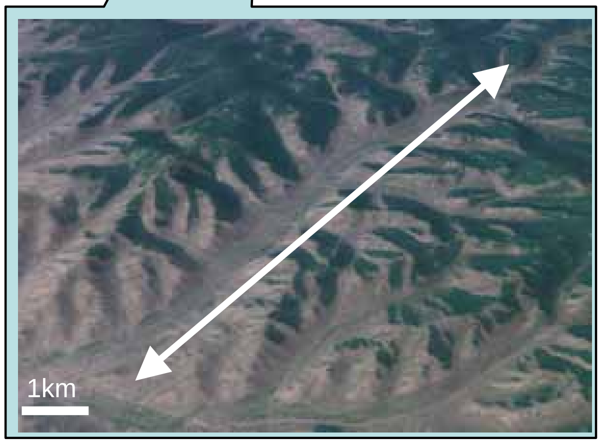


South end of Permafrost

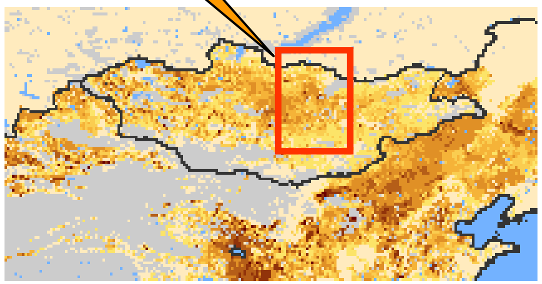
Regional-Scale

Steppe - Larch forest
Slope direction:
Water?
Discontinuous

Water is the principal factor to determine the Vegetation



Livestock Distribution



North end of Nomadic Pasturization

MODEL 1 Soil Water - 2Plants interaction model Qualitative

Assumption:

Plant growth is controled by the water supply during the grawing season (June-Sept.)

P1: Grass Biomass

P2: Tree Biomass

W: Soil Water

φ: Precipitation

competition facilitation

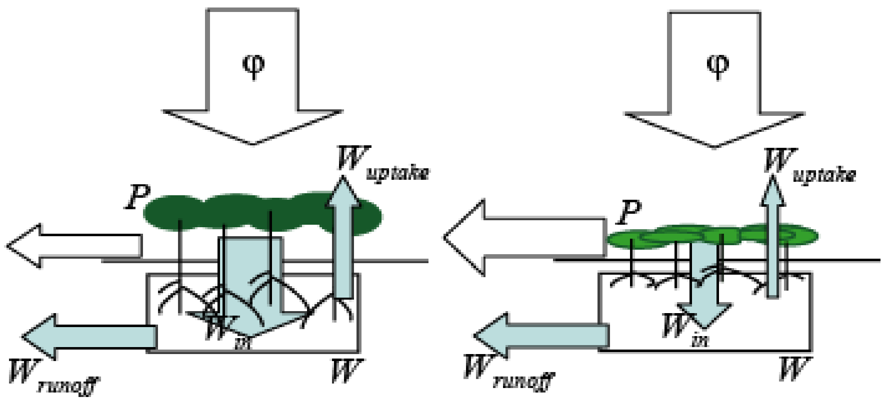
Dynamics of Plant biomass and Soil water:

Herbivory effect

$$\frac{dP1}{dt} = g_1 \frac{W}{W+k_1}(P1+sp_1) - (m_1 + m_{11}P1 + m_{21}P2 + h_1)P1$$

$$\frac{dP2}{dt} = g_2 \frac{W}{W+k_2}(P1+sp_2) - (m_2 + m_{12}P1 + m_{22}P2 + h_2)P2$$

$$\frac{dW}{dt} = W_{in}(P1,P2,\varphi) - W_{uptake}(P1,P2,W) - W_{runoff}(P1,P2,W)$$



$$W_{in}(P1,P2,\varphi) = \varphi \frac{P1+P2+ks\,w0}{P1+P2+ks}$$

$$W_{uptake}(P1,P2,W) = \frac{u_1 W}{W+ku_1}P1 + \frac{u_2 W}{W+ku_2}P2$$

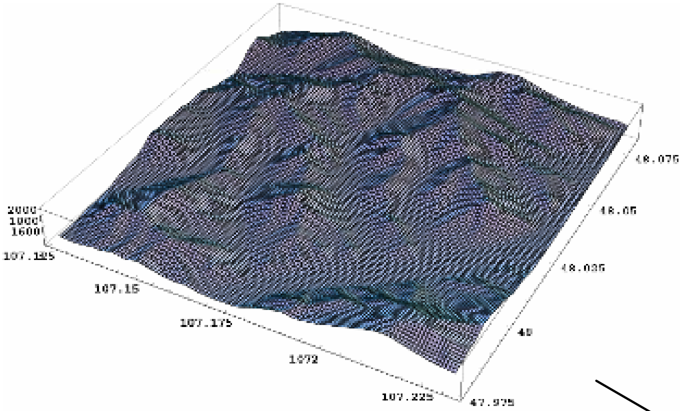
$$W_{runoff}(P1,P2,W) = rw(1 - ra\frac{P1+P2}{P1+P2+rb})W$$

Permafrost effect

MODEL 2 Estimate Potential Evaporation at the Slope-scale in Sample site

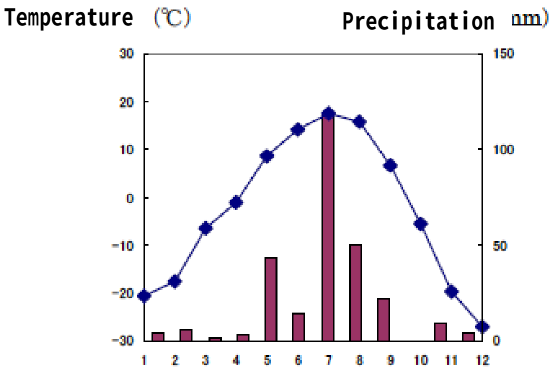
Quantitative

Topography (SRTM 3sec 90m-grid)

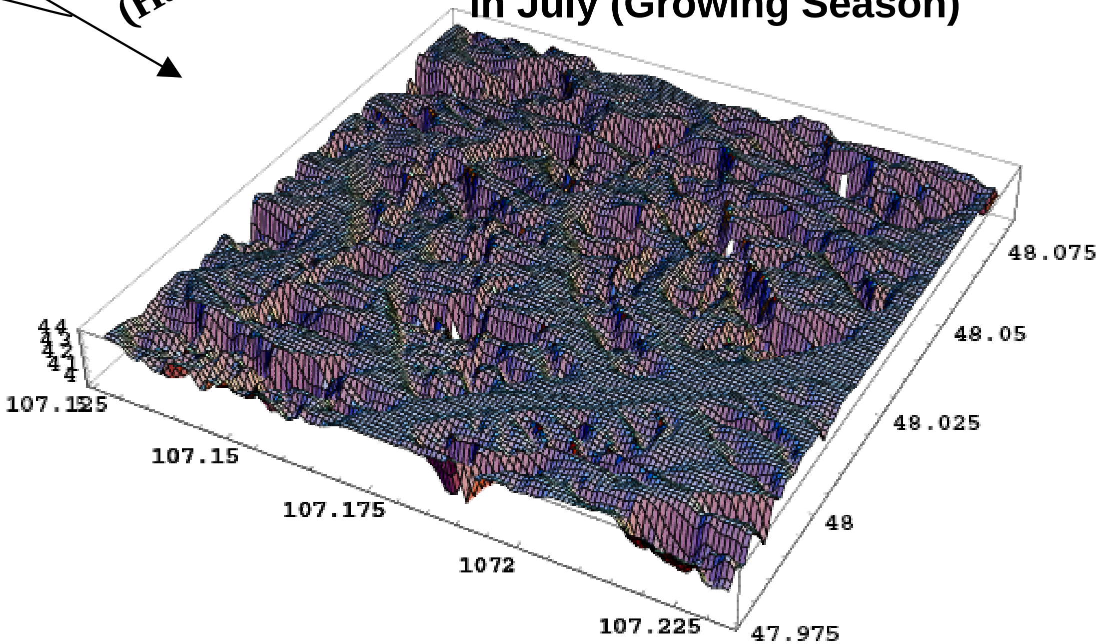


Daily[Slope,Aspect,DOY]
(Topographic Radiation model, Corripio2003)
→PE[Radiation, Temp $_{air}$, Wind]
(Hargreaves-Samani 1982)

Climate Data at adjoining area:
(FOREST site in Kherlen watershed,2003)

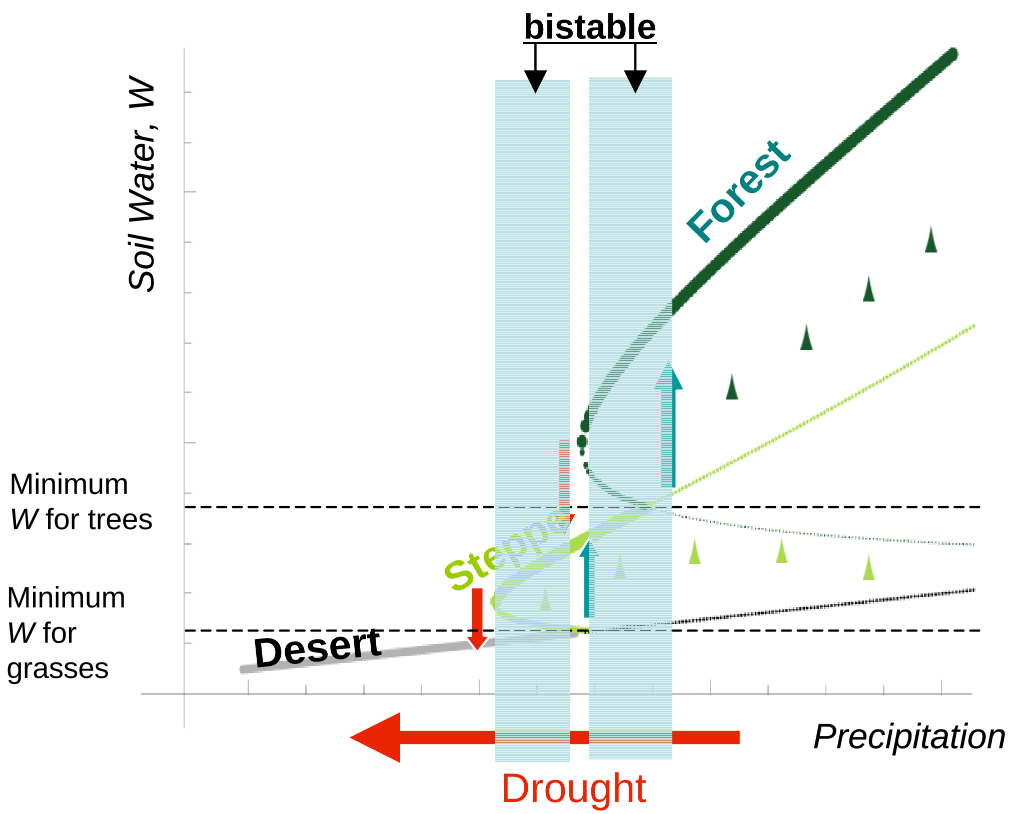


Potential Evaporation Rate in July (Growing Season)



MODEL 1

RESULTS EQUILIBRIA of Soil Water



Positive correlation between Biomass-Soil Water:
[Facilitation] enhances the succession (▲), while
Negative interaction [Competition for resources] stabilizes
the vegetation to the stable steady states:*climax*.

