United Nations
Educational, Scientific and
Cultural Organization

International
Hydrological
Programme

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MEXT MINISTRY OF EDUCATION,
CULTURE, SPORTS,
SCIENCE AND TECHNOLOGY-JAPAN

International Hydrological Programme

Forest Hydrology −Conservation of Forest, Soil, and Water Resources

The Twenty-fourth IHP Training Course

Photo: Katsuyoshi Kubota (Kyushu University Forests)

Hydrospheric Atmospheric Research Center, Nagoya University

Supported by

Water Resources Research Center, Disaster Prevention Research Institute,
Kyoto University

Ecohydrology Research Institute, The University of Tokyo Forests

Graduate School of Agricultural and Life Sciences, The University of Tokyo

International Hydrological Programme

Forest Hydrology −Conservation of Forest, Soil, and Water Resources

The Twenty-fourth IHP Training Course

23 November - 7 December, 2014

Nagoya, Japan

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Outline

A short training course “Forest Hydrology −Conservation of Forest, Soil, and Water Resources” will be programmed for participants from Asia-Pacific regions as a part of the Japanese contribution to the International Hydrological Program (IHP). The course is composed of a series of lectures and practice sessions.

Objectives

Incident rainwater is firstly intercepted by foliage and branches and evaporates from their surface to the atmosphere. Following interceptions by plant surfaces, the water is channeled along the plant body. Some of incident rainwater directly reaches the soils without touching foliage and branches. This rainwater infiltrates into the soils and is influenced by the soil pore structure, as it percolates to the groundwater table. Since soil water movement is slow, some of the soil water is absorbed by plant roots, where it is conducted through stem conduits, reaches leaves, and evaporates to the atmosphere through stomata. The groundwater flows to a river. This is an outline of water cycling in the forest ecosystems, and science on this water cycling is “Forest Hydrology”.

As one can see above, Forest Hydrology has two major scientific aspects: (1) discharge from forested watersheds; and (2) water use by trees (evaporation from the forest canopy). Soils in the forested watershed have a high hydraulic conductivity at the ground surface, which prevents soil erosion, and functions to make soil water flow slowly, resulting in a behavior like a dam. Rainfall subtracted by the forest water use denotes the upper limit of available water for the ecosystem including human use. This means that forest management, such as thinning and conversion of forest, can be expected to alter and enhance the forest’s abilities to prevent disasters and preserve water resources. These are the main practical applications of Forest Hydrology.

In this training course, the basics of forest hydrology and its application for conservation of forests, soil and water resources will be introduced. Its global scale implications will also be included. Practices are for understanding hydrological significance of forests and learning skills to manage forests so that managers may optimize their hydrological functions. As an important aspect, this training course will deal with the specific hydrological issues of East Asian countries. For example, many of the forest water use theories assume larger evaporative demand than annual precipitation and an evenly distributed precipitation throughout the year or large precipitation in winter. Scientists from the US and UK devised these theories for application to their familiar hydrologic environment. As such, there is a need for more detailed information of forest water use when precipitation is larger than evaporative demand and when there is greater precipitation in summer conditions, as in most East Asian countries, which would advance knowledge of forest hydrology both locally and globally.

Lecturers

L1: Basics of forest hydrology	T. Kumagai
L2: Discharge from forested watershed (1)	M. Tani
L3: Discharge from forested watershed (2)	K. Kosugi
L4: Effect of vegetation cover on sediment transportation and erosion	T. Gomi
L5: Nutrient and organic matter export from forested watershed	H. Haga
L6: Evapotranspiration from forest	Y. Kosugi
L7: Water resources in forested watershed	H. Komatsu
L8: Basics of forest dynamics	H. Sato
L9: Global/local hydrometeorology and forest (1)	T. Hiyama
L10: Global/local hydrometeorology and forest (2)	H. Fujinami

Exercise

E1: Forest dynamics modelling	H. Sato
E2: Global/local hydrometeorology map	H. Fujinami, H. Kanamori

Field Workshop

W1: Hydrologic regime change accompanied by forest recovery	K. Kuraji, N. Tanaka
W2: Hydrologic observations at Kiryu Experimental Watershed (Kyoto University) in Shiga Prefecture	

Schedule (23 November to 7 December, 2014)

23 (Sunday)	Arrival at Central Japan International Airport and movement to Nagoya University		
24 (Monday)	09：30 - 09：40	Registration & Guidance	
	09：40 - 12：10	Lecture 1	T. Kumagai
	14：00 - 16：00	Keynote 1	T. W. Giambelluca
	17：00 - 19：00	Welcome party	
25 (Tuesday)	09：30 - 11：30	Keynote 2	N. A. Chappell
	14：00 - 16：30	Lecture 2	M. Tani
26 (Wednesday)	09：30 - 12：00	Lecture 8	H. Sato
	14：00 - 16：30	Exercise 1	H. Sato
27 (Thursday)	09：30 - 12：00	Lecture 3	K. Kosugi
	14：00 - 16：30	Lecture 4	T. Gomi
28 (Friday)	09：30 - 12：00	Lecture 5	H. Haga
	14：00 - 16：30	Lecture 6	Y. Kosugi
29 (Saturday)	09：30 - 12：00	Lecture 10	H. Fujinami
	14：00 - 16：30	Exercise 2	H. Fujinami, H. Kanamori
30 (Sunday)	Free time		
1 (Monday)	09：30 - 12：00	Lecture 7	H. Komatsu
	14：00 - 16：30	Lecture 9	T. Hiyama
2 (Tuesday)	09：30 - 11：30	Field Workshop 1	K. Kuraji, N. Tanaka
	13：30 - 16：30	Field Workshop 1	K. Kuraji, N. Tanaka
3 (Wednesday)	Briefing for Field Workshop 2 and Tour for Japanese culture (Move to Kyoto)		
4 (Thursday)	Field Workshop 2 at Kiryu Experimental Watershed		
5 (Friday)	09：30 - 12：00	Making reports and discussions	T. Kumagai
	14：00 - 16：30	Making reports and discussions	T. Kumagai
6 (Saturday)	09：30 - 11：30	Report presentations and discussions	
	11：30 - 12：00	Completion ceremony of this course	
	13：30 - 15：30	Farewell party	
7 (Sunday)	Departure from Central Japan International Airport		

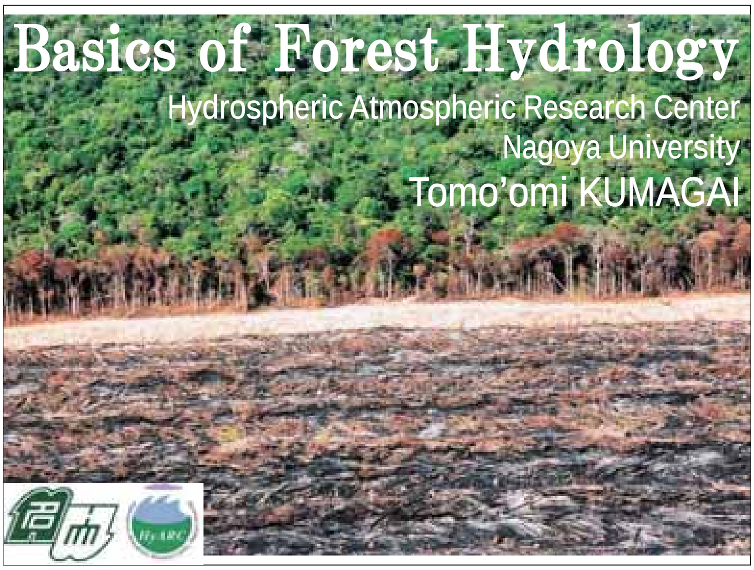
L1: Basics of forest hydrology

Tomo’omi Kumagai (*Hydrospheric Atmospheric Research Center, Nagoya University*)

Abstract

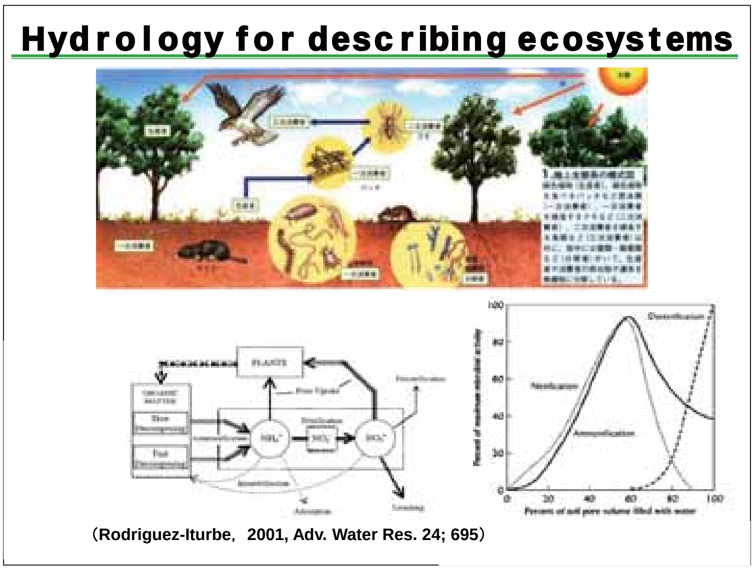
Forest Hydrology has two major scientific aspects, 1) discharge from forested watershed, and 2) water use by trees (evaporation from the forest canopy). Soils in the forested watershed have a high hydraulic conductivity at the ground surface, which prevents from soil erosion, and functions to make soil water flow slow, resulting in a behavior like a dam. Rainfall subtracted by the forest water use denotes the upper limit of available water for the ecosystem including human use. These mean that forest management such as thinning and forest conversions can be expected to alter and enhance the forest’s abilities to prevent from disasters and preserve water resources, Forest Hydrology’s main practical applications.

Such forests’ hydrological functions can be explained along a context of water cycling in the forest ecosystems as follows: Incident rainwater is firstly intercepted by foliage and branches and evaporates from their surface to the atmosphere. From the surface full of rainwater, the rainwater conducts to soils along the plant body, and also, some of incident rainwater directly reaches the soils without touching foliage and branches. These rainwaters coming to the soils infiltrate into the soils with being influenced by the soil pore structure, and reaching to groundwater table. During the slow soil water movement, some of the soil water is absorbed by plant roots. It conducts through stem conduits, reaches leaves, and evaporates to the atmosphere through stomata. The ground water flows to a river. We have to recollect that science on this description of water cycling is “Forest Hydrology”. In my lecture, the basics of Forest Hydrology including both observations (methods and results) and theories will be introduced.



Basics of Forest Hydrology

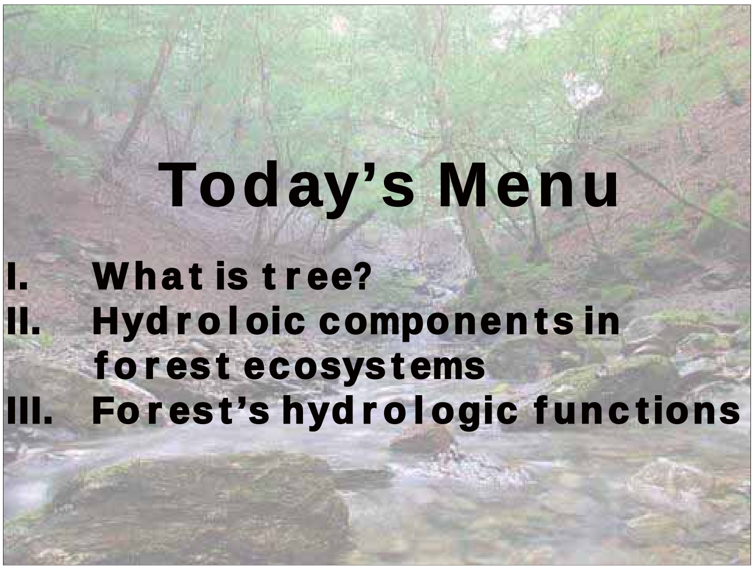
Hydrospheric Atmospheric Research Center
Nagoya University
Tomo’omi KUMAGAI



Hydrology for describing ecosystems

（Rodriguez-Iturbe，2001, Adv. Water Res. 24; 695）

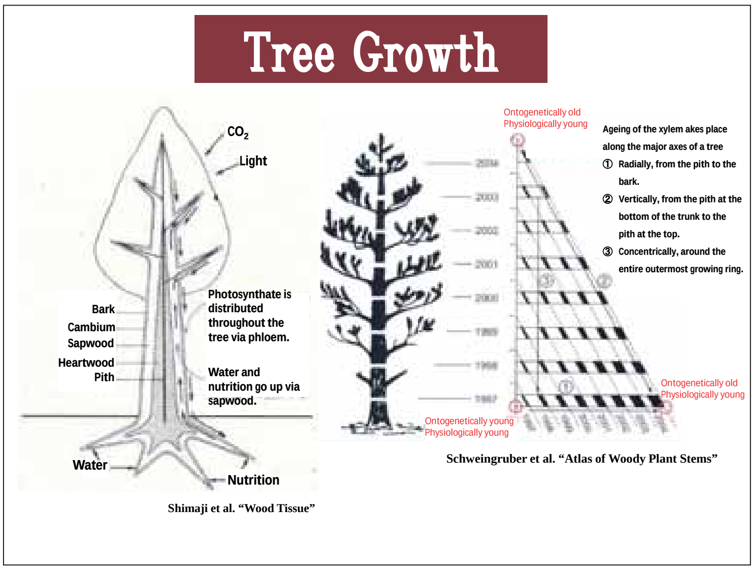
This is not a good forest. Rather, a degraded forest.



Today’s Menu

I. What is tree?
II. Hydroloic components in forest ecosystems
III. Forest’s hydrologic functions

What is tree?



Tree Growth

Photosynthate is distributed throughout the tree via phloem.

Water and nutrition go up via sapwood.

Shimaji et al. “Wood Tissue”

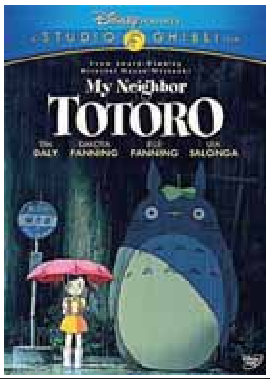
Ageing of the xylem akes place along the major axes of a tree

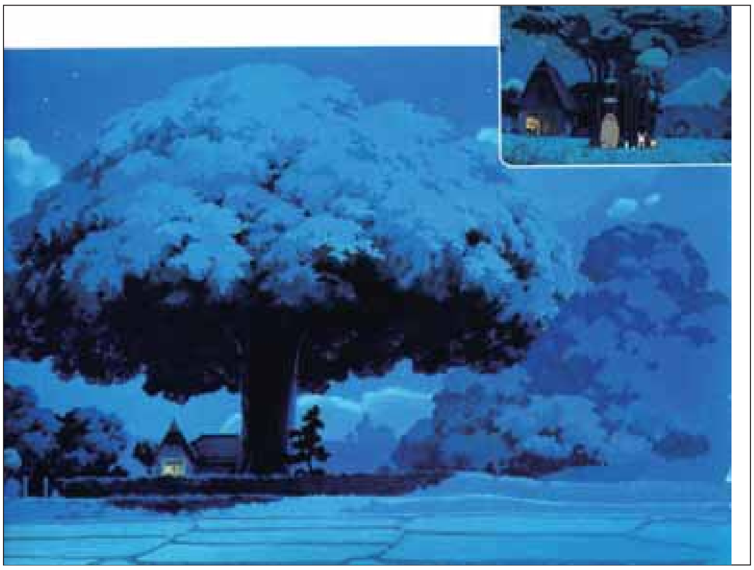
① Radially, from the pith to the bark.
② Vertically, from the pith at the bottom of the trunk to the pith at the top.
③ Concentrically, around the entire outermost growing ring.