●●● : Stable

... : Unstable

Points

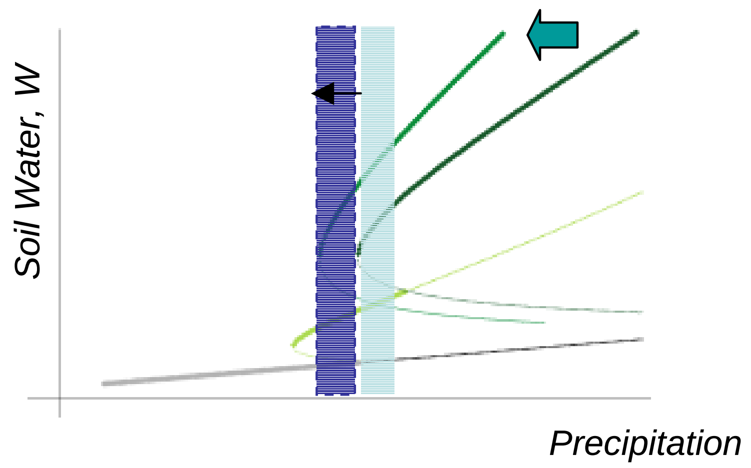
1. Multiple stable steady states of vegetation might occur for a given precipitation.
2. Grazing pressure enlarge the bistable precipitation-range.

Qualitative Predictions

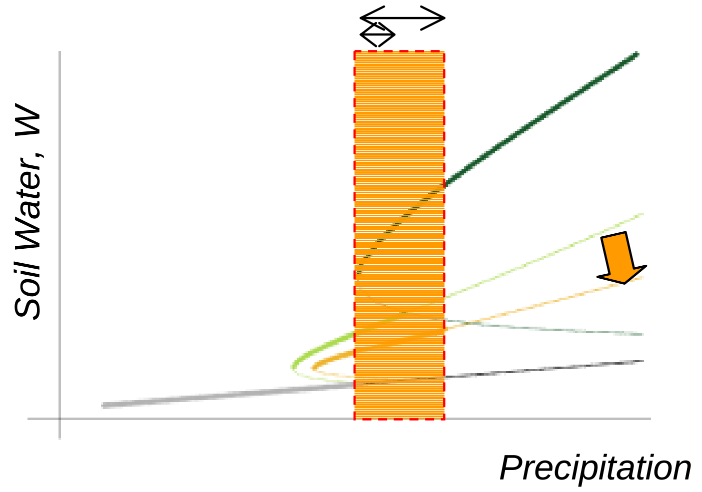
1. Drought might induce catastrophic vegetation-transitions Forest→Grassland→Desert (**Red arrows**)
2. Because of the Histeresis, it is difficult to recover the vegetation once it is shifted.

MODEL 1

RESULTS EQUILIBRIA of Soil Water with/without Permafrost & Grazing pressure



Permafrost prevents the loss of soil water due to percolation. Assuming that it can exist only under sufficient plant's shade, we can incorporate the effect of permafrost by increasing the *ra* value in eq. of W_{runoff}.'



Herbivory increases the loss of biomass directly. Assuming that the grazers can consume only grass species, we can incorporate the effect of herbivory by setting the *h1* value in eq. for *P1'*.

Points

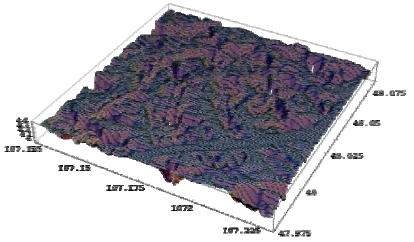
1. Permafrost (⇦) shifts the forest zone to less precipitation condition (←)
2. Selective Herbivory(⇩) enlarges the bistable precipitation-range of forest-steppe(⟷).

Qualitative Predictions

1. Once permafrost is lost due to rising temp. or forest logging, the equilibrium curve shifts to higher precipitation (to the right), that is, more difficult the condition of tree species to re-invade becomes.
2. **Heavy grazing pressure on steppe by livestock might enhance the clear**

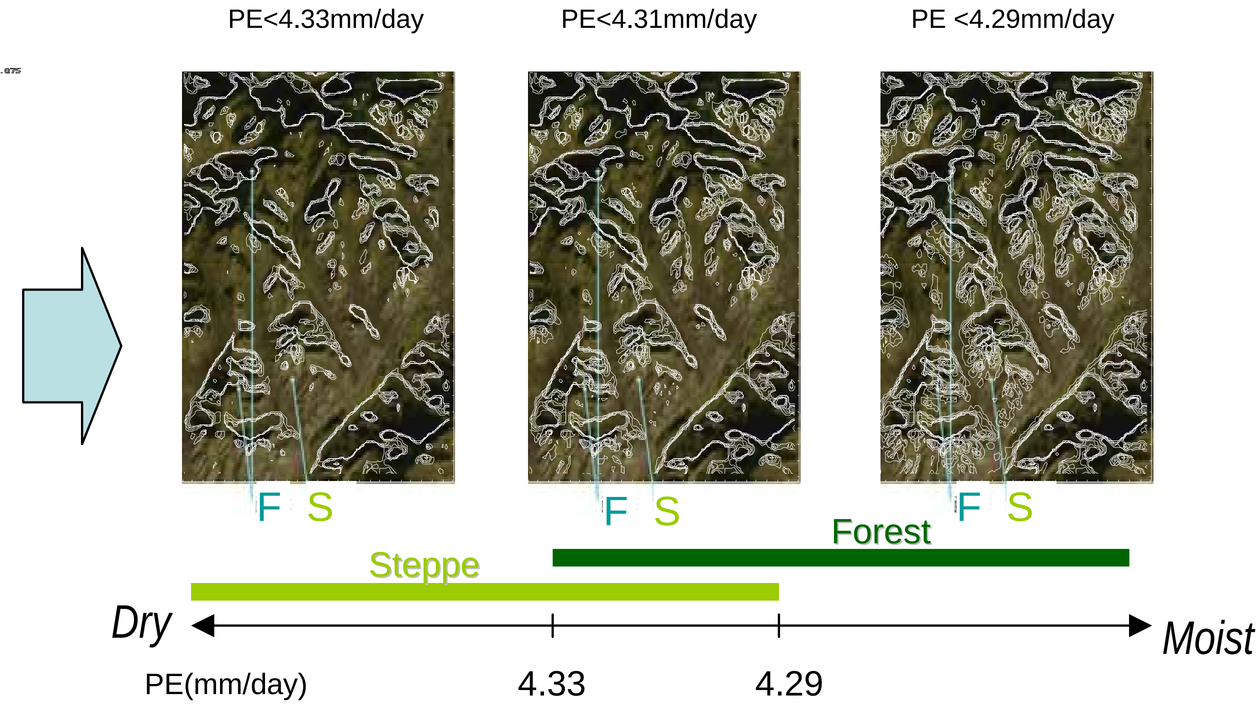
MODEL 2

RESULTS Vegetation-Potential Evaporation (PE) compairison



PE landscape estimated from Model2

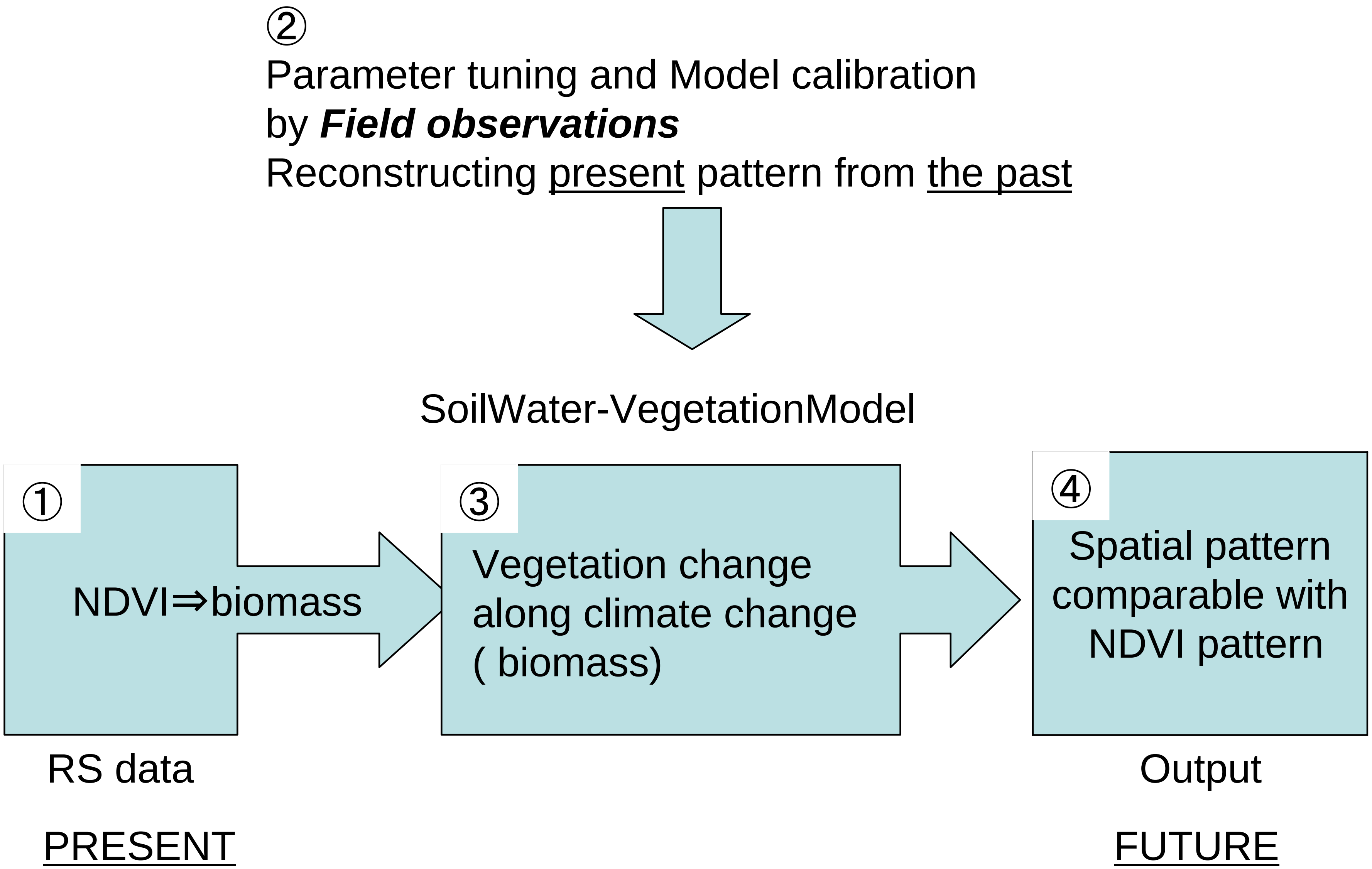
Vegetation pattern estimated with LANDSAT Image (validated by Ground-truth)