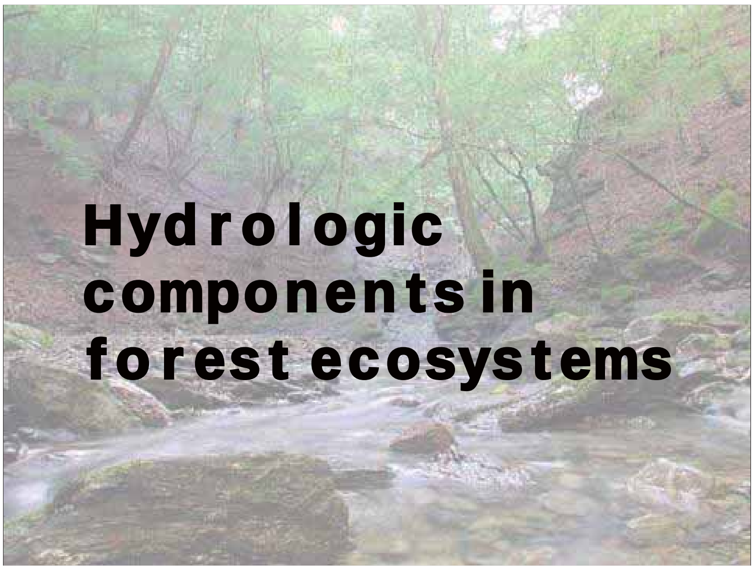
Schweingruber et al. “Atlas of Woody Plant Stems”

Tree Growth

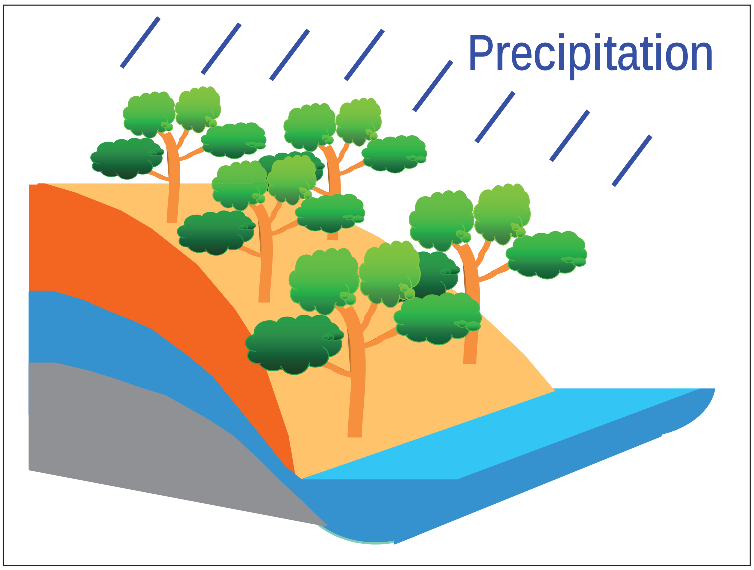
Cones of Tree Growth
(generating growth "rings" in cross-section)



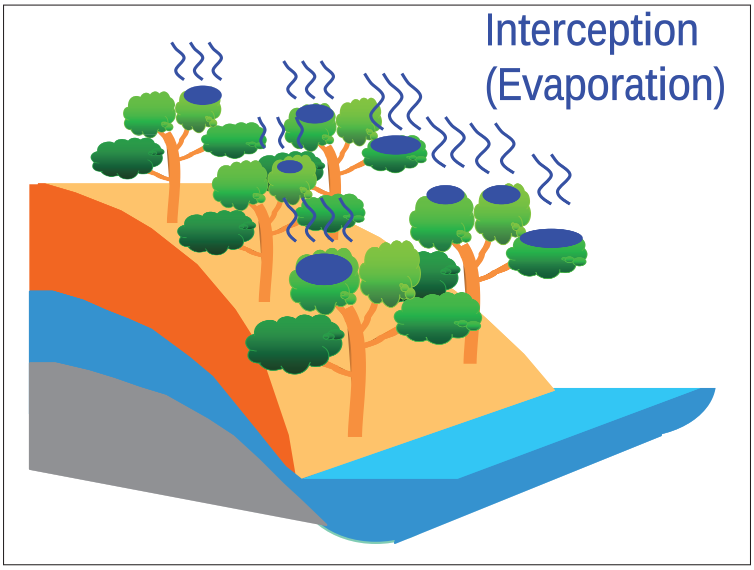




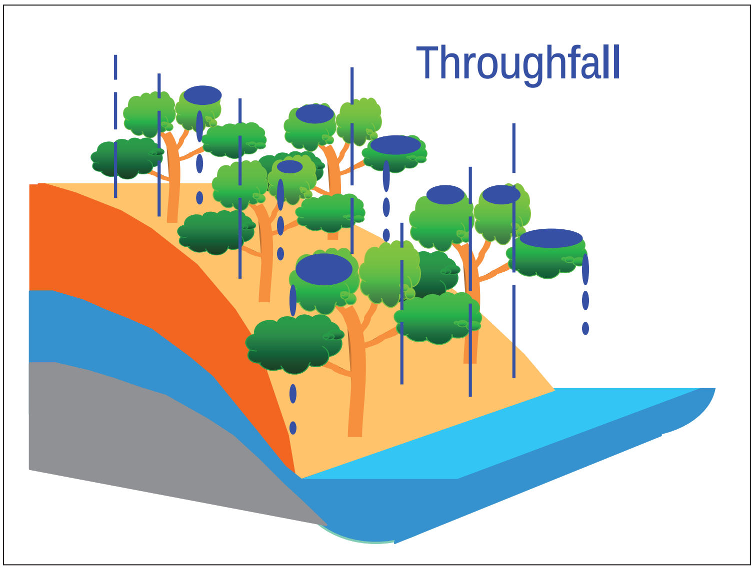
Hydrologic components in forest ecosystems



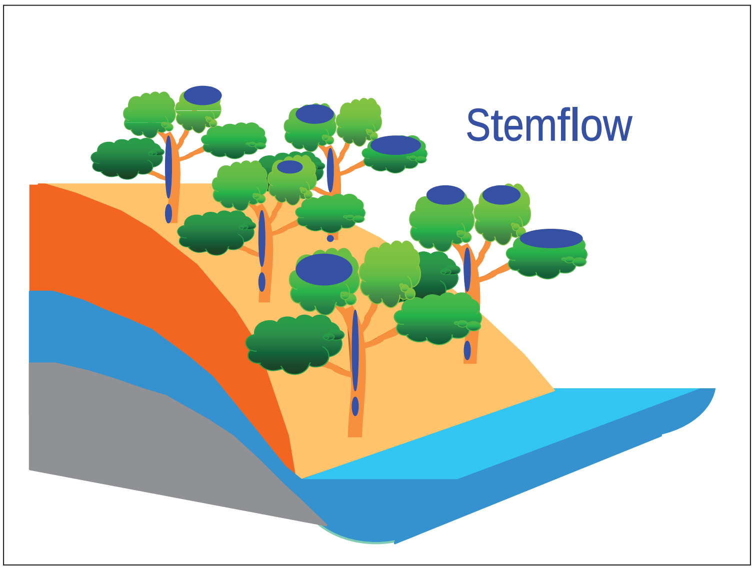
Precipitation



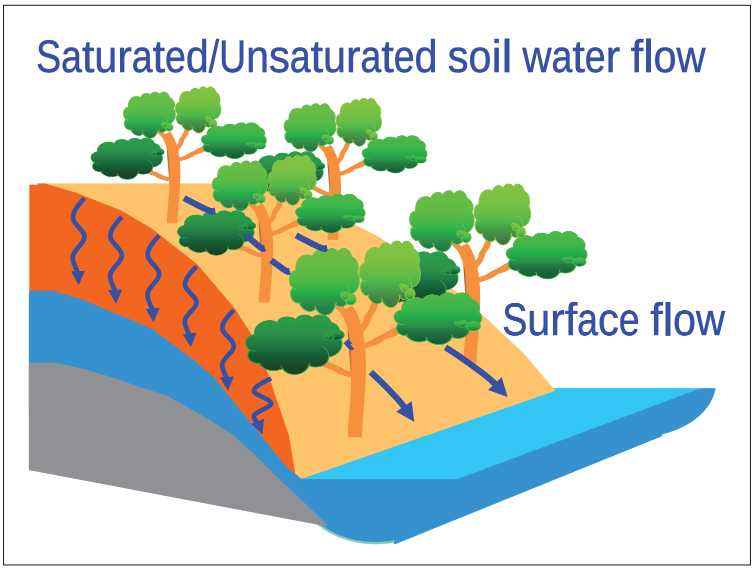
Interception (Evaporation)



Throughfall

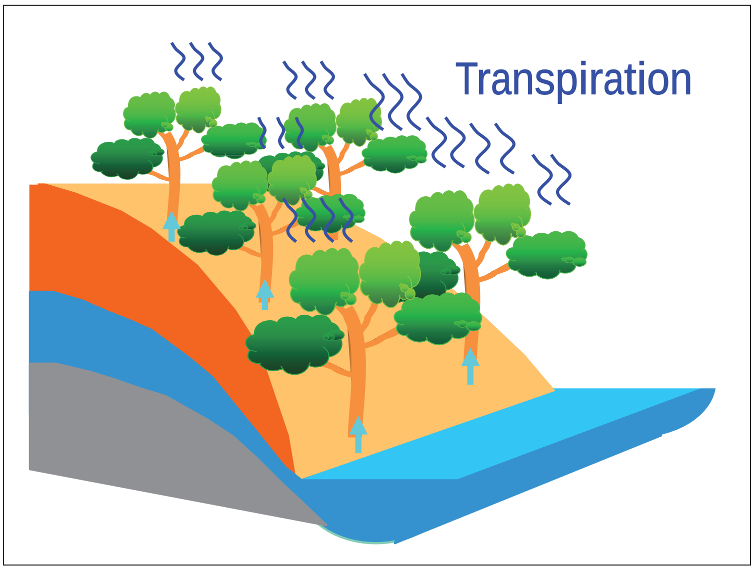


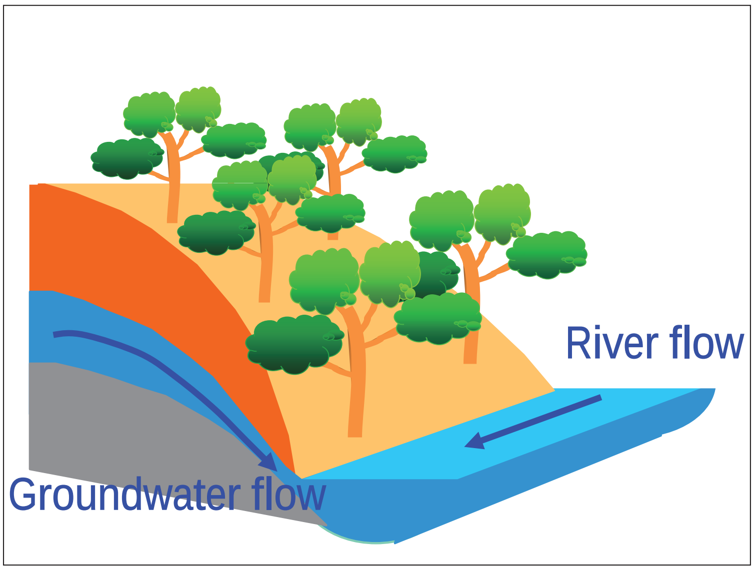
Stemflow

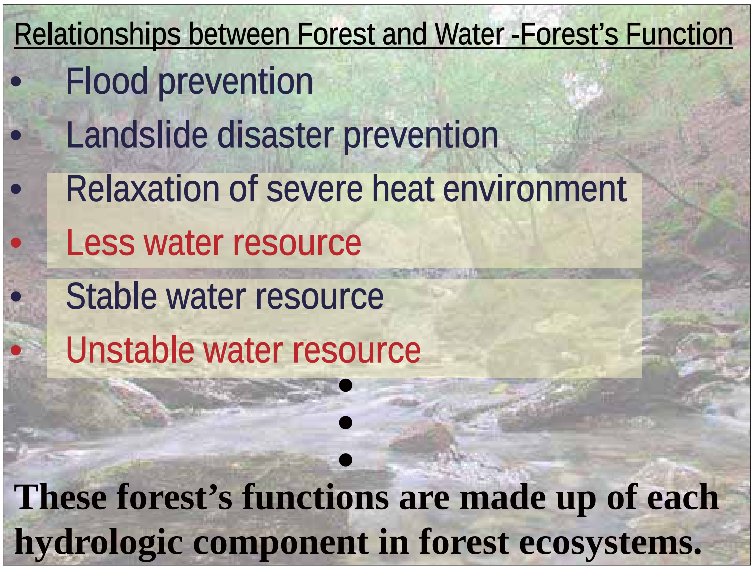


Saturated/Unsaturated soil water flow

Surface flow





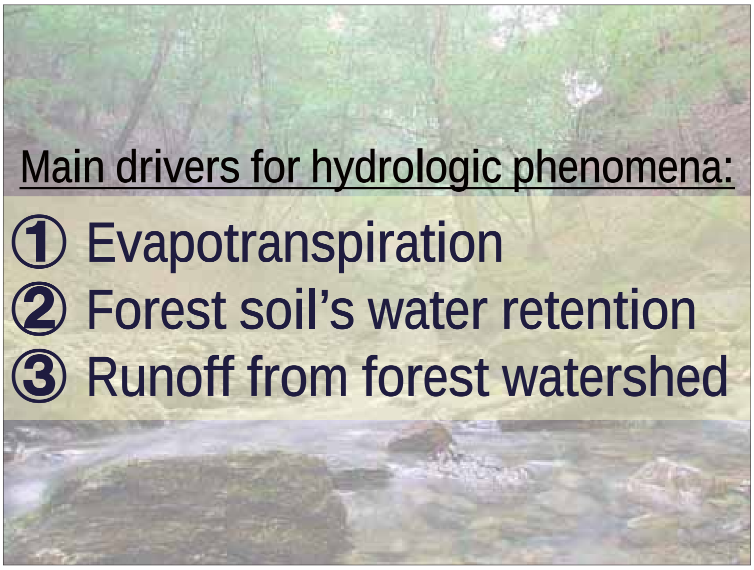


Relationships between Forest and Water -Forest's Function

- Flood prevention
- Landslide disaster prevention
- Relaxation of severe heat environment
- Less water resource
- Stable water resource
- Unstable water resource

⋮

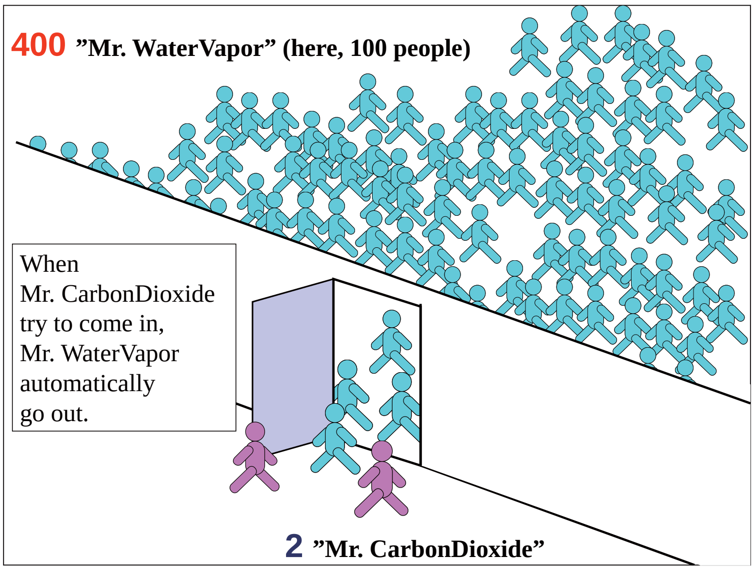
These forest's functions are made up of each hydrologic component in forest ecosystems.



Main drivers for hydrologic phenomena:

① Evapotranspiration
② Forest soil's water retention
③ Runoff from forest watershed

① Evapotranspiration



400 ”Mr. WaterVapor” (here, 100 people)

When
Mr. CarbonDioxide
try to come in,
Mr. WaterVapor
automatically
go out.