Points

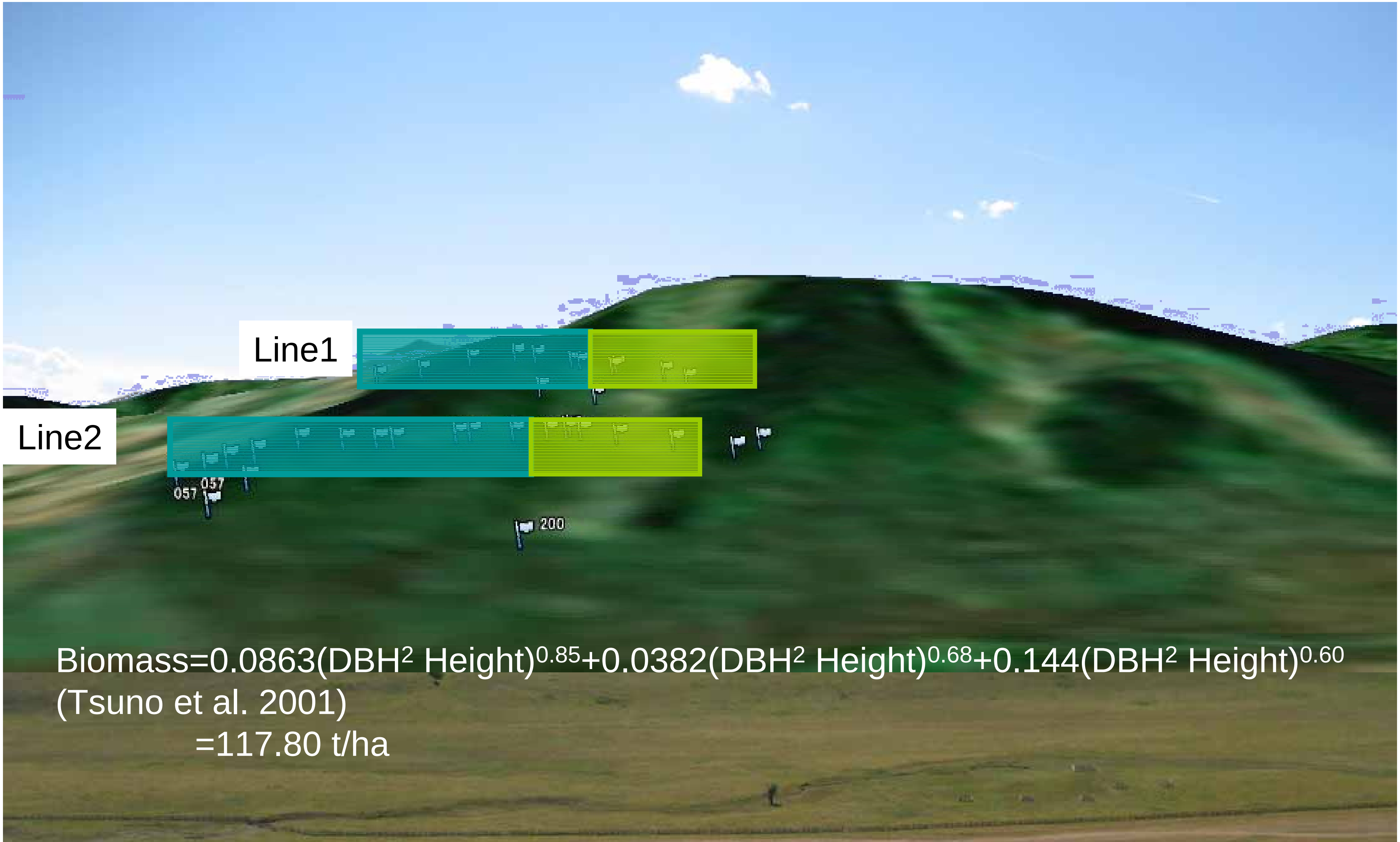
1. The spatial gradient of Potential evaporation rate in the plant growing season can mostly account for the spatial pattern of vegetation.
2. Both of Forest and Steppe are observed in the intermediate PE range.

Summary-Scheme



① Field measurement at Gachuurt

DBH(cm), Height(m) & Soil Water(%) content setting 2 Line transects



$$Biomass=0.0863(DBH^2\ Height)^{0.85}+0.0382(DBH^2\ Height)^{0.68}+0.144(DBH^2\ Height)^{0.60}$$

(Tsuno et al. 2001)

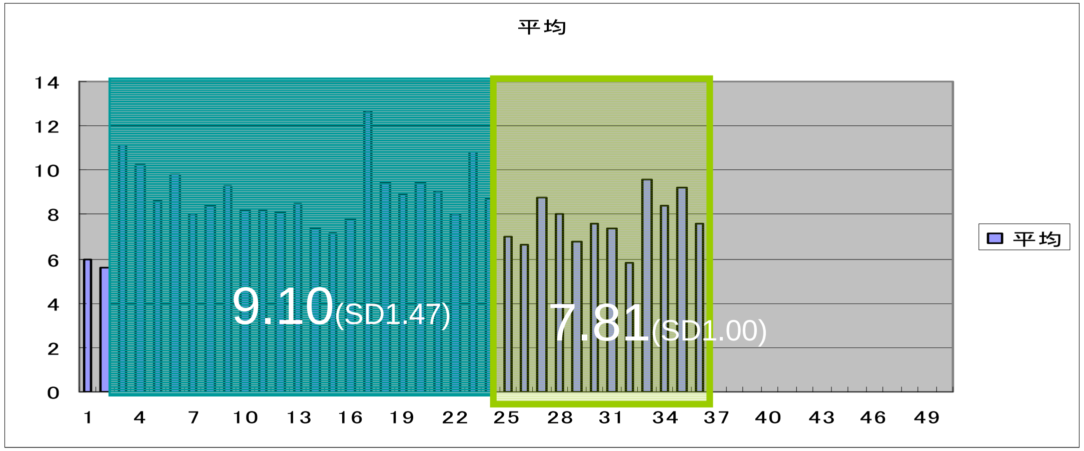
=117.80 t/ha

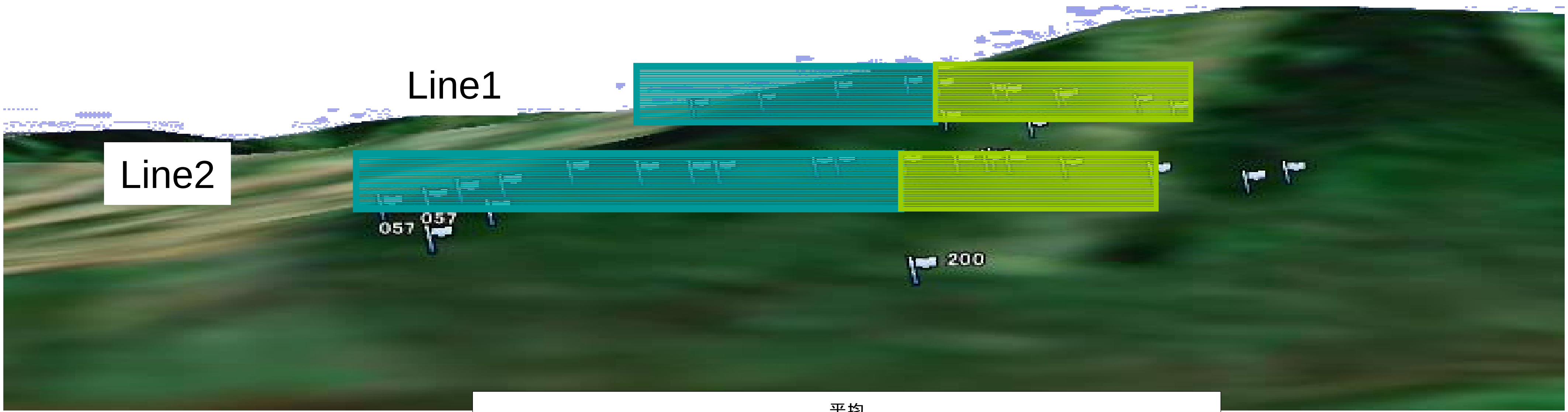
①

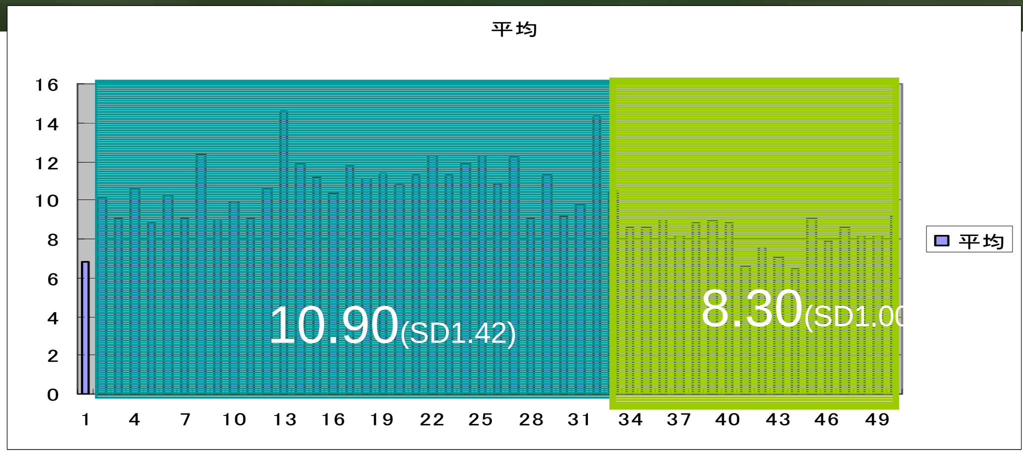
Soil moisture(%) in September 2007

Estimated BIOMASS：
Larch　Forest
=117.80t/ha

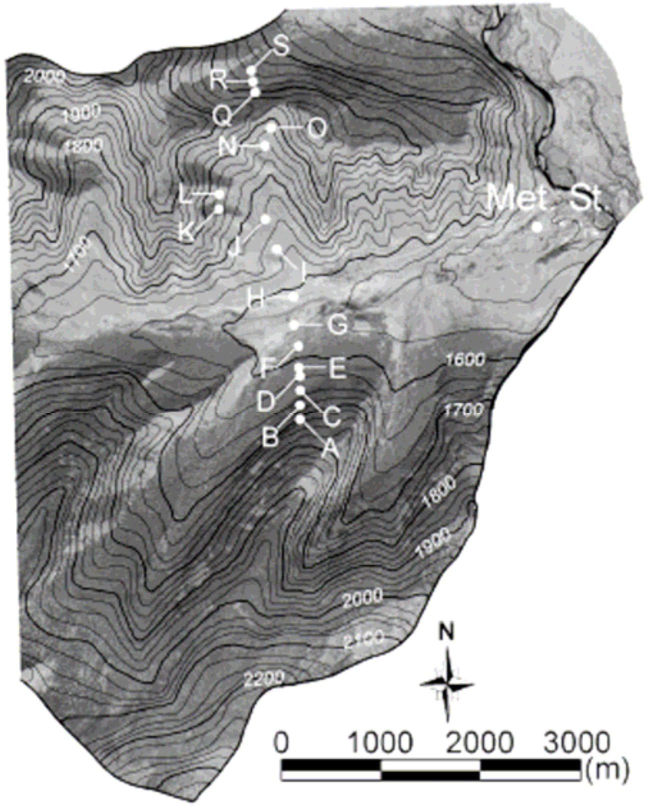
Steppe＜10t/ha
（Fujita2003）

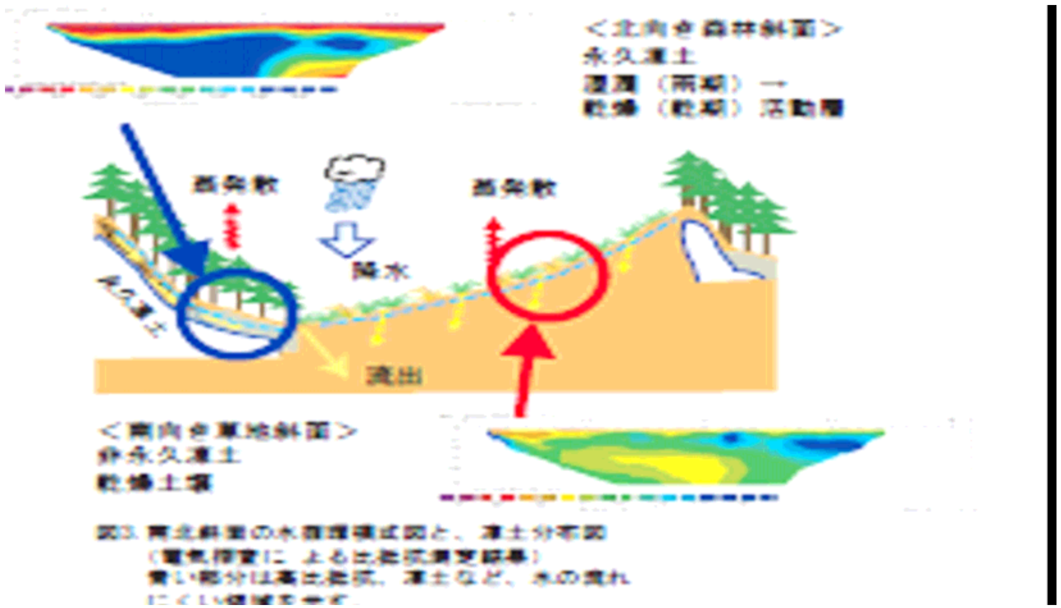






Permafrost-Topographical scale





South slopes: Grassland + no permafrost
North slopes: Larch forest+permafrost

Ishikawa et al. (IORGC)

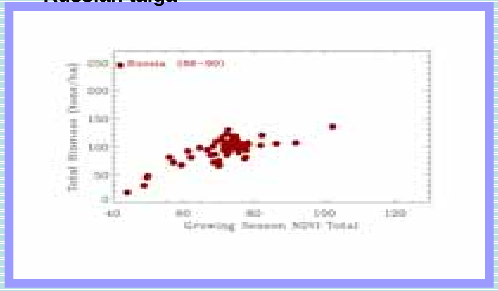
MODEL 1+2 Topography Plant-Biomass model

NDVI (from LANDSAT)

⇕

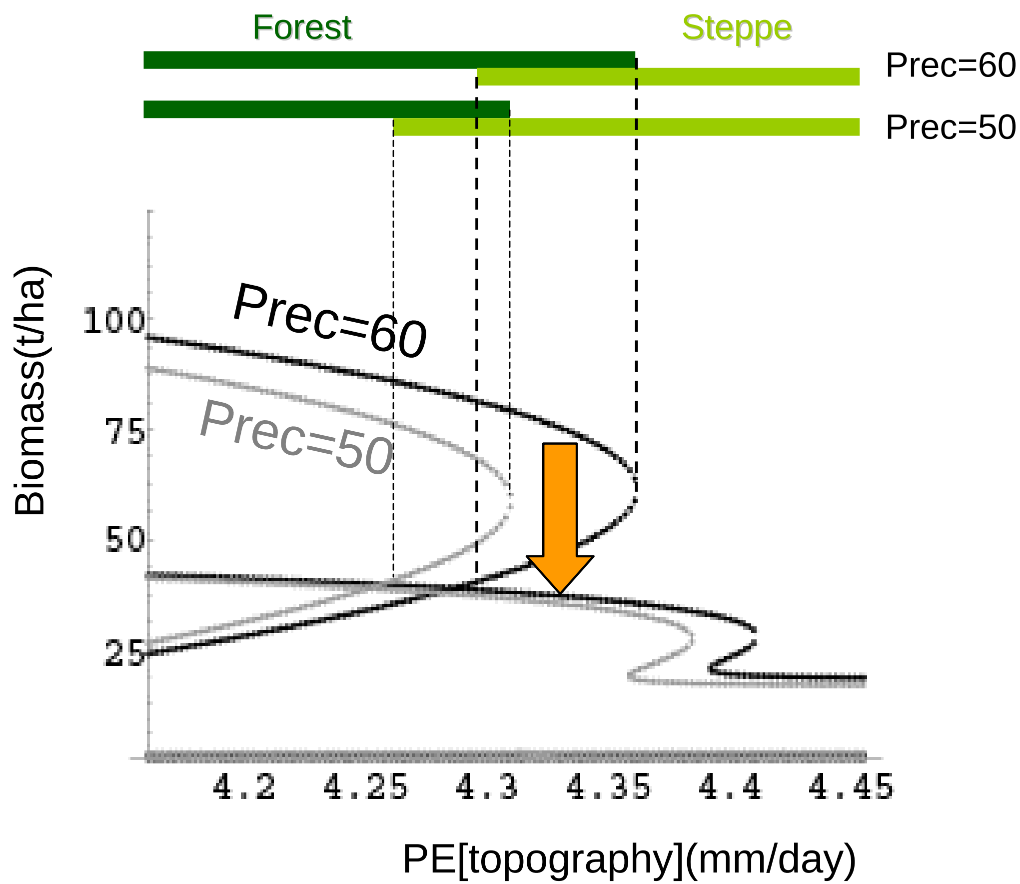
Biomass

Average cumulative growing season NDVI-BIOMASS relationship in Russian taiga



$$1/\text{Biomass} = \alpha + \beta\,[(1/\text{NDVI})/\text{Latitude}^2] + \gamma\,\text{Latitude},$$

$\alpha = 0.0377$, $\beta = .0006$ $\gamma = 3809.65$



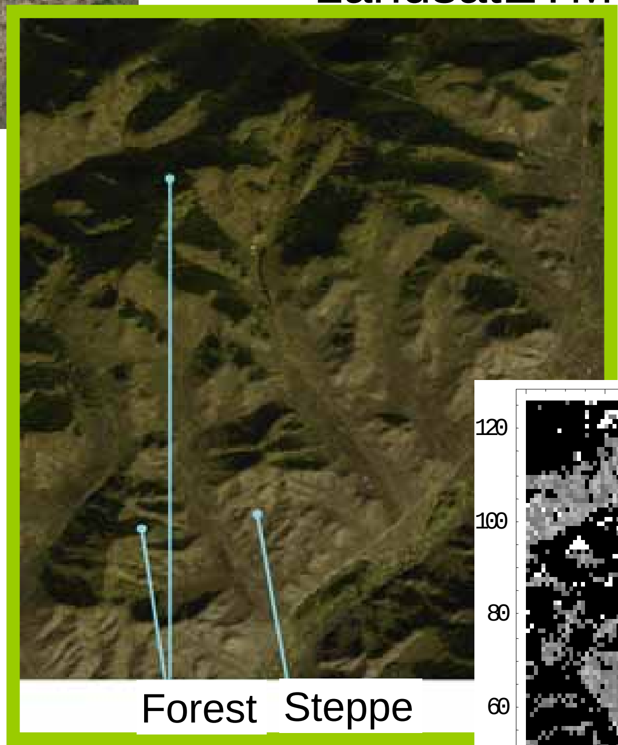
As precipitation decrease, the forest stands on North -Slopes might become steppe catastrophically(↓), and will not recover even precipitation regains.

If Permafrost is lost, forest recovery becomes even more difficult!

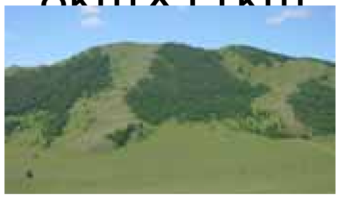
Classification of Vegetation using Satellite Image

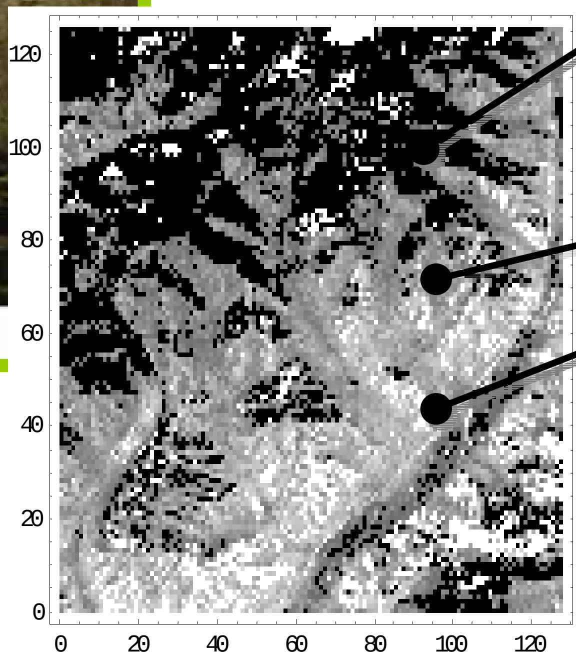
Land Cover Classification
Using NDVI threshold LandsatETM+ (Sugita et al. 2007)

LandsatETM+



8kmX11km





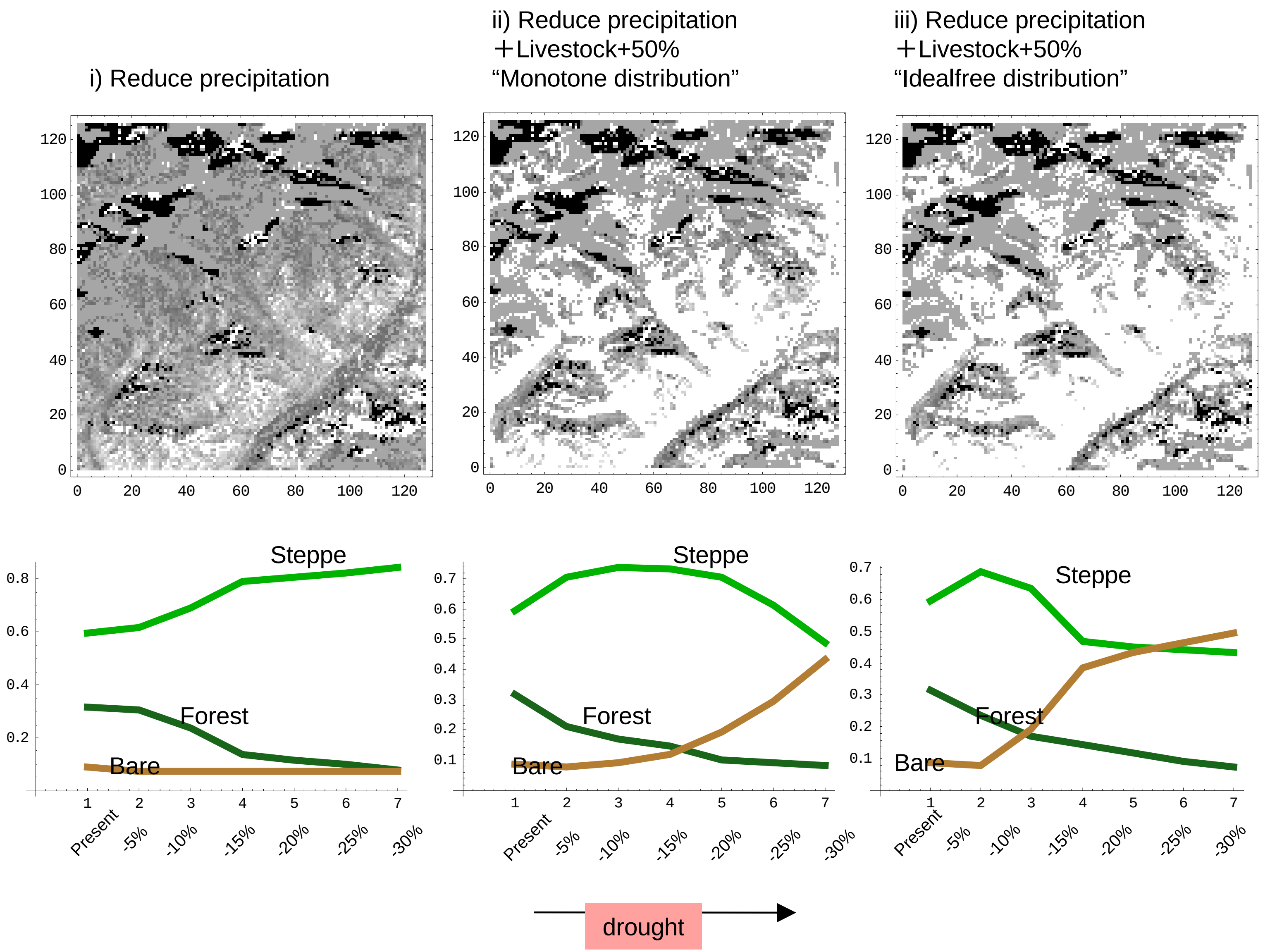
Black(NDVI>0.6) : *Forest*

Gray(0.2<=NDVI<=0.6) : *Steppe*
(Darker are larger in NDVI)