2 ”Mr. CarbonDioxide”

- Enhanced CO_2 concentration induced closing stomata. (Wullschleger & Norby, 2001)
- Decrease in the number of stomata

As a result,

Decrease in transpiration

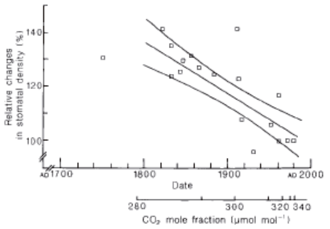
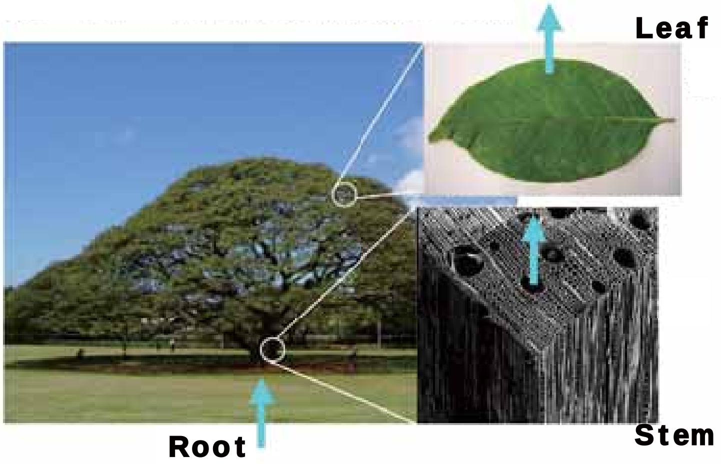


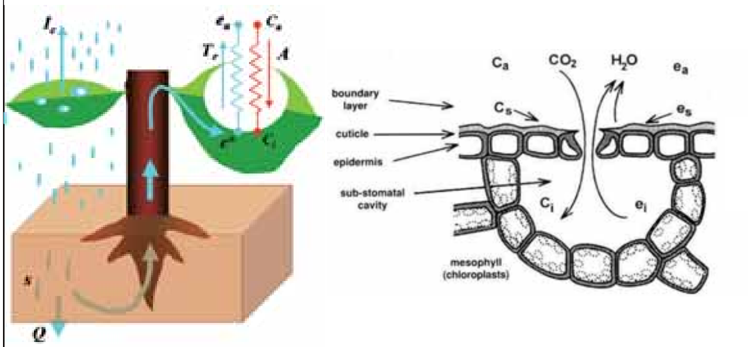
Fig. 1 Abaxial stomatal densities of herbarium stored leaves of *Acer pseudoplatanus*, *Carpinus betulus*, *Fagus sylvatica*, *Populus nigra*, *Quercus petraea*, *Q. robur*, *Rhamnus catharticus* and *Tilia cordata*. Leaves had been stored in the herbarium in the Department of Botany, University of Cambridge. Only leaves on reproductive shoots were sampled, with the assumption that these leaves had developed in full irradiance. Five leaves of each species were sampled from different dates, back to AD 1750, and from collections made in the midlands of England. Stomatal densities varied between species by a factor of about two, however the changes in stomatal densities relative to the recent collections (1970 to 1981) were similar for all species. Reconstructed changes in atmospheric CO_2 based on ice-core studies[1] are also included. The linear regression line, with 95% confidence limits, shows a 40% reduction in the ratio of stomatal densities over a period of 200 years, $r = -0.828$.

Woodward (1987;Nature)

Leaf-Stem-Root Continuity



Transpiration and Photosynthesis



Soil moisture availability controls photosynthetic rate through stomatal control

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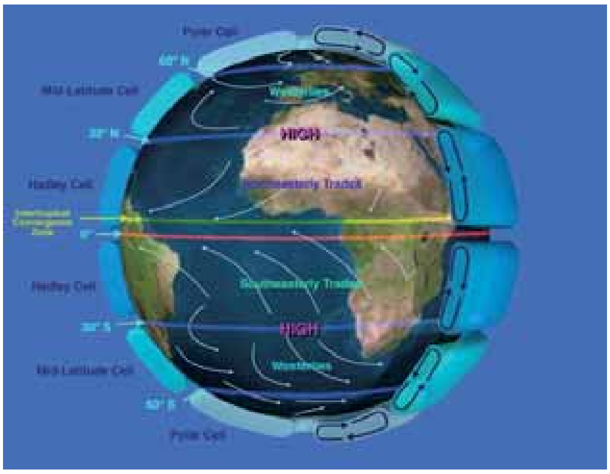
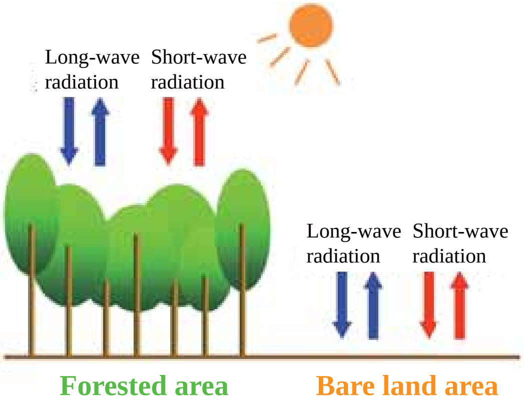
How much water a tree consumes per day?



Solar energy is the driver of circulation.

$$R_n = (1-a)R_S + R_L - \varepsilon\sigma T_s{}^4$$



Long-wave radiation

Short-wave radiation

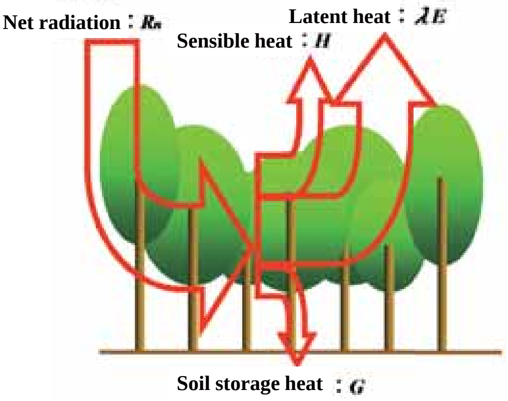
Long-wave radiation

Short-wave radiation

Forested area

Bare land area

$$R_n = H + \lambda E + G$$



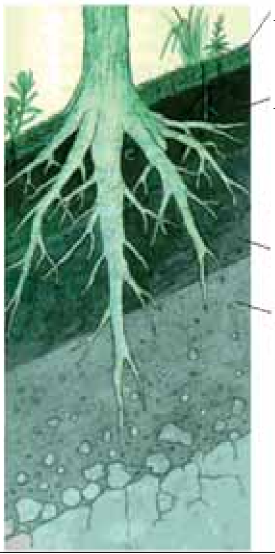
Net radiation：R_n

Latent heat：λE

Sensible heat：H

Soil storage heat ：G

② Forest soil's water retention



A_0 Horizon
- L Horizon
- F Horizon
- H Horizon

A Horizon

B Horizon

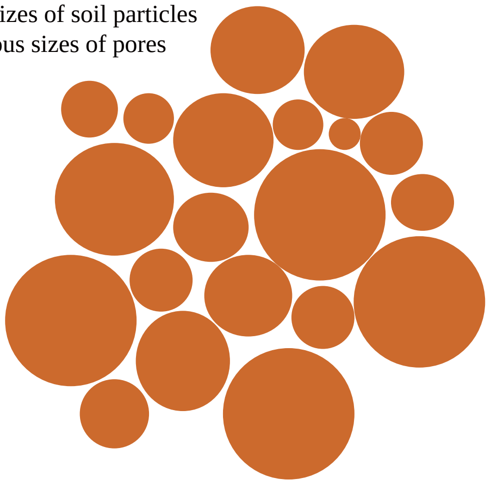
C Horizon

Forest soil is layered.

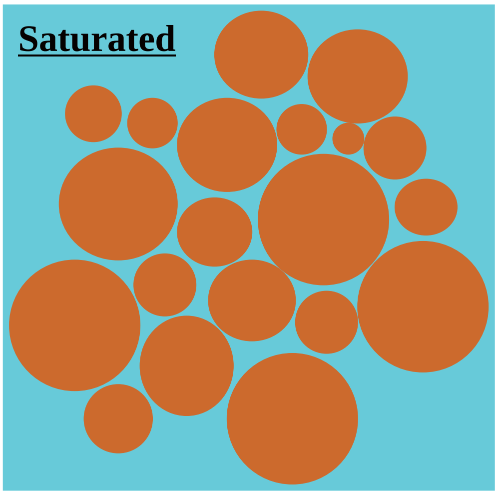
Schematic presentation of forest soil profile
(Ohta, 1996)

Schematic diagram of soil particles

Various sizes of soil particles
and Various sizes of pores



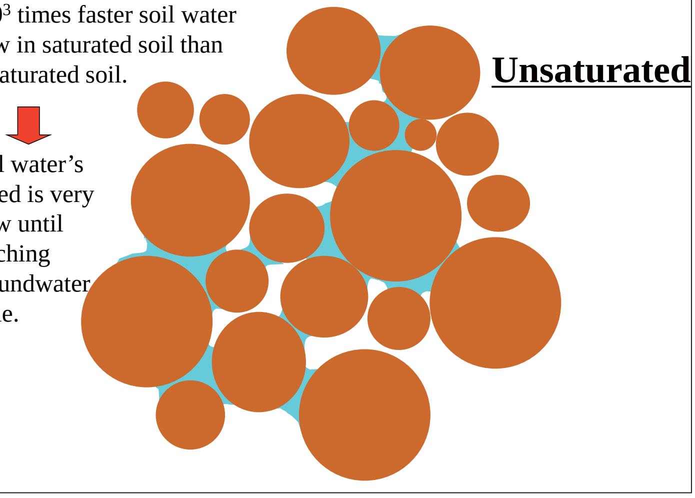
Schematic diagram of soil particles



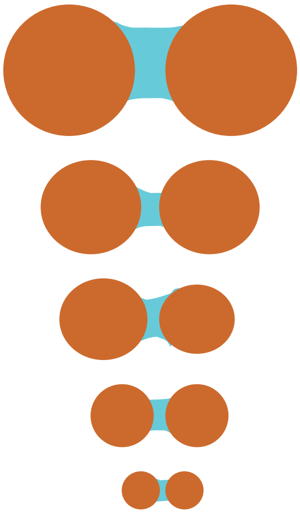
Schematic diagram of soil particles

~10^3 times faster soil water flow in saturated soil than unsaturated soil.

Soil water's speed is very slow until reaching groundwater table.



How soil water held within the cavity is extracted?



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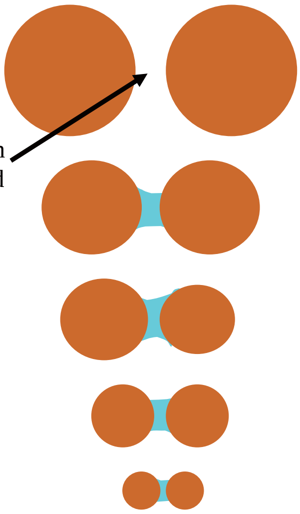

Soil water that can be easily extracted by gravity immediately after rainfall

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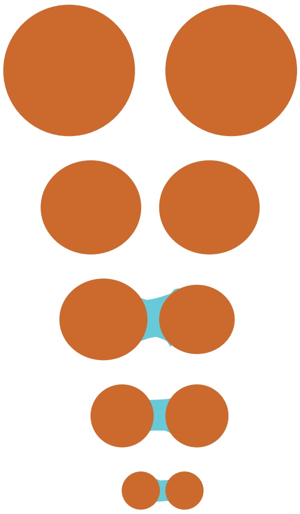
How soil water held within the cavity is extracted?



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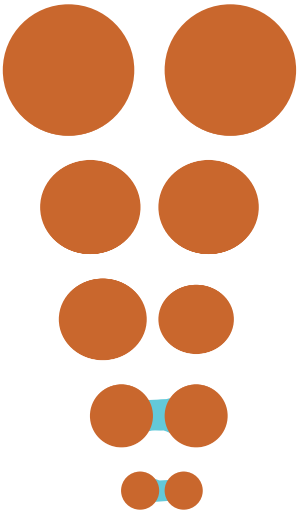
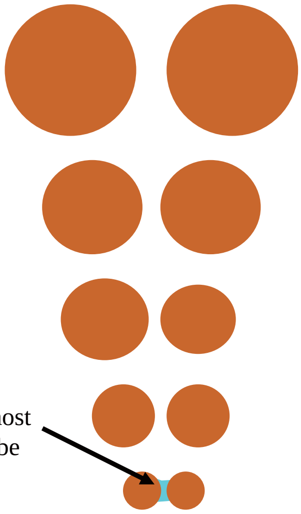
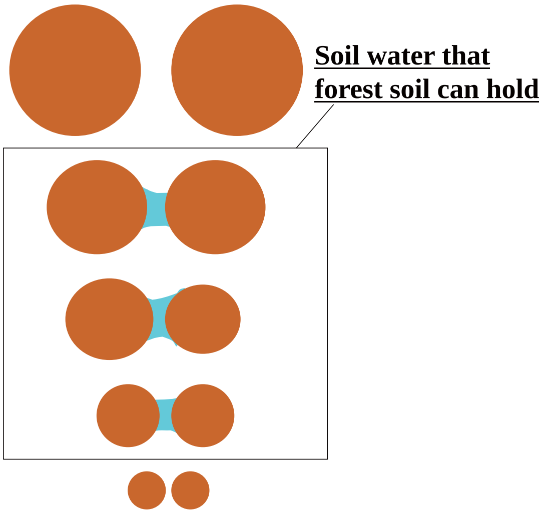


How soil water held within the cavity is extracted?



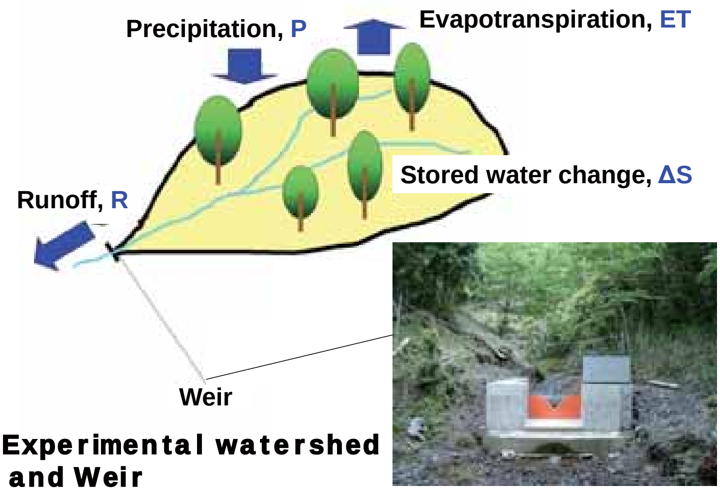
Soil water almost impossible to be extracted

How soil water held within the cavity is extracted?



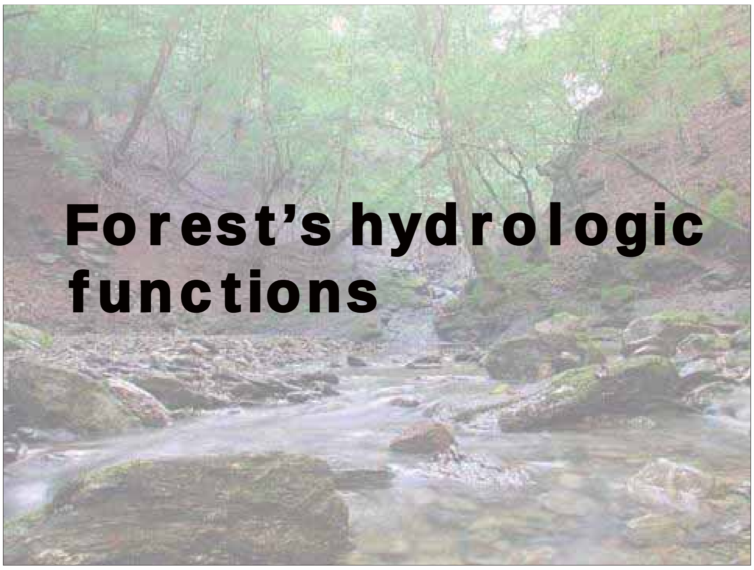
Soil water that forest soil can hold

③ Runoff from forest watershed

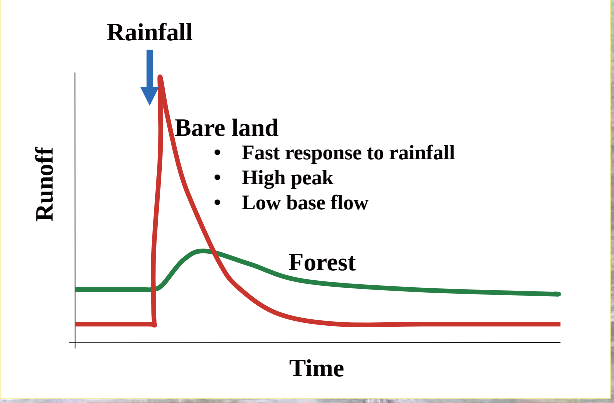


Experimental watershed and Weir

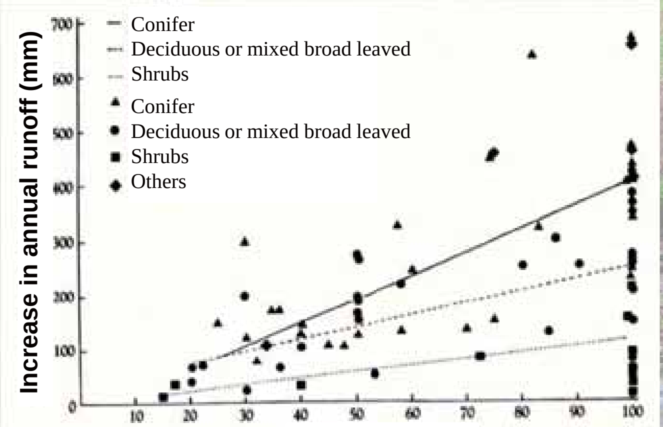
$$[R]=[P]-[ET]-[\Delta S]$$



Forest's hydrologic functions



Schematic presentation of runoff responding to rainfall

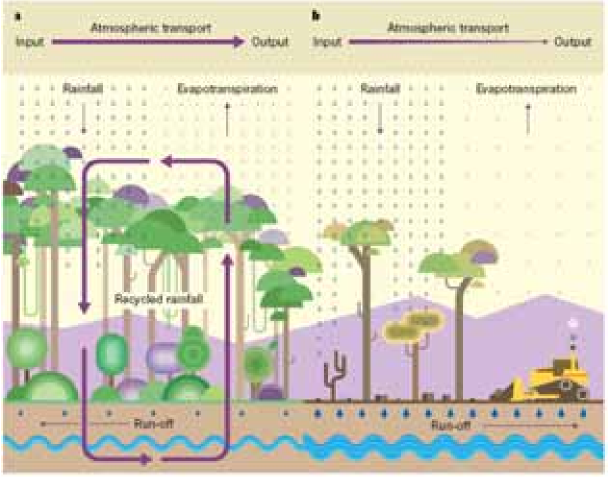


Increase in runoff with decreasing forest From Bosch and Hewlett (1982)

- Forests do not make water. Rather, they reduce it.
- Forests gently release water.
- There is runoff without rainfall.
- Forest looks like a dam, but

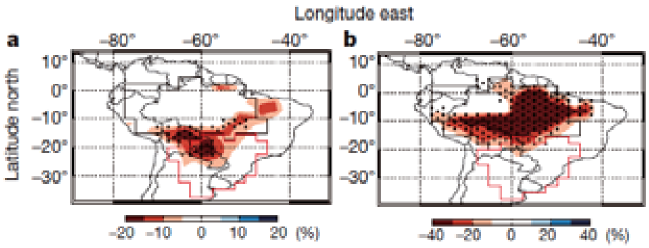
This is **conditional**.

Impact of deforestation on precipitation

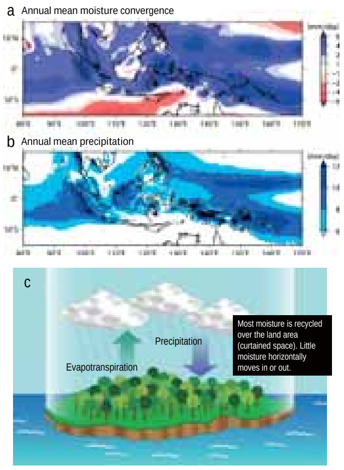


Aragao（2012）*Nature* 489, 217

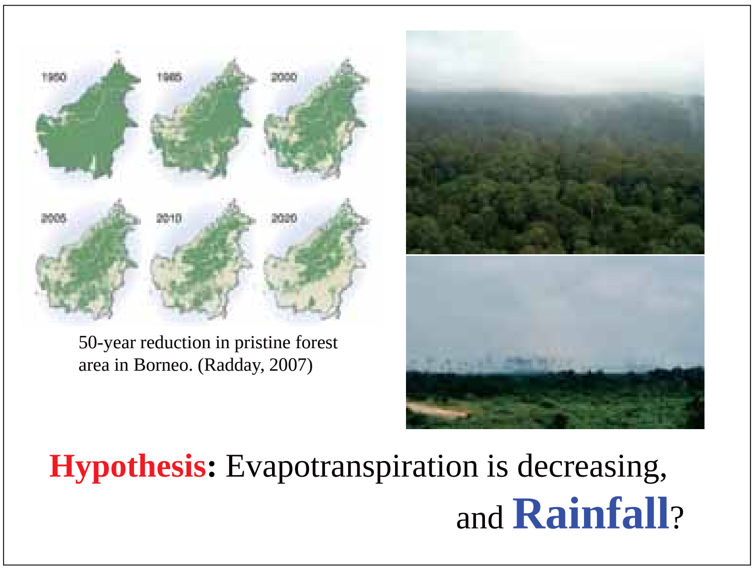
Impact of deforestation on precipitation



If the current status of deforestation in Amazon lasts for long years, how will the rainfall regime be?
Changes in the period 2000-2050. Black dots denote particular changes from the 1998-2010 rainfall.
a: Wet season and b: Dry season
(Spracklen et al. 2012, Nature 489, 282)

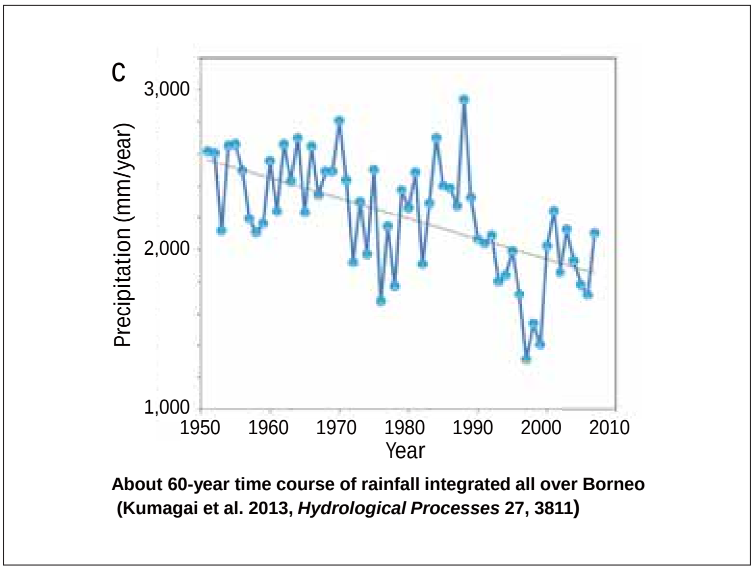


Plenty of rainfall despite little moisture convergence all over Borneo
← **Active rainfall recycling** from forest evapotranspiration
(Kumagai et al. 2013, *Hydrological Processes* 27, 3811)



50-year reduction in pristine forest area in Borneo. (Radday, 2007)

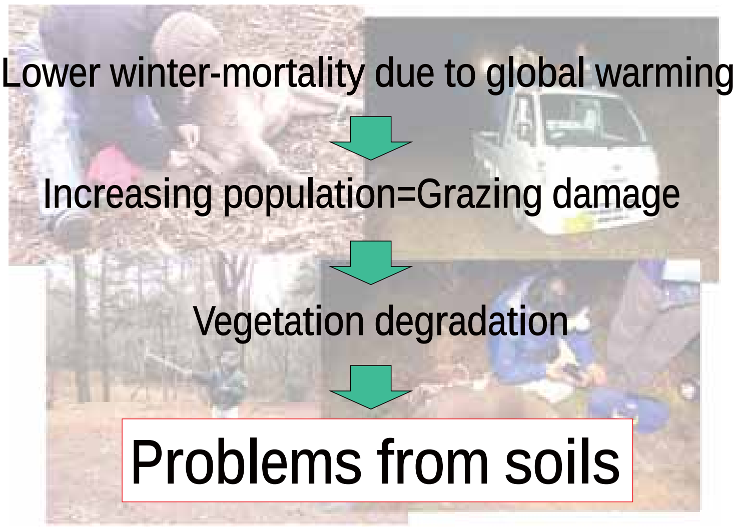
Hypothesis: Evapotranspiration is decreasing, and **Rainfall**?



About 60-year time course of rainfall integrated all over Borneo (Kumagai et al. 2013, *Hydrological Processes* 27, 3811)

Shiiba Research Forest, Kyushu University

Park-like landscape



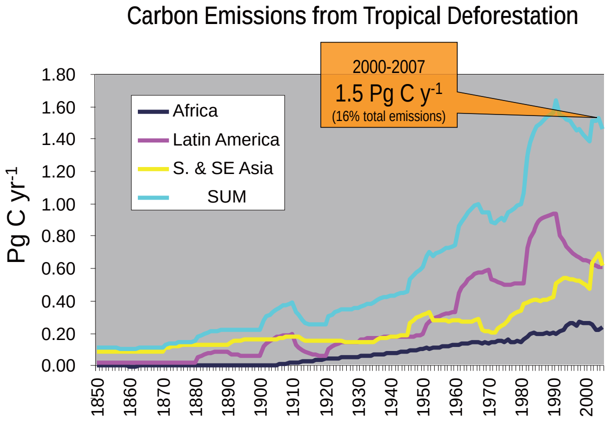
Lower winter-mortality due to global warming

Increasing population=Grazing damage

Vegetation degradation

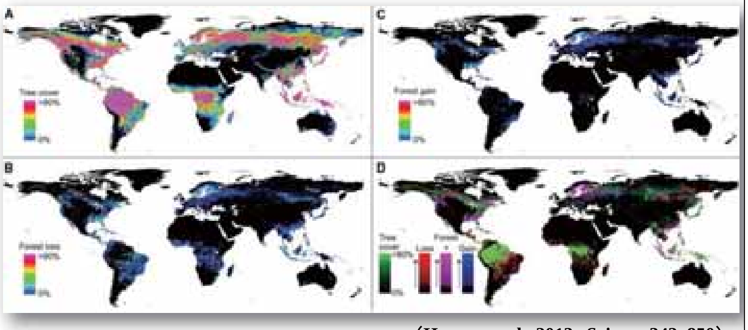
Problems from soils

Historical Emissions from Land Use Change



Canadell et al.（2009）“Carbon Budget 2007”

Changes in Forest Cover in 2000-2012

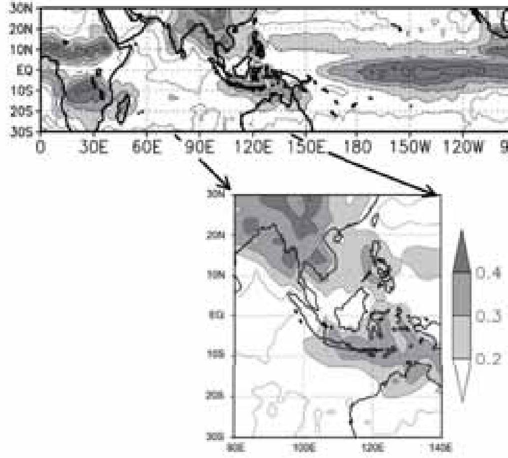


（**Hansen et al., 2013.** ***Science*** **342；850**）

Findings

1. Lost forests: 2.3million km^2; Established forests: 0.8million km^2 in 2000-2012. 0.2million km^2 experienced both processes (i.e., **forestry**).
2. Forest loss rate is increasing only in tropics (**2101 km^2/year**).
3. Tropical rainforests loss is **32 %** of the world forest loss.
4. South American tropical dry forest is lost at the highest speed in the lost tropical forests.
5. In tropical forests: forest loss rate in Brazil is decreasing (40000 km^2 in 2003-2004 to 20000 km^2 in 2010-2011). While, forest loss in Indonesia is drastically increasing (8000 km^2 in 2000-2001 to 20000 km^2 in 2010-2011). **Asian tropical forest loss wastes Brazilian efforts.**

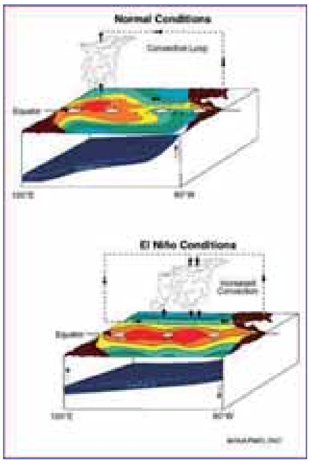
Seasonality: wet and dry seasons

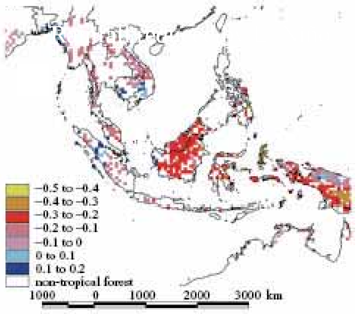


Seasonality is
↑**HIGH**
↓**LOW**

Kumagai *et al.* (2005) ***Agricultural and Forest Meteorology*** 128, 81–92

Inter-annual variation in rainfall



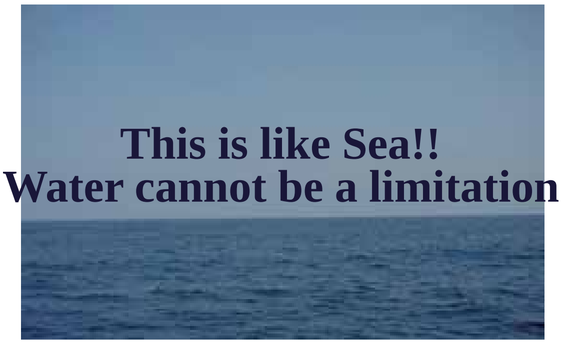


Malhi and Wright (2004)
***Phil. Trans. R. Soc. Lond.* B**, 359, 311–329

Transpiration cannot be affected by episodic soil moisture depletion, and is almost constant throughout year

in a Malaysian tropical rainforest:

Kumagai et al. (2005: ***Agricultural and Forest Meteorology***, 128, 81-92)
Kumagai et al. (2004: ***Journal of Hydrology***, 287, 237-251)



This is like Sea!!
Water cannot be a limitation.

Can this be applied to "SPECIAL DROUGHT?

M.Nakagawa et al.: Impact of severe drought associated with the 1997-1998 El Nino in a tropical forest in Sarawak (*J.Trop.Ecol.*, 16, 355, 2000)

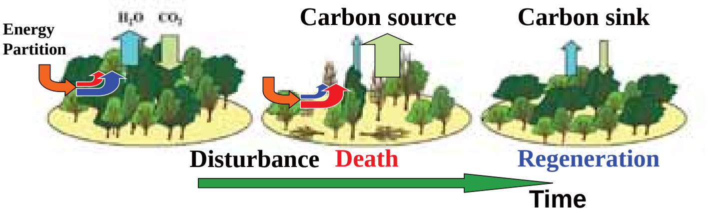
El Nino Effect; <u>Decrease in above-ground biomass</u>

1993-1996: 8.6 t/ha year **1997-2001: -4.5 t/ha year**

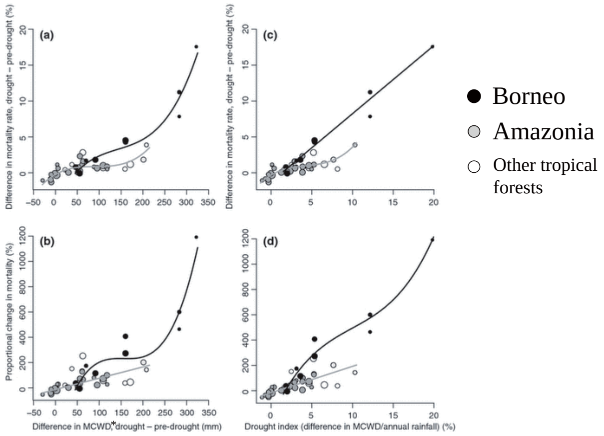
<u>Increase in mortality</u>

1993-1996: 0.89 %/year **1997-2001: 6.37-4.35 %/year**

NOTE!! Mortality of Dipterocarpaceae had 12-30 times in 1997-2001.

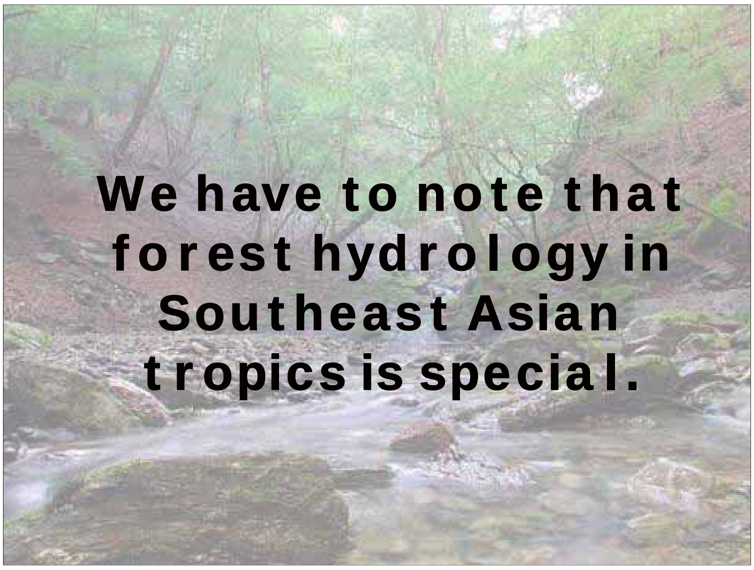


Mortality sensitivity to drought for Bornean and Amazonian forests



*MCWD, monthly cumulative water deficit.

（Phillips et al，2010. *New Phytol.* 187；631）



We have to note that forest hydrology in Southeast Asian tropics is special.