White(NDVI< 0.2):
Bare ground or dead vegetation

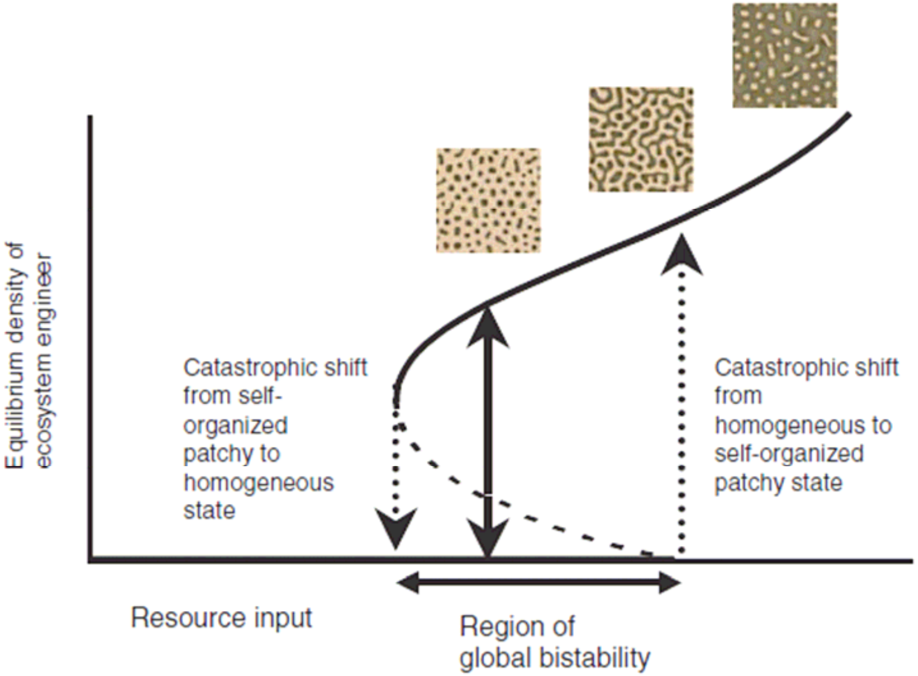
MODEL 1+2 Spatial Projection of 40yrs future

MODEL 1+2 Spatial Projection of 40yrs future

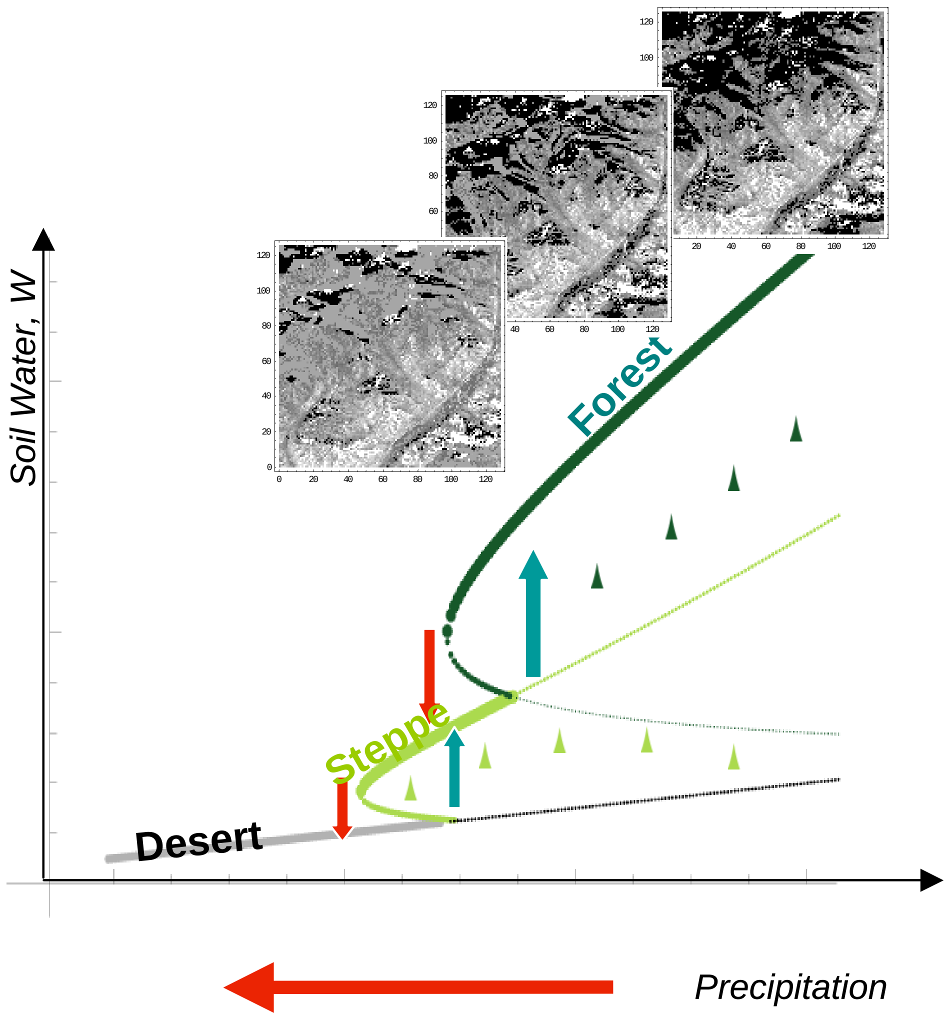


Deforestation & Desertification might proceed heterogeneously acording to the topography

Population distribution → Slope scale-transition



Slope scale distribution → Continental scale-transition



Conclusion

- Using a water-plant interaction model at the slope-scale(<100m), the spatial vegetation pattern can be reconstructed.
- The model calibration and validation can be done with Field observation and Satellite image data.
- The existence of Permafrost and heavy Grazing pressure can be considered to enhance the clear discontinuity and the catastrophic transition of vegetation.

Future Perspectives

- Need more *in situ* data of
  - -Hydrological effects of Vegetation (Permafrost, infilteration, shading,…) IMH + IORGC/JAMSTEC
  - -Plant parameters (growth , mortality,…)
  - -Quantitative Human-impacts on Vegetation (livestock, logging,…) RIHN + IMH

Related ongoing projects :

Research Institute of Humanity and Nature (Kyoto)

“Collapse and Restoration of Ecosystem Networks with Human Activity” with

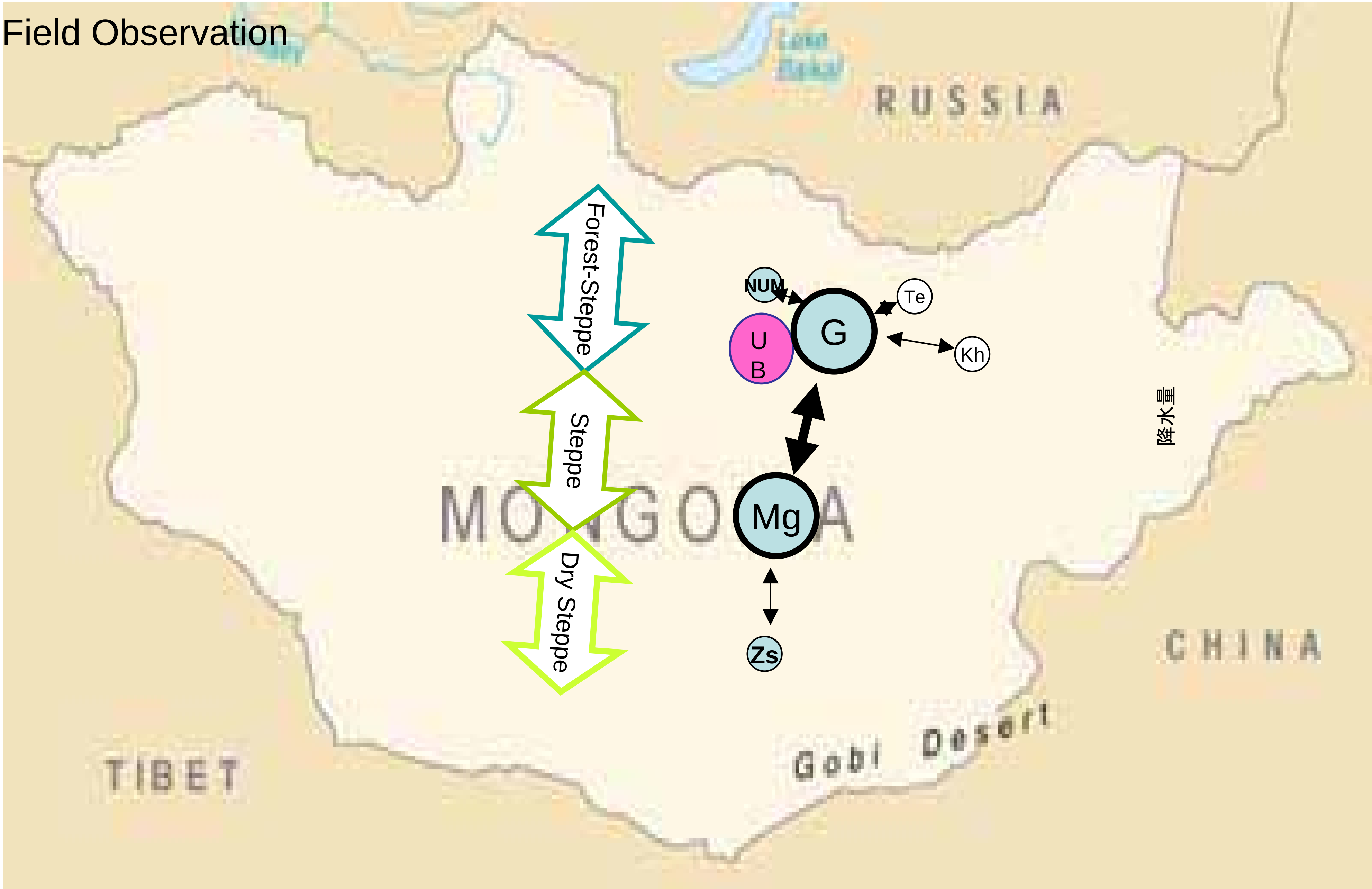
Institute of Meteorology & Hydrology (Mongolia)

Forest Department Sarawak (Malaysia)

Global Land Project (GLP) ,

"Decreasing uncertainty in predicting biome boundary shifts"

Field Observation



Intensive Sites （Hydrology Veg･）

G Gachuurt

Mg Mandalgovi

Minor Sites （Veg.･FoodWb）

NUM NUM（***Grazing Presure***）

Dz Dalanzadgad（**Driness**）

Ref. Sirtes

Te Terelj (**Permafrost & Hydrology**

Kh Kherlen （ Hydrology）

General Recommendation

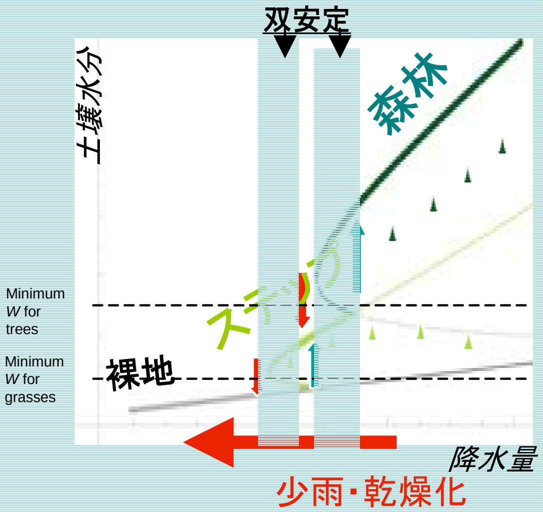
- Construct good field stations to observe vegetation change/transition across broad spatial scales to extract the essential mechanisms to generate vegetation patterns together with key environmental conditions.