L2: Discharge from forested watershed (1)

- Forest role in stormflow responses in active tectonic regions with large storms -

Makoto Tani (*Graduate School of Agriculture*, *Kyoto University*)

Abstract

In an active tectonic region with large storms such as Pacific Rim, it is still difficult to predict stormflow responses by runoff models from the catchment properties without a parameter calibration using observational data. One of the key reasons for this difficulties is based on the structure of distributed runoff models. Based on classical simulations for hillslopes by Freeze (Water Resour. Res., 1972), the source of stormflow is usually considered as a saturation-excess overland flow (Beven and Kirkby, Hydrol. Sci. Bull, 1979) because of too small saturated hydraulic conductivity of the soil layer for subsurface flow. However, hillslope hydrology has demonstrated that preferential paths such as natural pipes could play an important role in the subsurface flow (Anderson et al., Water Resour. Res., 1997; Uchida et al., Hydrol. Process., 2003), and this quick downslope water movement with a quick wave-form transmission along the vertical infiltration (Tani, J. Hydrol., 1997;Montgomery & Dietrich, Water Resour. Res., 2002) strongly suggested the stormflow generation through the underground runoff processes.

Some portion of the rainwater is absorbed by the soil through the wetting-front advance (Tani, J. Hydrol., 1997) and deep percolated into the weathered bedrock (Kosugi et al., Water Resour. Res., 2006). Effective rainfall is then produced as the rest of these two rainwater distribution processes. After sufficient rainwater falls and exceeds the threshold, however, all the rainwater except the deep percolation can contribute to the stormflow, but this contribution may not occur as an overland flow but as a wave-form transmission in a hydraulic continuum created within the soil layer (Tani, Hydrol. Earth Syst. Sci., 2013).

Why can the soil layer function as the hydraulic continuum with preferential pathways? This may be explained only from a long-term process of the soil-layer evolution against strong erosional forces in the active tectonic regions with large magnitude storms. Runoff and erosional processes are closely linked. This link will be discussed in this lecture based on a comparison in the runoff and erosion processes between forested and denuded hillslopes, which was obtained from detailed field observations in a weathered granite mountain, Tanakami, in Shiga Prefecture, Japan (Suzuki and Fukushima, Suirikagaku, 1989). A new insight into the forest effect on the stormflow mitigation will be proposed from this discussion as a conclusion.

International Hydrological Programme
Forest Hydrology −Conservation of Forest, Soil, and Water Resources

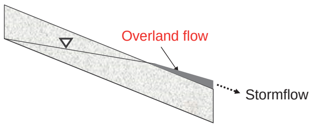
Discharge from forested watershed (1)

- Forest role in stormflow responses in active tectonic regions with large storms -

Makoto Tani
Graduate School of Agriculture
Kyoto University

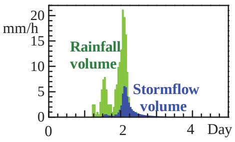
Superstitions for stormflow

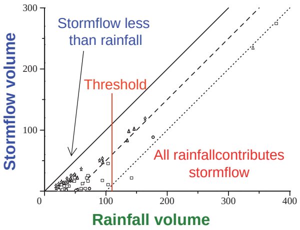
1 Overland flow is a main source for the stormflow



Maybe doubtful for steep mountains

2. Forest gives no influence on large-magnitude stormflow





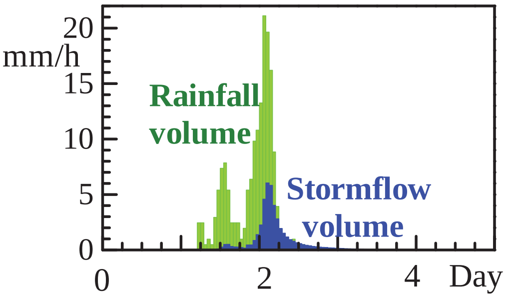
This talk consists of

1. Basic characteristics of stormflow response

2. Mechanism of stormflow response

3. Forest effects on the stormflow mitigation

Part 1 Basic characteristics of stormflow response

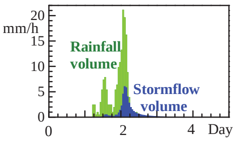


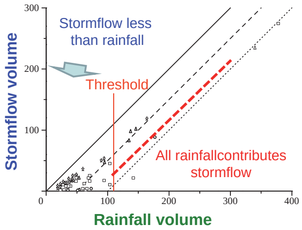
Allocation of rainwater to stormflow

Rainfall allocation to stormflow depends on the wetness and increases with rainfall

All the rainwater contributes to the stormflow after enough rainfall volume

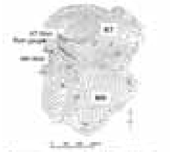
This looks like a limitation for the stormflow mitigation but needs careful consideration.....





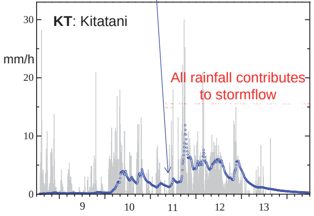
Stormflow response to rainfall in the wettest stage

During a large magnitude storm event,
all the rainfall contributes to stormflow
after the catchment become the wettest stage

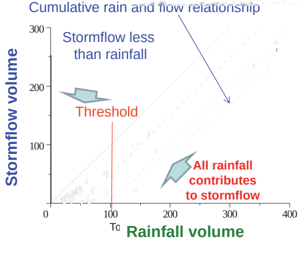


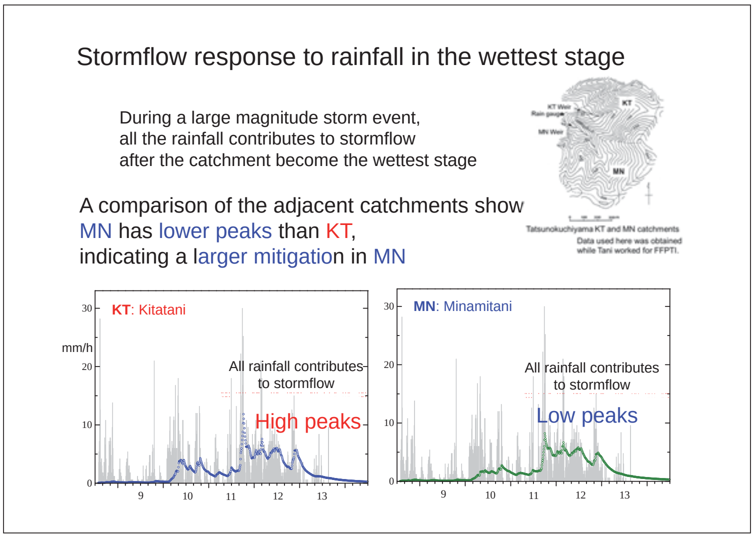
The same event of large magnitude storm

Temporal changes of rainfall and flow rate



Cumulative rain and flow relationship



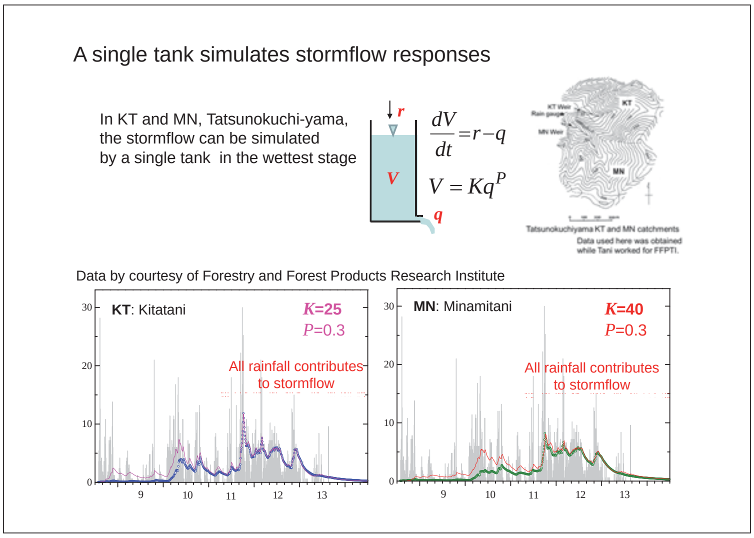


Stormflow response to rainfall in the wettest stage

During a large magnitude storm event,
all the rainfall contributes to stormflow
after the catchment become the wettest stage

A comparison of the adjacent catchments show
MN has lower peaks than KT,
indicating a larger mitigation in MN

Tatsunokuchiyama KT and MN catchments
Data used here was obtained while Tani worked for FFPTI.



A single tank simulates stormflow responses

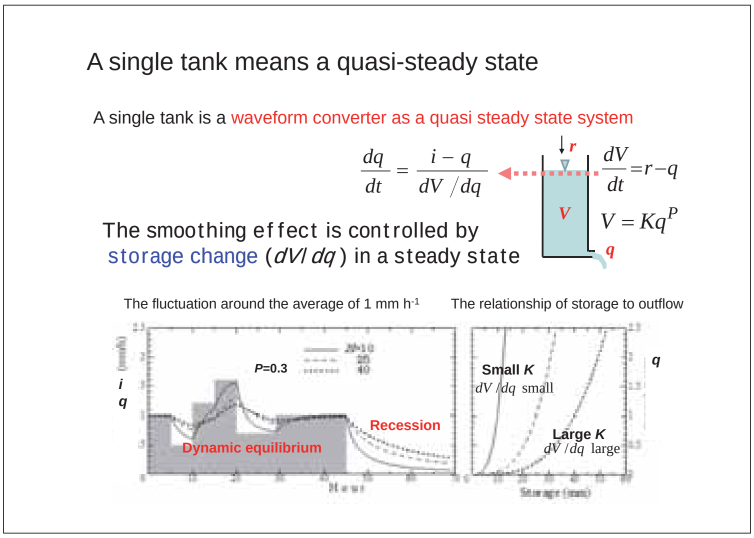
In KT and MN, Tatsunokuchi-yama,
the stormflow can be simulated
by a single tank in the wettest stage

$$\frac{dV}{dt}=r-q$$

$$V = Kq^P$$

Tatsunokuchiyama KT and MN catchments
Data used here was obtained while Tani worked for FFPTI.

Data by courtesy of Forestry and Forest Products Research Institute



A single tank means a quasi-steady state

A single tank is a waveform converter as a quasi steady state system

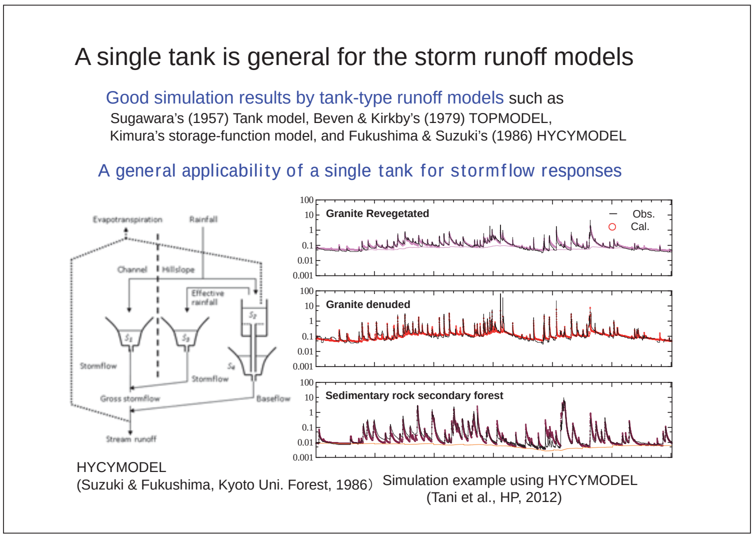
$$\frac{dq}{dt} = \frac{i-q}{dV\,/dq}$$

$$\frac{dV}{dt}=r-q$$

$$V = Kq^P$$

The smoothing effect is controlled by
storage change (dV/dq) in a steady state

The fluctuation around the average of 1 mm h^{-1} The relationship of storage to outflow



A single tank is general for the storm runoff models

Good simulation results by tank-type runoff models such as
Sugawara's (1957) Tank model, Beven & Kirkby's (1979) TOPMODEL,
Kimura's storage-function model, and Fukushima & Suzuki's (1986) HYCYMODEL

A general applicability of a single tank for stormflow responses

HYCYMODEL
(Suzuki & Fukushima, Kyoto Uni. Forest, 1986)

Simulation example using HYCYMODEL
(Tani et al., HP, 2012)

Part 1 Basic characteristics of stormflow response

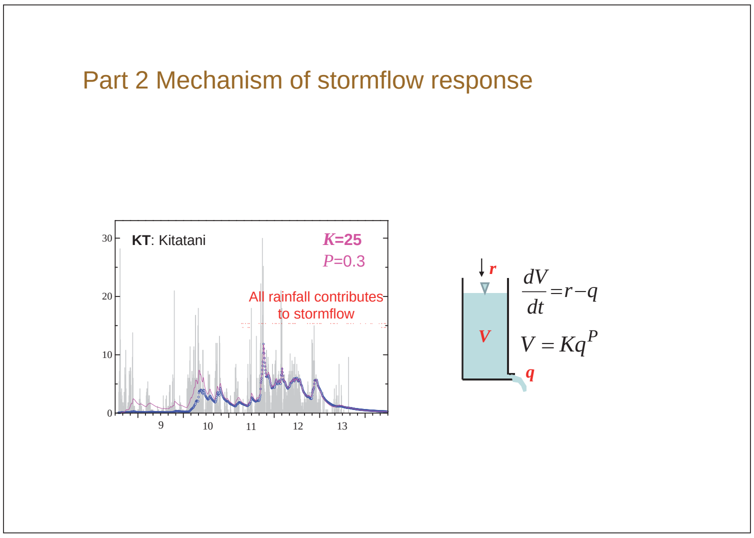
Summary

Soil absorption and deep percolation control
the rainwater allocation to stormflow

All the rainfall may contribute to stormflow
in the wettest stage

Stormflow can be simulated by a single tank

Storage change (dV/dq) makes flow smoothing



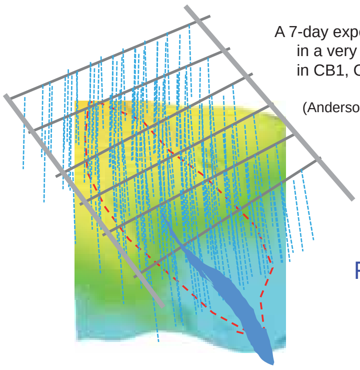
Part 2 Mechanism of stormflow response

$$\frac{dV}{dt}=r-q$$

$$V = Kq^P$$

Response to constant rainfall by the simulator

How does a zero-order catchment respond to a constant rainfall?