- Develop network of the field observation sites to cover broad variety of vegetation changes.

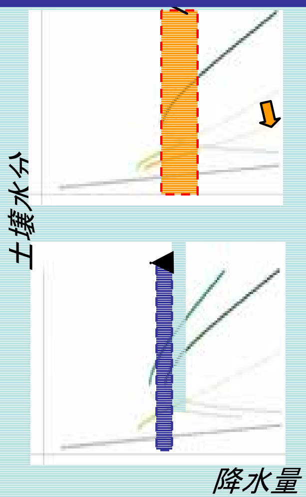

Thank you!

Summary

数理モデルの解析



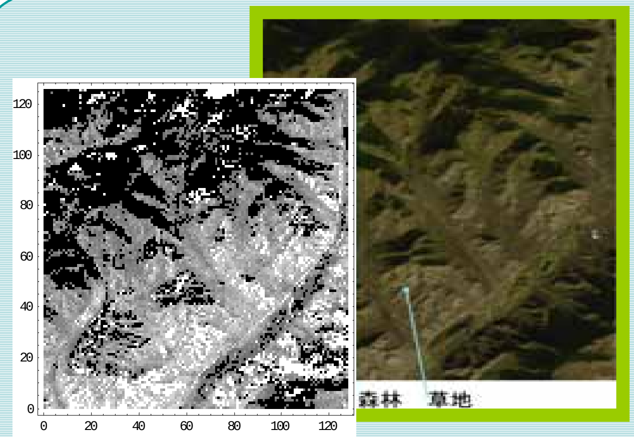
水をめぐる植物間相互作用がもたらす植生の双安定性による「ヒステリシス」と「カタストロフィックな移行」



家畜の増加による双安定領域の拡大

永久凍土の消失による森林成立条件の変化

植生被覆解析

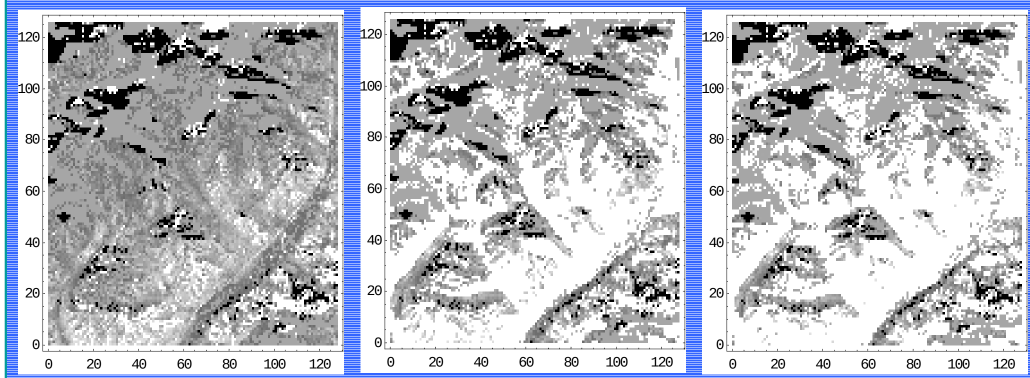


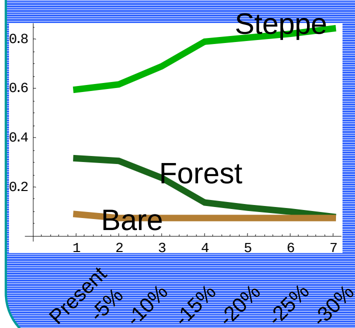
将来植生被覆予測

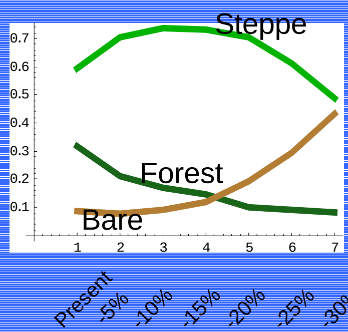
i) 降水量減少

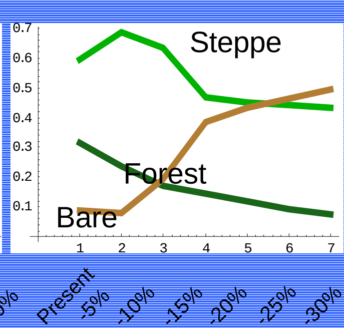
ii) 降水量減少＋放牧圧50%増加（一様分布）

ii) 降水量減少＋放牧圧50%増加（理想自由分布）









草地化・裸地化の進行は乾燥化＋放牧圧のあり方に大きく影響を受ける

Action Plan of future development

Application

Theory

DGVM

Wider Range

Malaysia – Water, Nutrient
Alaska –Permafrost, Fire
Africa

Improve sub-sub model

Hydrology (Ma Sugita IORGC)
Animal ecology (Takatsuki)
*Human dimension** (Nakamaru Yamamura)

Vegetation Validation

*RS-Land cover analyses ** (Matsuoka)
RS-Biomass (Suzuki)
Field observation (Fujita)

Vegetation-Transition Model
Mongolia, Forest-Steppe-Water

Interaction Mechanism

Front-motion theory with Rossberg

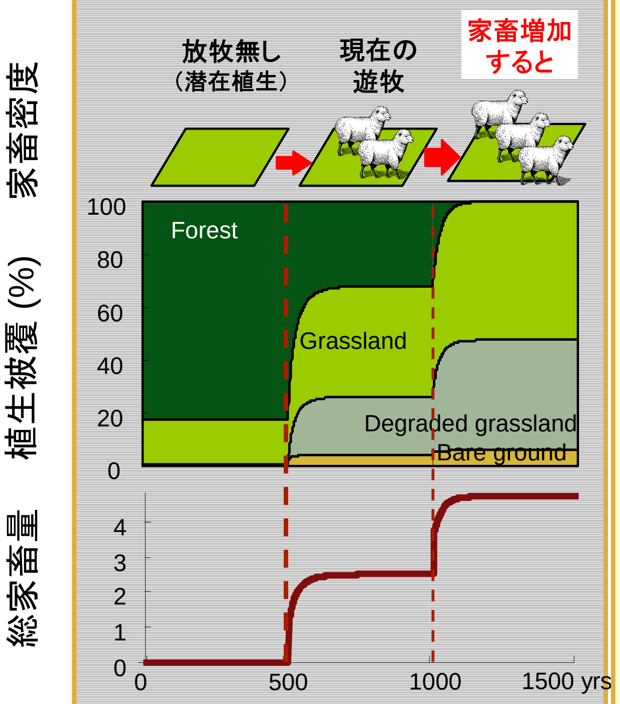

To acquire parameters of
vegetation and environment

To Improve Herbivory sub model

植生への植食の影響

Preliminary result of vegetation transition prediction （with Kobayashi）

従来のモデル

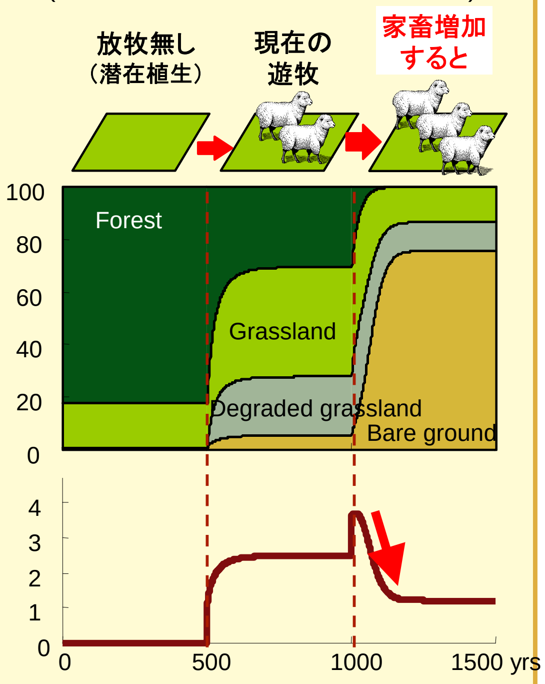


放牧密度を上げると:

・植生が変化する（森林→草原、草原→劣化草原）
・総家畜量は増加する
⇒ トレードオフが成立

新モデル

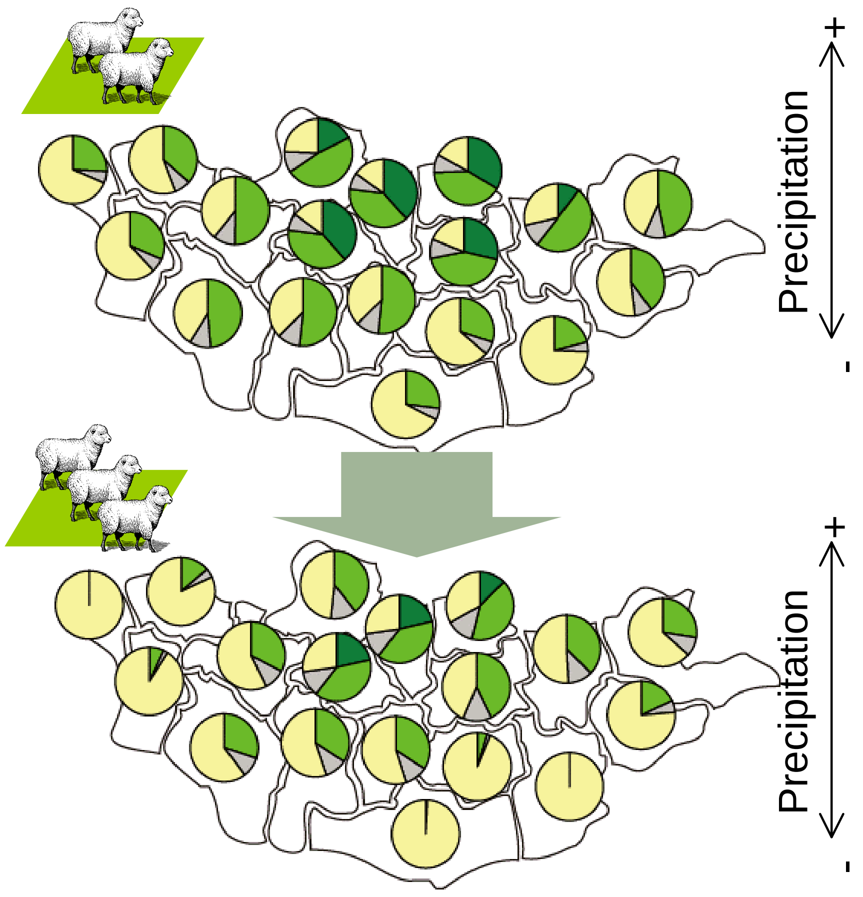
森林が草原に与える間接効果を考慮
(保水･涵養効果、分散･送粉への効果)