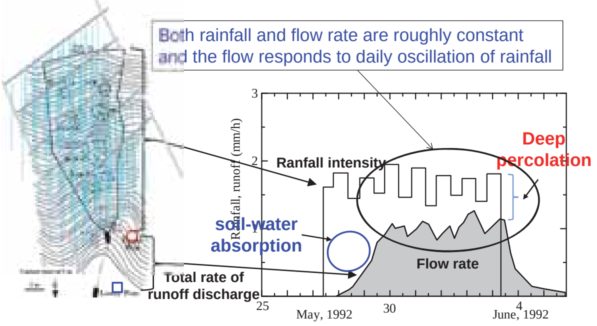
A 7-day experiment
in a very steep zero-oreder catchment
in CB1, Oregon, USA

(Anderson et al., Water Resour Res, 1997)

Result is………

Soil absorption and deep percolation for the loss

The allocated water is:
1) escaping **soil abosrption** in early days
2) escaping **deep percolation** in late days



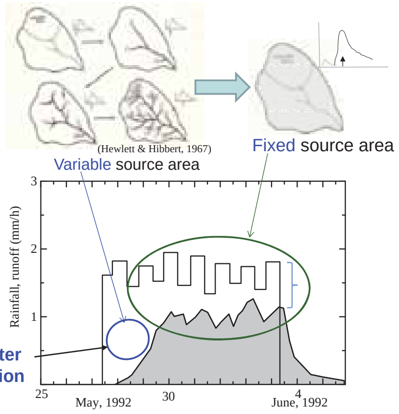
Both rainfall and flow rate are roughly constant and the flow responds to daily oscillation of rainfall

Anderson et al., Water Resour. Res.1997

Expansion of the stormflow source area

The area is small
nar the stream
in an early stage

The area expands
as rainfall increases
to the entire catchment

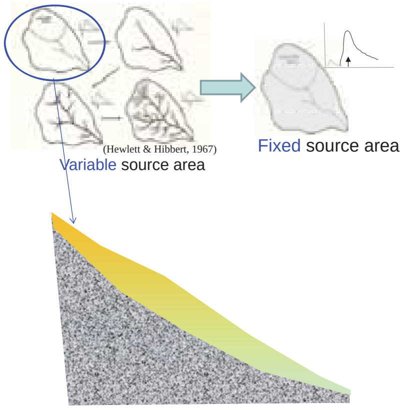


Soil-water absorption

Anderson et al., Water Resour. Res.1997

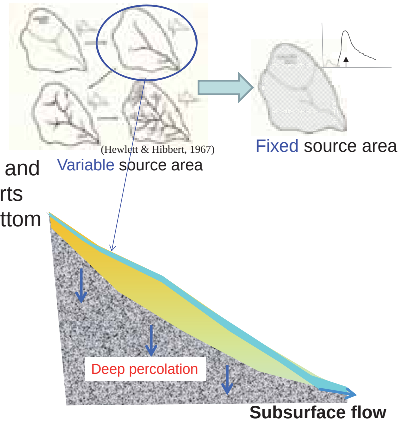
Mechanism of the source area expansion

The soil is dry
and no stormflow



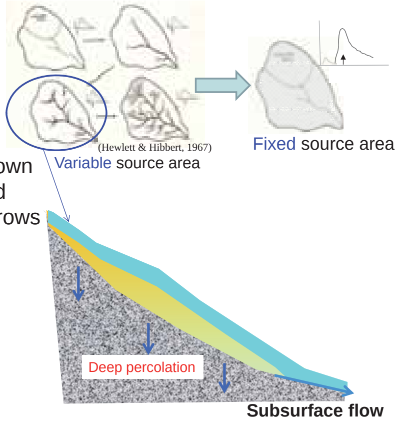
Expansion of the source area

Wet zone goes down and
subsurface flow starts
close to the slope bottom



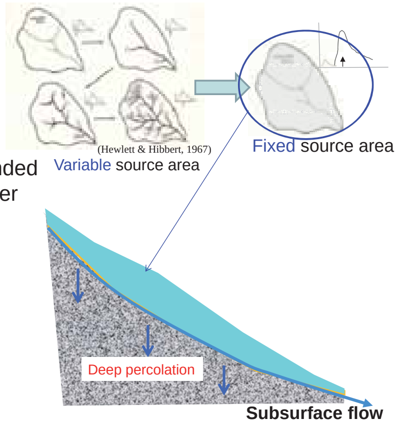
Expansion of the source area

The wet zone goes down
from the srface and
the subsurface flow grows
upslope



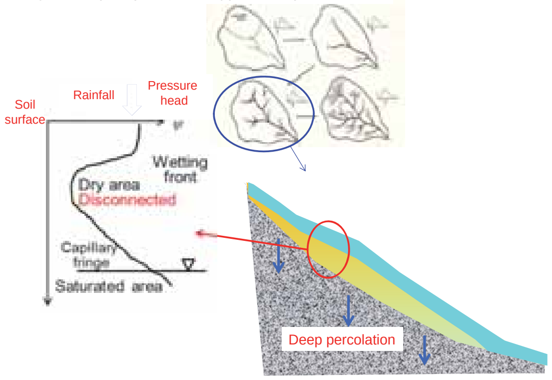
The fixed source area expanded to the entire area

The wet zone is expanded
to the entier soil layer



Wet zone connection contributes to stormflow

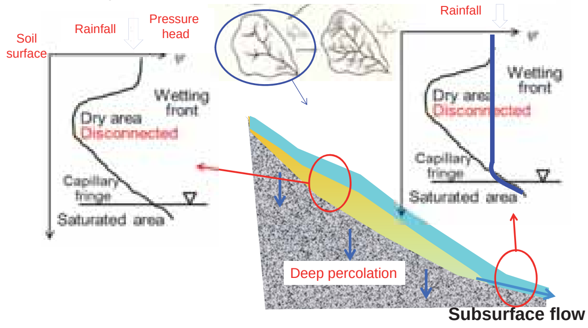
Dry zone (low permeability) intercepts the flow



Wet zone connection contributes to stormflow

Dry zone (low permeability) intercepts the flow

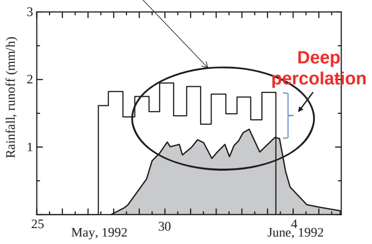
Unsarturated but wet zone grows down,
contributing to subsurface stormflow



Temporal flow response yields a mitigation

All rainwater except deep percolation contributes to stormflow,
but smoothing may remain as a mitigation

Both rainfall and flow rate are roughly constant
and the flow responds to daily oscillation of rainfall



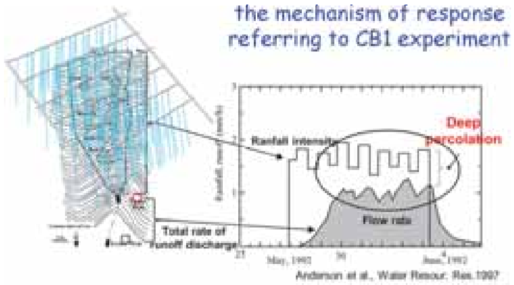
Anderson et al., Water Resour. Res.1997

Daily oscillation of rainfall and flow discharge

After the source area is fixed,

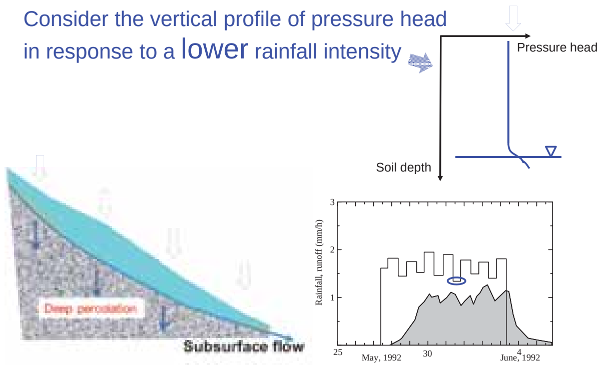
what mechanism functions for the flow response to rainfall?

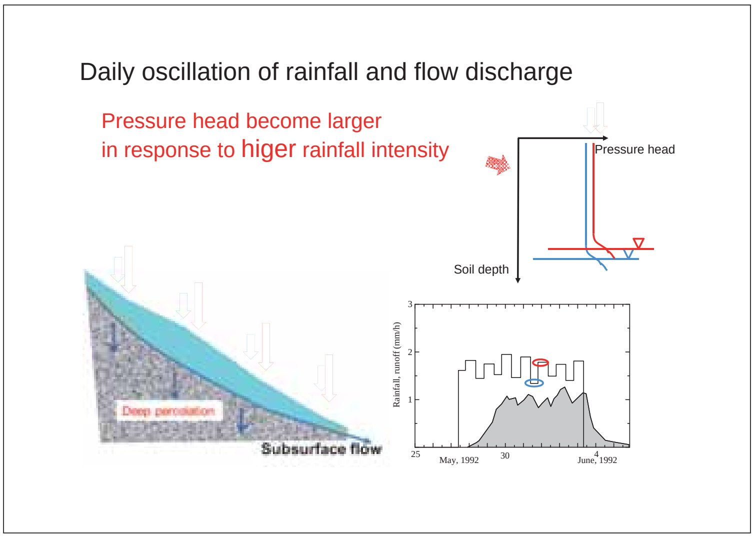
Let us investigate
the mechanism of response
referring to CB1 experiment



Daily oscillation of rainfall and flow discharge

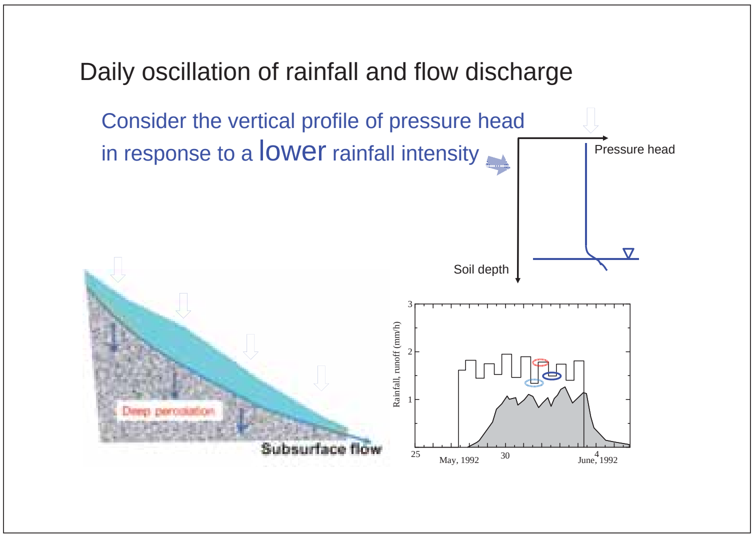
Consider the vertical profile of pressure head
in response to a lower rainfall intensity





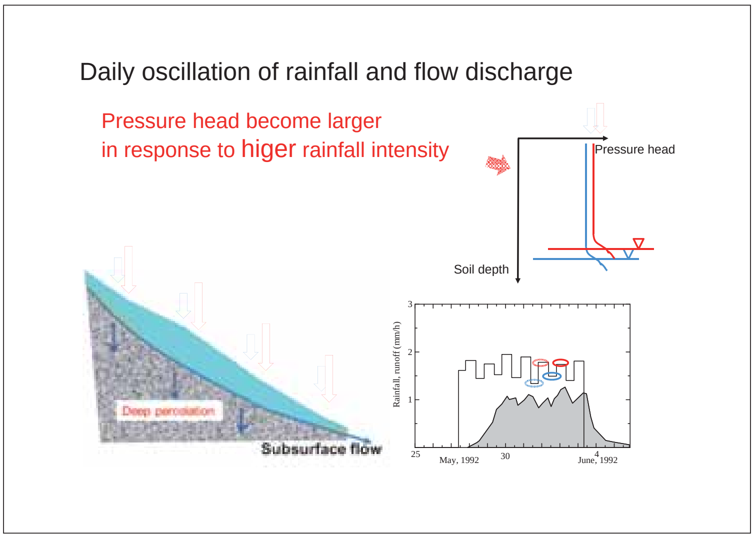
Daily oscillation of rainfall and flow discharge

Pressure head become larger
in response to higer rainfall intensity



Daily oscillation of rainfall and flow discharge

Consider the vertical profile of pressure head
in response to a lower rainfall intensity



Daily oscillation of rainfall and flow discharge

Pressure head become larger
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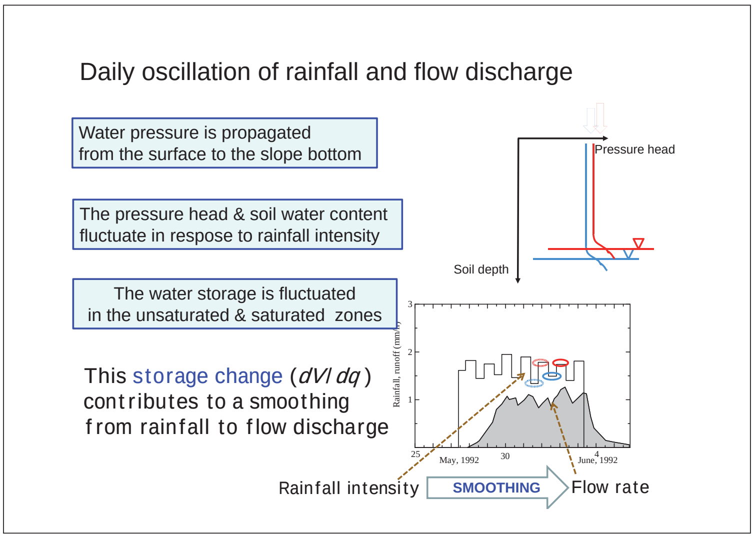


Daily oscillation of rainfall and flow discharge

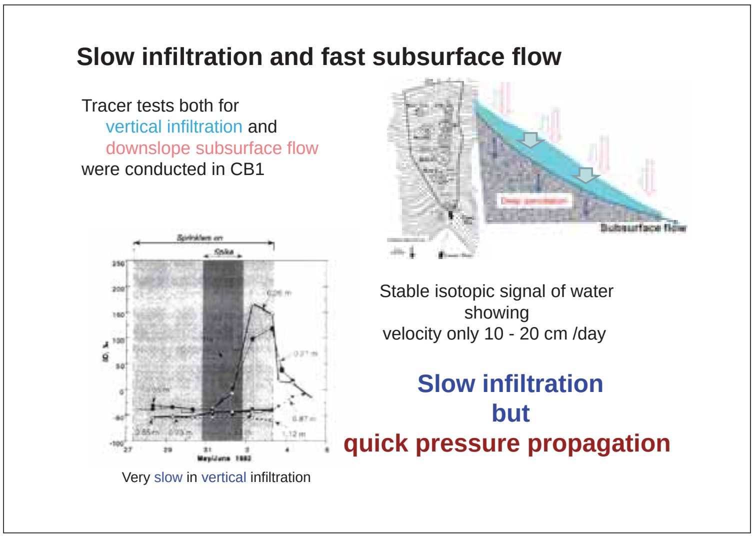
Water pressure is propagated
from the surface to the slope bottom

The pressure head & soil water content
fluctuate in respose to rainfall intensity

The water storage is fluctuated
in the unsaturated & saturated zones

This storage change (dV/dq)
contributes to a smoothing
from rainfall to flow discharge

Rainfall intensity **SMOOTHING** Flow rate



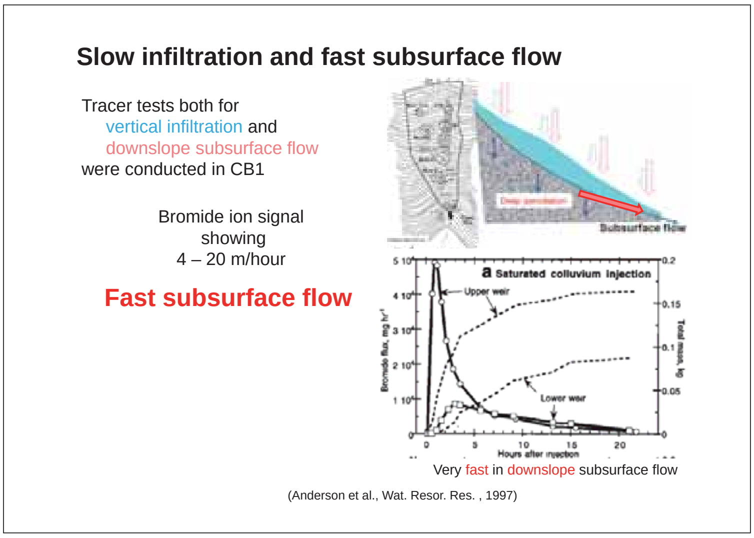
Slow infiltration and fast subsurface flow

Tracer tests both for
vertical infiltration and
downslope subsurface flow
were conducted in CB1

Stable isotopic signal of water
showing
velocity only 10 - 20 cm /day

Slow infiltration
but
quick pressure propagation

Very slow in vertical infiltration



Slow infiltration and fast subsurface flow

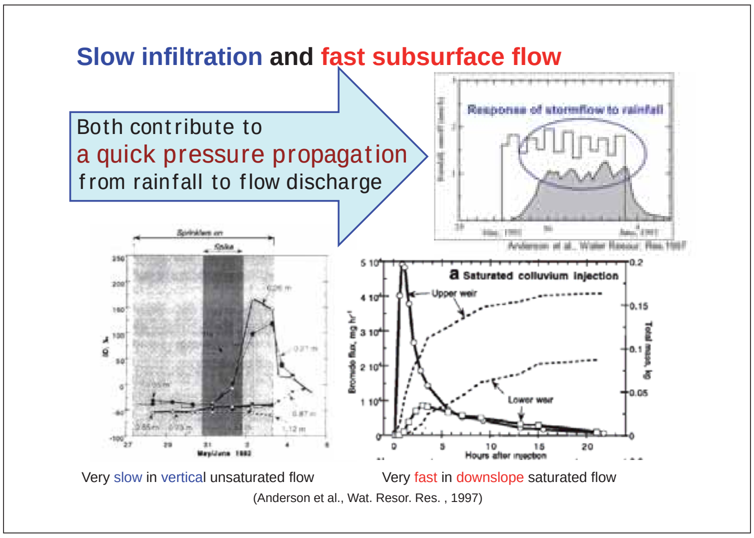
Tracer tests both for
vertical infiltration and
downslope subsurface flow
were conducted in CB1

Bromide ion signal
showing
4 – 20 m/hour

Fast subsurface flow

Very fast in downslope subsurface flow

(Anderson et al., Wat. Resor. Res. , 1997)