放牧密度を上げると:

・植生が変化する（森林→草原、草原→砂漠）
・総飼育家畜数は一旦増加するが徐々にもとの値より落ち込む可能性
⇒ トレードオフが成立しない

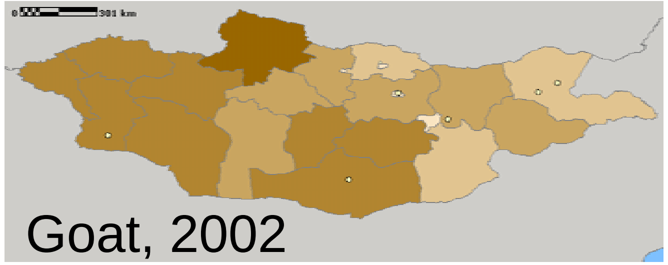
新モデルを用いた モンゴルにおける家畜増加（1.5倍）による 100年後の植生被覆予測例 （各県別データを使用）

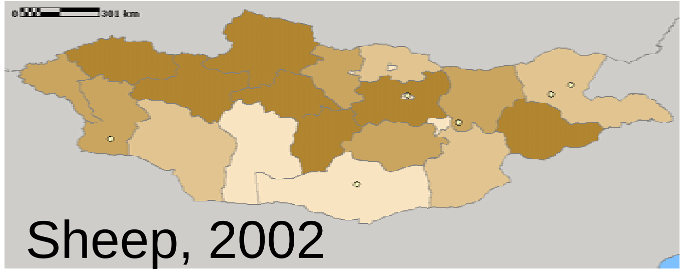


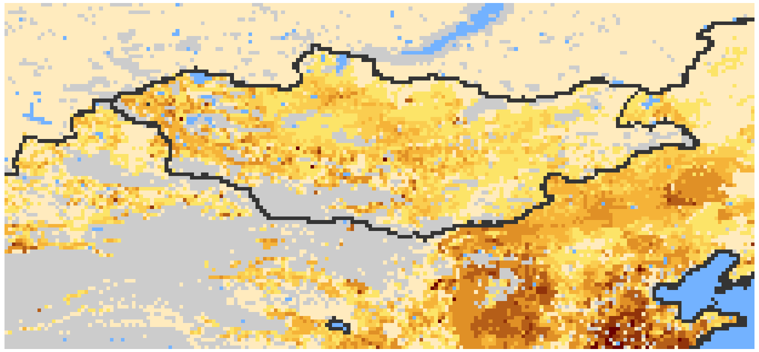
南部では草原が、北部では森林が著しく減少することが予測される。

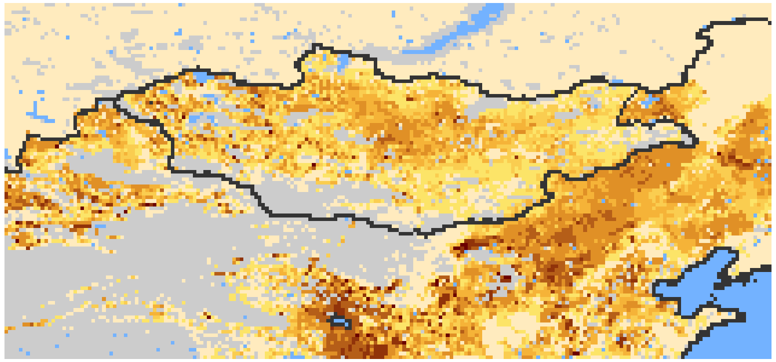
Need more finer data

From Statistical Data









（家畜密度データのスケールダウン法）

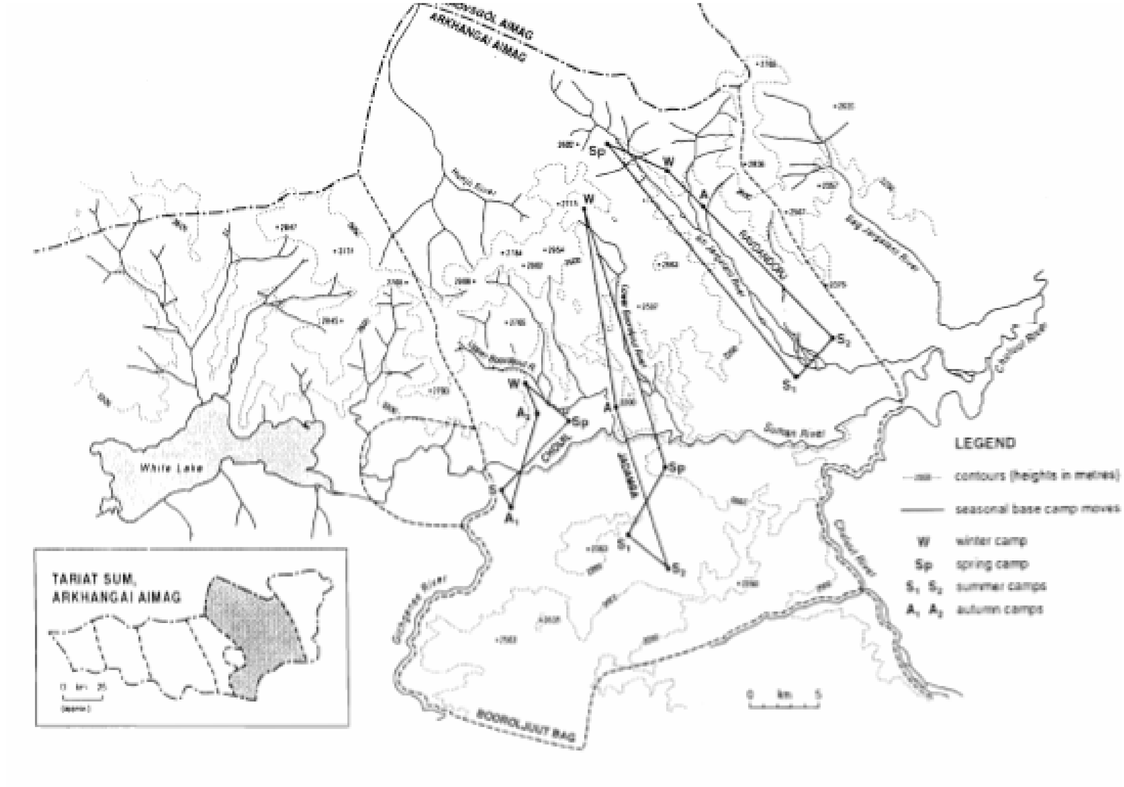
1. 国・県などの統計データを得る
2. 地形データをもとに”unsuitable land for livestock”を面積からのぞき、適地面積から密度を求める。
3. NDVI（植生指数）などの衛星画像データ（1km）から取得できる環境傾度と家畜密度の関係（経験則）をあてはめ、適地内での家畜密度の分布を推定する

(by FAO's Animal Production and Health Division in collaboration with ERGO and the TALA research group, University of Oxford, UK)