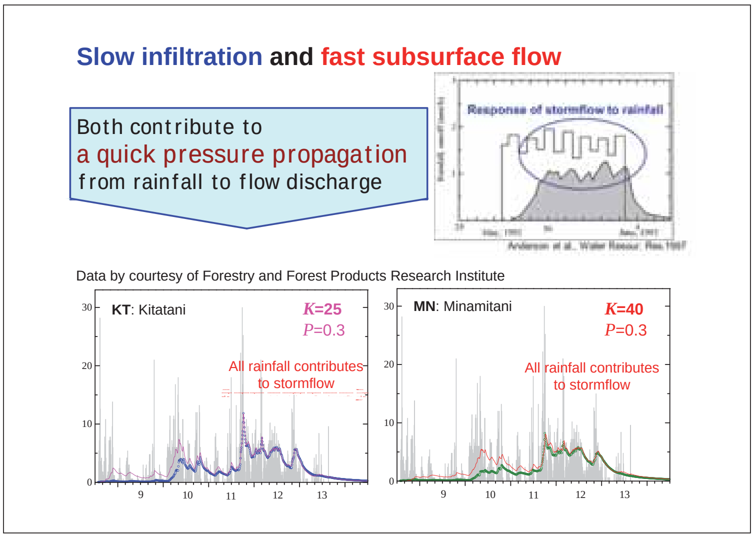
Slow infiltration and fast subsurface flow

Both contribute to
a quick pressure propagation
from rainfall to flow discharge

Very slow in vertical unsaturated flow

Very fast in downslope saturated flow

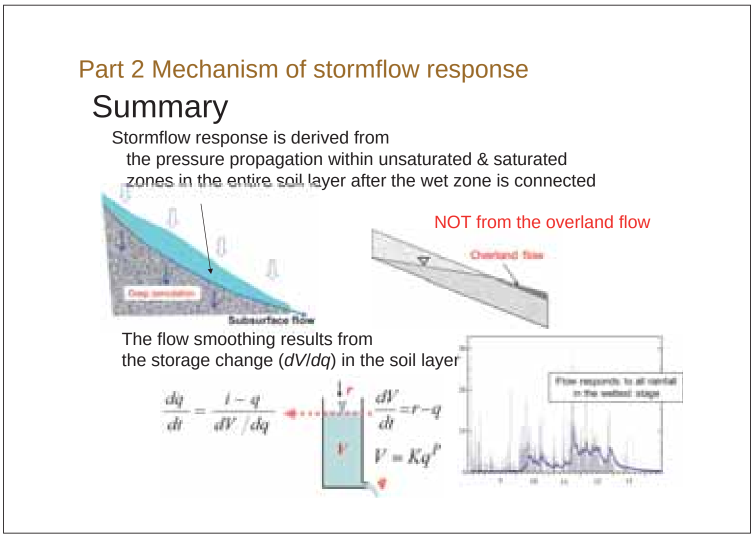
(Anderson et al., Wat. Resor. Res. , 1997)



Slow infiltration and fast subsurface flow

Both contribute to
a quick pressure propagation
from rainfall to flow discharge

Data by courtesy of Forestry and Forest Products Research Institute



Part 2 Mechanism of stormflow response

Summary

Stormflow response is derived from
the pressure propagation within unsaturated & saturated
zones in the entire soil layer after the wet zone is connected

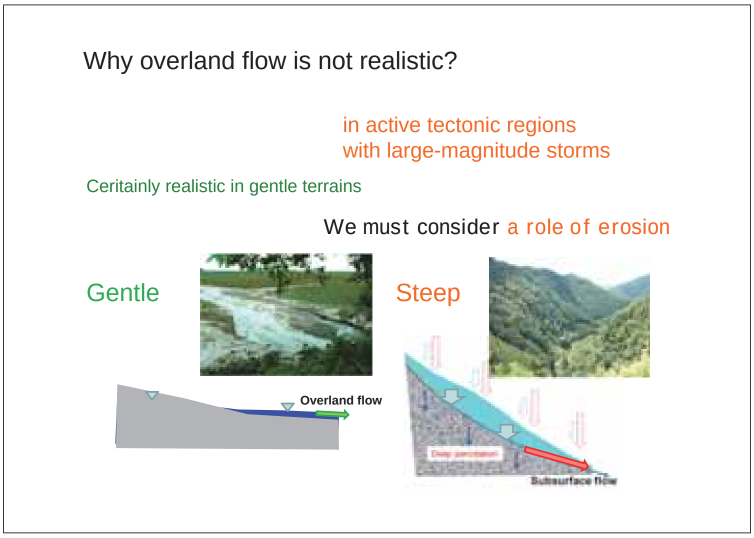
NOT from the overland flow

The flow smoothing results from
the storage change (*dV*/*dq*) in the soil layer

$$\frac{dq}{dt} = \frac{r-q}{dV/dq} \qquad \frac{dV}{dt} = r - q \qquad V = Kq^P$$

Part 3 Forest effects on the stormflow mitigation

in active tectonic regions
with large-magnitude storms



Why overland flow is not realistic?

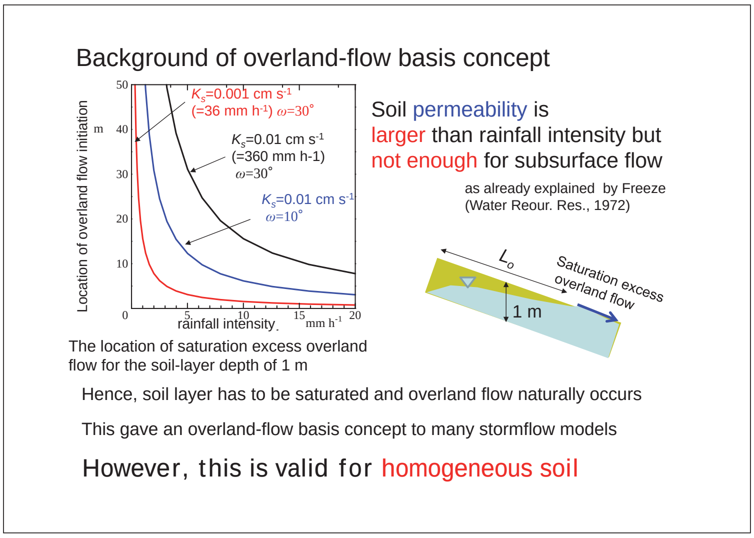
in active tectonic regions
with large-magnitude storms

Ceritainly realistic in gentle terrains

We must consider a role of erosion

Gentle

Steep



Background of overland-flow basis concept

Soil permeability is
larger than rainfall intensity but
not enough for subsurface flow

as already explained by Freeze
(Water Reour. Res., 1972)

The location of saturation excess overland flow for the soil-layer depth of 1 m

Hence, soil layer has to be saturated and overland flow naturally occurs

This gave an overland-flow basis concept to many stormflow models

However, this is valid for homogeneous soil

Long-term evolution results in heterogeneities

The soil layer was naturally evolved over hundreds years
against severe erosion force

NOT made in a couple of days by a worker

Homogeneous slope produces saturation overland flow

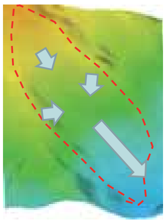
Heterogeneous slope

Let us the history of soil layer evolution

Soil and water move in a zero order catchment

Look at a zero order catchment (important in geomorphological evolution)

(Tsukamoto, Journal of the Japan Society of Erosion Control Engineering, 1974)



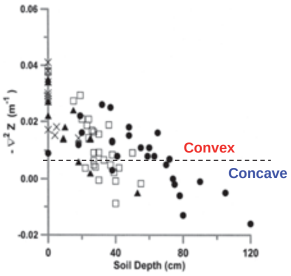
Soil produced from the weathered bedrock moves into the hollow

Water also moves into the hollow during storms

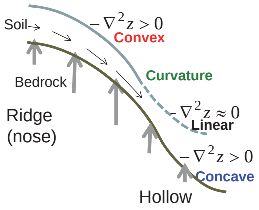
Soil movement by the gravity force consists of
two categories as ....

Soil creep near ridge (category No. 1)

Near ridge (nose), soil depth depends on the curvature
accounts for a diffusive transportation by soil creep

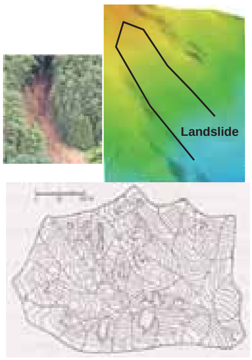


Hemsath et al., Geomorphology, 1999



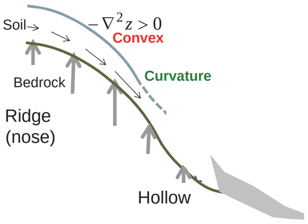
However, soil depth
increases infinitely
in a hollow

Landslide in hollow (category No. 2)



(Tsukamoto, Journal of the Japan Society
of Erosion Control Engineering, 1978)

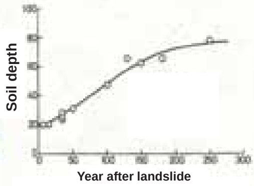
Soil cumulated in a concave hollow
is removed by landslide occurrences



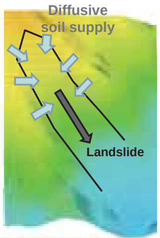
Landslide occurs in hollows
not in other topographic zones

Collaboration of two-type soil movements

Soil-layer evolution after a landslide in a hollow is
supported by soil supply from the ridge by creep



(Shimokawa, Proceeding of Symposium on
Effects of Forest Land Use on Erosion and
Slope Stability, 1984)



Landslide ocasionally occurs in response to a large storm
but creep gurantees the soil-layer evolution

The collaboration owing to vegetation

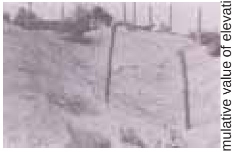
A long-term observation in a denuded slope in a granite mountain,
Shiga Prefecture near Kyoto, Japan, gives the evidence

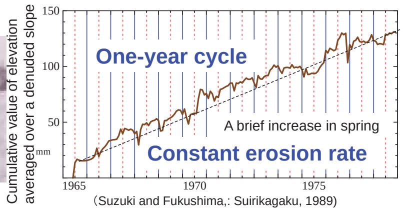
by Suzkuki and Fukushima

（Suzuki and Fukushima, International Syposium on Erosion, Debris Flow and Disaster Prevention, 1985)

Soil movement in a denuded slope

Long term observation on the micro topography on a denuded slope shows





（Suzuki and Fukushima,: Suirikagaku, 1989)

A freezing-thawing process in spring detached soil particles, causing the annual constant rate of soil erosion

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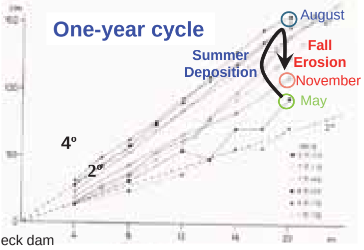
Stream erosion

Deposit behind a check dam also measured

Summer

Fall



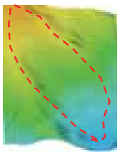
One-year cycle of the sand deposit behind a check dam

The deposit increased by soil inflow from the slope in summer and decreased by erosion in fall due to no soil inflow.

Soil moves as one-year cycle without vegetation

Importance of root network

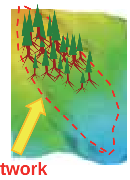
Without vegetation



Soil produced from the bedrock is constantly transported downstream
Soil stay no longer than one year on the slope

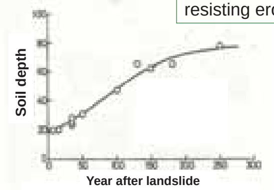
With vegetation

Kitahara, Suirikagaku, 2010



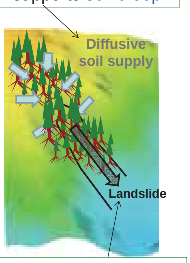
Soil remains on the slope supported by the root network
Soil layer evolves after a landslide for over hundreds years
till an occurrence of the next landslide

Two-type soil movements supported by root system



(Shimokawa, Proceeding of Symposium on Effects of Forest Land Use on Erosion and Slope Stability, 1984)

Soil aggregation by the root network resisting erosion supports soil creep



Shear strength enforced by the root network decreasing landslide frequency supports soil-layer evolution

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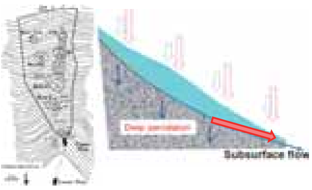
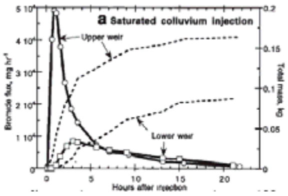
Remember fast subsurface flow

Tracer tests both for
vertical infiltration and
downslope subsurface flow
were conducted in CB1

Bromide ion signal
showing
4 – 20 m/hour





Very fast in downslope subsurface flow

Fast subsurface flow
inhibits watertable rise

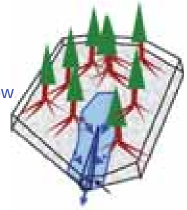
Not only root networks
but also this fast flow
contributes to soil-layer evolution
against erosion forces during storms

(Anderson et al., Wat. Resor. Res. , 1997)

Reduction of overland flow by pipe in a hollow

Overland flow may accelerate both the surface erosion and landslide,

The development of pipe network along the hollow is responsible to the soil layer evolution in active tectonic regions



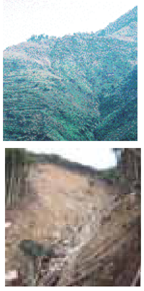
Fast subsurface flow
inhibits watertable rise

Not only root networks
but also this fast flow
contributes to soil-layer evolution
against erosion forces during storms

Long-term evolution results in heterogeneities

Simultaneous evolutions of
soil layer and pipe drainage creates
perfectly different spatial characters
from a manmade soil layer

Homogeneous slope
artificially made in **a few days**



Heterogeneous slope
naturally created over **hundreds of years**
Under tectonic uplift and erosion force

Part 3 Forest effects on the stormflow mitigation

Summary

Soil layer evolution and landslide are repeated
in active tectonic regions with large-magnitude storms

Soil movement on a forest slope consists of
creep near the ridge and landslide in the holow

A comparison with a denuded slope demonstrates
a role of forest root netowork in the soil layer evolution

The soil layer evolution is also supported by
fast subsurface flow through pipes in a hollow

Long-term evolution of soil layer with forest
creates the stormflow mitigation

Answer to superstitions

1 Overland flow is a main source for the stormflow

This is not true
Water pressure propagation
within unsaturated zone (vertical infiltration)
and saturated zones (subsurface flow)
produce the stormflow responses

2. Forest gives no influence on large-magnitude stormflow

This is not true
Stormflow responses as the water pressure propagation
are responsible for the soil layer evolution
supported by the root network as well as pipe drainage

CONCLUSION

Rainfall stormflow response can be simulated by a sigle tank

This response is explained by the pressure propagation in the soil layer

Soil layer evolution is supported by the root network and fast
subsurface flow, and responsible for stormflow responses

Long-term evolution of soil layer accompanied with forest
causes the stormflow mitigation
in active tectonic regions with large magnitude storms
such as Pacific Rim

MESSAGE for hazards on soil and water

Movements of soil and water by gravity force are inevitable
due to strong erosional environment in active tectonic regions

Long-term cycle by soil evolution and landslide is derived
from an intraction of forest resilience against this environment

Forest management considering the balance of use and conservation
plays a key role even during large-magnitude storms

Comprehensive land-use strategy is important because
forest use, housing project, erosion control work, and evacuation planning
are closely corelated each other

L3 : Discharge from forested watershed (2)

Ken'ichirou KOSUGI (*Graduate School of Agriculture, Kyoto University*)

Abstract

Understanding a discharge hydrograph is one of the leading interests in catchment hydrology. Recent research has provided credible information on the importance of bedrock groundwater on discharge hydrographs from headwater catchments. However, intensive monitoring of bedrock groundwater is rare in mountains with steep topography. Hence, how bedrock groundwater controls discharge from a steep headwater catchment is in dispute. This lecture introduces results of long-term hydrological observations using densely located bedrock wells in a headwater catchment. We demonstrate that understanding regionalized bedrock aquifer distribution is pivotal for explaining discharge hydrograph from headwater catchments.

Then, distributed hydrological models, which calculate topographically-driven rainwater movement within a catchment, are explained. The models are combined with mechanical analyses of slope stability, producing spatial and temporal variations in safety factors against slope failures. The models have been used as practical tools in real-time warning systems for shallow landslide and debris flow hazards. In this lecture, we examine accuracies and limitations of one of these models, by using hydrological data obtained through intensive observations conducted at a head-water catchment. The model succeeded in predicting decreases in safety factors at some past landside locations, where topographically-driven rainwater convergences were computed. However, for some past landslides, which were located in downstream regions along the main hollow of the catchment, the model failed to detect decreases in the safety factor. As a result, rainwater convergence by bedrock groundwater exfiltration was suggested to be one of the controlling factors for the occurrences of these landslides.