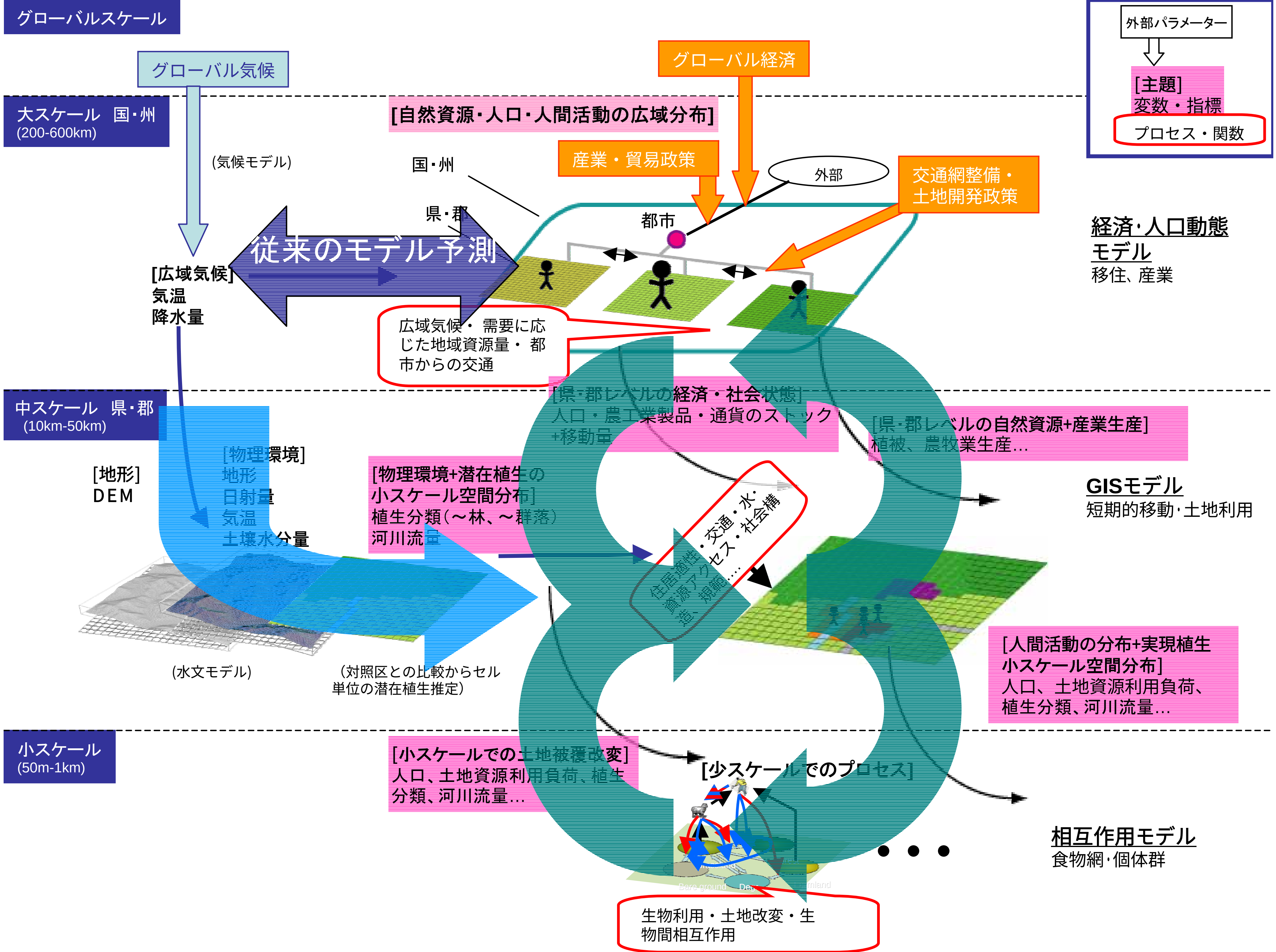
From Field Data

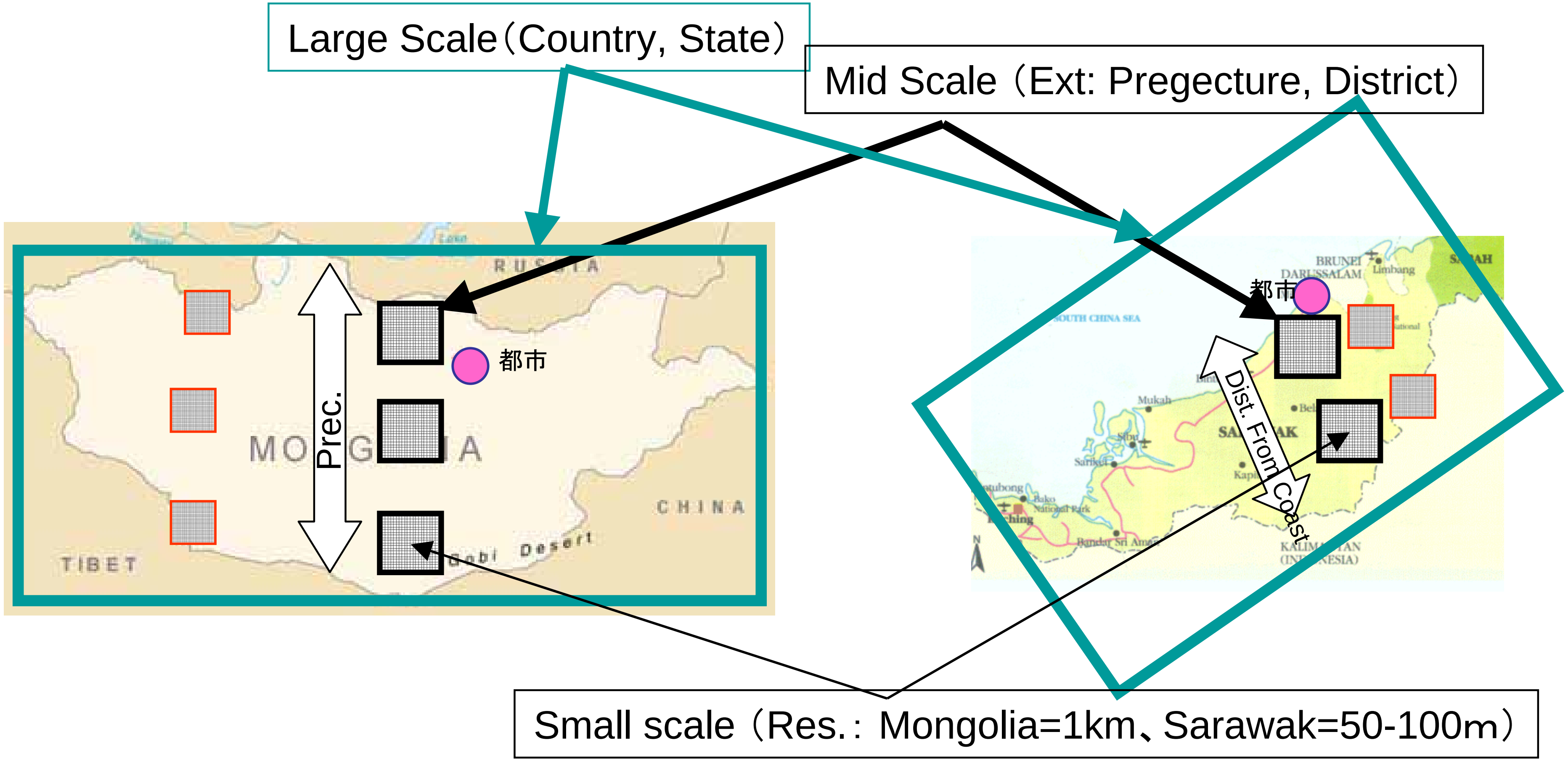
Estimate the grazing pressure at fine-scale using livestock-GPS

2 sheep +2
horses *6 families
=24 GPS



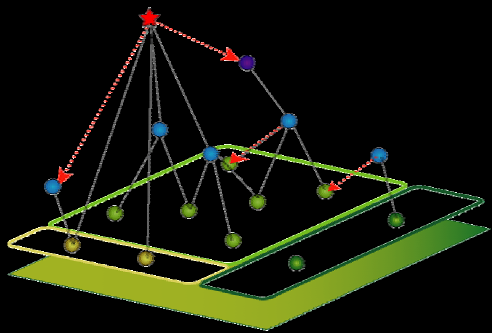
Overlay animal track on the NDVI-map

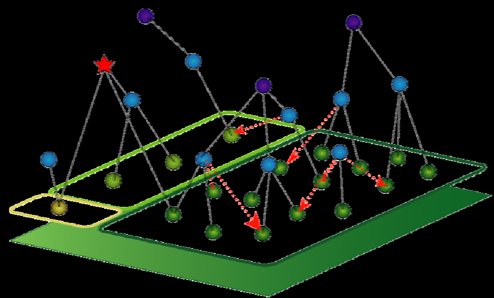

グローバルスケール
グローバル気候
グローバル経済
外部パラメーター
[主題]
変数・指標
プロセス・関数
大スケール　国・州
(200-600km)
[自然資源・人口・人間活動の広域分布]
(気候モデル)
国・州
産業・貿易政策
外部
交通網整備・
土地開発政策
県・郡
都市
従来のモデル予測
[広域気候]
気温
降水量
経済･人口動態
モデル
移住、産業
広域気候・需要に応じた地域資源量・都市からの交通
中スケール　県・郡
(10km-50km)
[県･郡レベルの経済・社会状態]
人口・農工業製品・通貨のストック
+移動量
[県･郡レベルの自然資源+産業生産]
植被、農牧業生産…
[地形]
DEM
[物理環境]
地形
日射量
気温
土壌水分量
[物理環境+潜在植生の
小スケール空間分布]
植生分類（～林、～群落）
河川流量
・交通・水・
セス・社会構
GISモデル
短期的移動･土地利用
(水文モデル)
(対照区との比較からセル
単位の潜在植生推定)
[人間活動の分布+実現植生
小スケール空間分布]
人口、土地資源利用負荷、
植生分類、河川流量…
小スケール
(50m-1km)
[小スケールでの土地被覆改変]
人口、土地資源利用負荷、植生
分類、河川流量…
[少スケールでのプロセス]
相互作用モデル
食物網･個体群
生物利用・土地改変・生物間相互作用



Large Scale（Country, State）
Mid Scale（Ext: Pregecture, District）
Small scale（Res.：Mongolia=1km、Sarawak=50-100m）
Prec.
都市
RUSSIA
CHINA
TIBET
Gobi Desert
都市
Dist. From Coast
BRUNEI
DARUSSALAM
Limbang
SOUTH CHINA SEA
Mukah
Sibu
Bandar Sri Aman

Collapse and Restoration of Ecosystem Networks with Human Activity





Norio Yamamura

Action Plan of future development

Application

DGVM

<u>Wider Range</u>

Malaysia – Water, Nutrient
Alaska –Permafrost, Fire
Africa

<u>Improve sub-sub model</u>

Hydrology (Ma Sugita IORGC)
Animal ecology (Takatsuki)
*Human dimension** (Nakamaru Yamamura)

<u>Vegetation Validation</u>

*RS-Land cover analyses ** (Matsuoka)
RS-Biomass (Suzuki)
Field observation (Fujita)

Vegetation-Transition Model
Mongolia, Forest-Steppe-Water

<u>Interaction Mechanism</u>
Front-motion theory with Rossberg

Theory

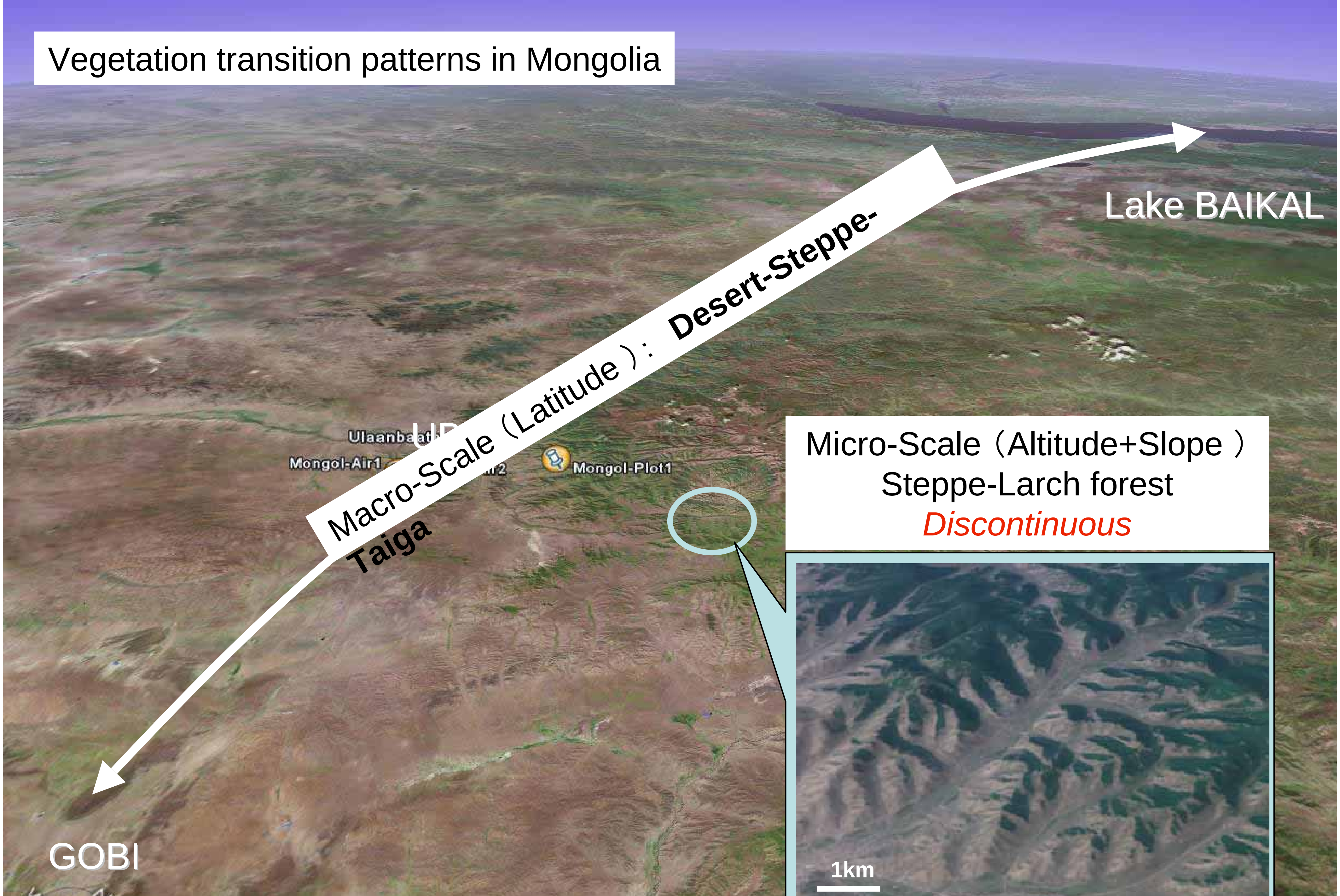
Introduction

Vegetations show different spatial patterns depending on the spatial scale it is observed reflecting the scale-specific mechanisms and conditions. Forest-Steppe ecotone along precipitation gradient in central asia (e.g., northen Mongolia) exisbits a slope direction dependent discontinuous vegetation pattern at a finer scale: grassland on the south slopes and Larch forest on the north slopes (see **Target area & Sample site**).

Why the transition is so discontinuous and how did the pattern emerge?
Why this pattern are not seen everywhere with the similar climatic conditions?

To answer these questions, we modeled the dynamics of plant-soil water interactions at the *slope-scale* (resolution ≈100m, extention:10-50km) using the data at our sample site in Mongolia (N48,E107) (**Fig.2**). Here, the plant growth is mostly controled by the water supply during the grawing season (June-Sept.) and Within the preciptation (<300mm/yr), more than 90% is evaporated and/or transpirated to the air.

Vegetation transition patterns in Mongolia



Problem

At the Slope scale, vegetation pattern reflects topography.

Grazing pressure local-global