Groundwater, which is formed in a soil mangle as well as in a bedrock layer, is reported to be one of the main factors governing discharge from watersheds and occurrences of landslides. In the last part of this lecture, a simple functional model is introduced, which correlate antecedent precipitation indices (APIs) to groundwater level changes caused by rainwater infiltration. Performances of the model are examined by using hydrological data observed at 25 locations with various geological settings. Then, based on the model, a new method is proposed for evaluating slope failure vulnerability in steep mountainous regions. The method has a potential to establish credible warning and evacuation systems against landslide and debris flow disasters.

International Hydrological Program
Forest Hydrology –Conservation of Forest, Soil, and Water Resources
The Twenty-fourth IHP Training Course
23 November - 7 December, 2014
Nagoya, Japan

L3 : Discharge from forested watershed (2)

Ken'ichirou KOSUGI
Graduate School of Agric.
Kyoto Univ.
& JST CREST

CREST

Introduction

Understanding of rainwater movement in headwater catchment is essential for
- ➢ Water resources exploitation
- ➢ Flood and landslide mitigations
- ➢ Ecosystem management

Various hydrological models have been proposed and used
→ topography and soil thickness distribution (i.e., TOPMODEL)

For some catchments, performances of such models are unsatisfactory

This lecture demonstrates importance of bedrock groundwater for hydrological processes in headwater catchments

---

In Japan, mountains cover 73% of the national landmass

Annual precipitation is 1,700 mm

A lot of rain/snow water is stored in mountainous regions

It helps us to develop rich life and culture related to water

---

Water stored in mountains sometimes trigger enormous landslides which cause huge damages

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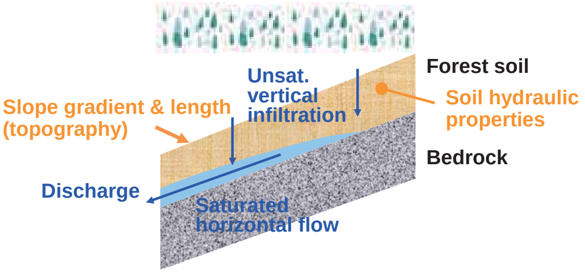
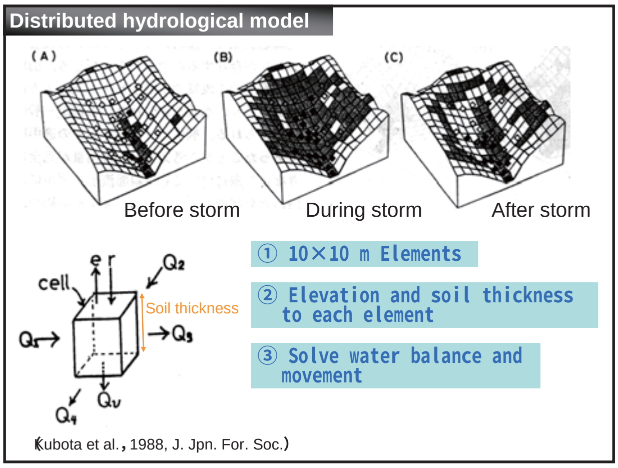
Water flow in hillslope

Yoshimatsu in Kagoshima Pref. (Photo by Prof. Jitousono)

Rainwater movement in hillslope





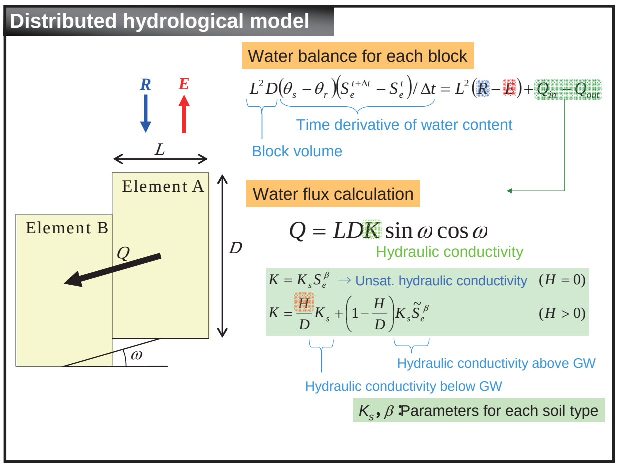
Distributed hydrological model

① 10×10 m Elements

② Elevation and soil thickness to each element

③ Solve water balance and movement

(Kubota et al., 1988, J. Jpn. For. Soc.)



Distributed hydrological model

Water balance for each block

$$\underbrace{L^2 D}_{\text{Block volume}}\underbrace{(\theta_s-\theta_r)(S_e^{t+\Delta t}-S_e^t)/\Delta t}_{\text{Time derivative of water content}}=L^2(R-E)+Q_{in}-Q_{out}$$

Water flux calculation

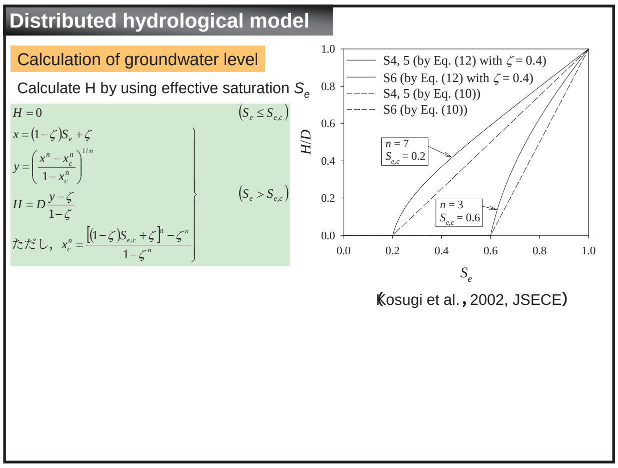
$$Q = LDK\sin\omega\cos\omega$$

Hydraulic conductivity

$K = K_s S_e^{\beta}$ → Unsat. hydraulic conductivity $(H=0)$

$$K=\underbrace{\frac{H}{D}K_s}_{\text{Hydraulic conductivity below GW}}+\left(1-\frac{H}{D}\right)\underbrace{K_s\tilde{S}_e^{\beta}}_{\text{Hydraulic conductivity above GW}} \qquad (H>0)$$

K_s, β :Parameters for each soil type



Distributed hydrological model

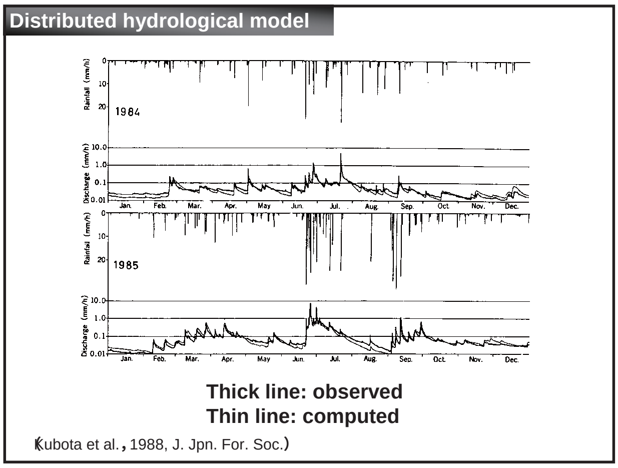
Calculation of groundwater level

Calculate H by using effective saturation S_e

$$H=0 \qquad (S_e \le S_{e,c})$$

$$\left.\begin{aligned} x&=(1-\zeta)S_e+\zeta\\ y&=\left(\frac{x^n-x_c^n}{1-x_c^n}\right)^{1/n}\\ H&=D\frac{y-\zeta}{1-\zeta}\\ \text{ただし，}\ x_c^n&=\frac{[(1-\zeta)S_{e,c}+\zeta]^n-\zeta^n}{1-\zeta^n}\end{aligned}\right\} \qquad (S_e > S_{e,c})$$

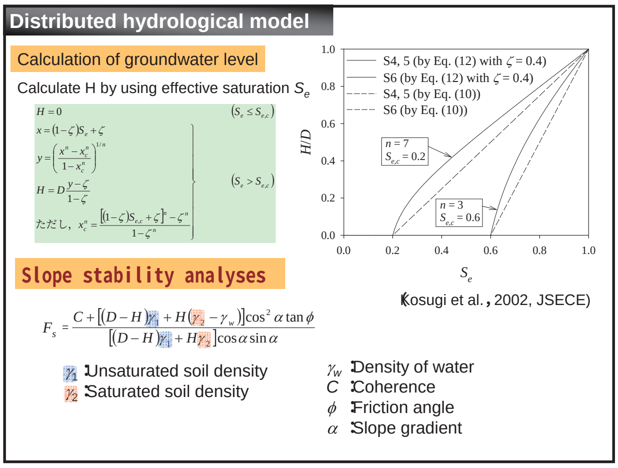
(Kosugi et al., 2002, JSECE)



Distributed hydrological model

Thick line: observed
Thin line: computed

(Kubota et al., 1988, J. Jpn. For. Soc.)



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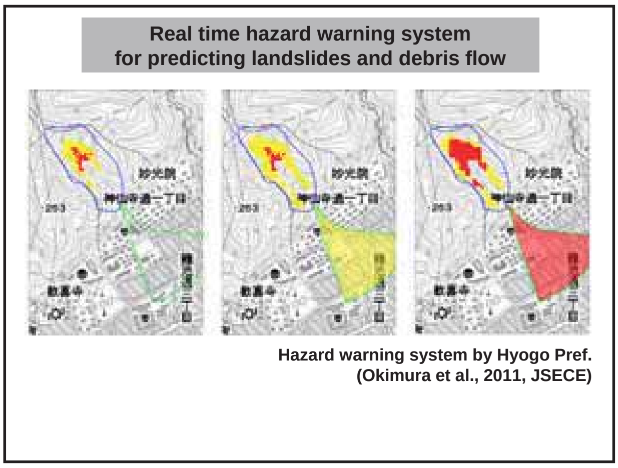
(Kosugi et al., 2002, JSECE)

Slope stability analyses

$$F_s=\frac{C+[(D-H)\gamma_1+H(\gamma_2-\gamma_w)]\cos^2\alpha\tan\phi}{[(D-H)\gamma_1+H\gamma_2]\cos\alpha\sin\alpha}$$

γ_1 :Unsaturated soil density
γ_2 :Saturated soil density

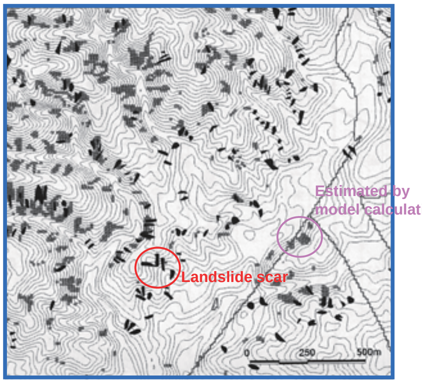
γ_w :Density of water
C :Coherence
ϕ :Friction angle
α :Slope gradient



Real time hazard warning system for predicting landslides and debris flow

Hazard warning system by Hyogo Pref.
(Okimura et al., 2011, JSECE)

Accuracy
> 90%



Estimation results of landslides caused by a huge storm in 1967

(Okimura et al., 2011, JSECE)

Study area

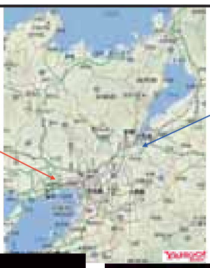
Sumiyoshi watershed
Area :14 km^2
Elevation :100-931 m

Headwater-scale
Q1 watershed

Area :2.10 ha
Gradient :35 °
Soil depth :1.4 m

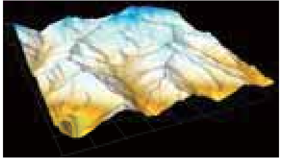
Comparison between two WS

Granitic bedrock



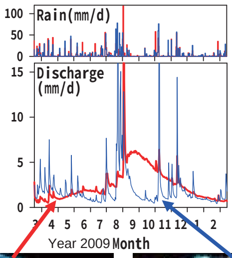
Q1 watershed
Area :2.10 ha
Gradient :35 °
Soil depth :1.4 m

K watershed
Areal: 5.99 ha
Gradient: 12 °
Soil depth:1.5 m



Comparison between two WS

Granitic bedrock



Q1 watershed
Area :2.10 ha
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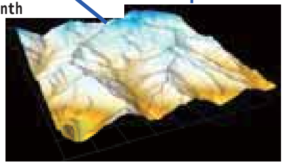
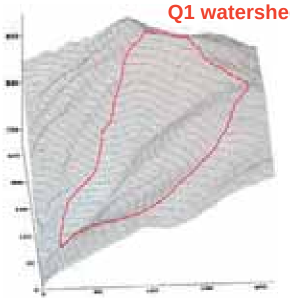
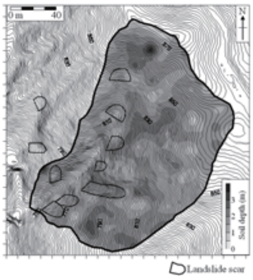


Topography and soil thickness distribution

Q1 watershed





(Kosugi et al., 2012, JSECE)

Distributed hydrological model

81 runs of model calculations with different parameter sets

Table 1 Maximal, average, and minimal values of parameters used in distributed hydrological model

	θ_e	K_s(cm/s)	β	$S_{e,c}$
Max.	0. 47	0. 25	7	0. 6
Ave.	0. 33	0. 05[1]	5	0. 4
Min.	0. 19	0. 01	3	0. 2

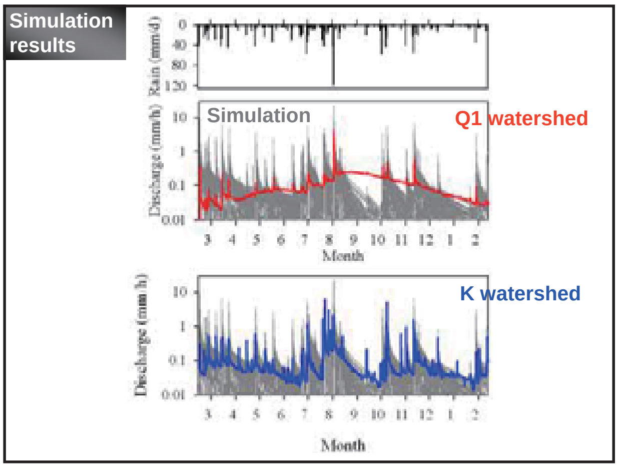
1) Geometric mean

(Kosugi et al., 2012, JSECE)

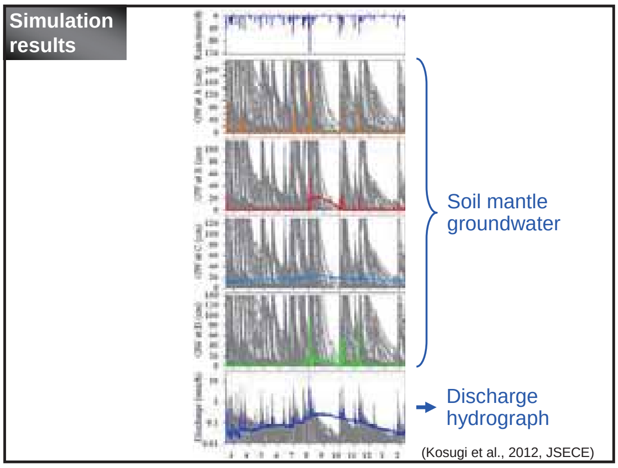
3^4 = 81 cases

Other parameters

θ_r	0.275
S_{ecet}	0.1
C (t/m^2)	1.2
tanϕ	0.7
ρ	2.65



Simulation results

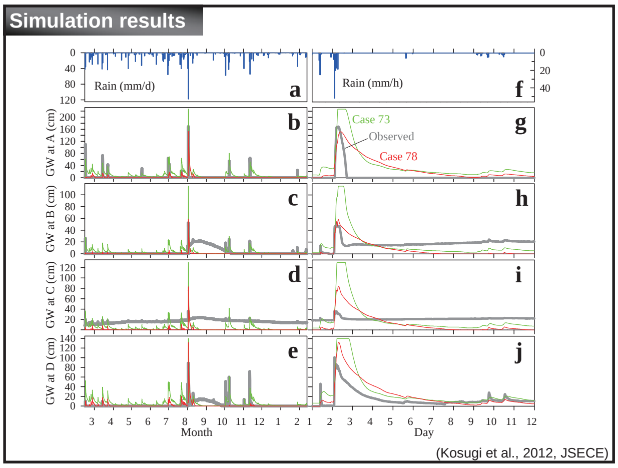


Simulation results

Soil mantle groundwater

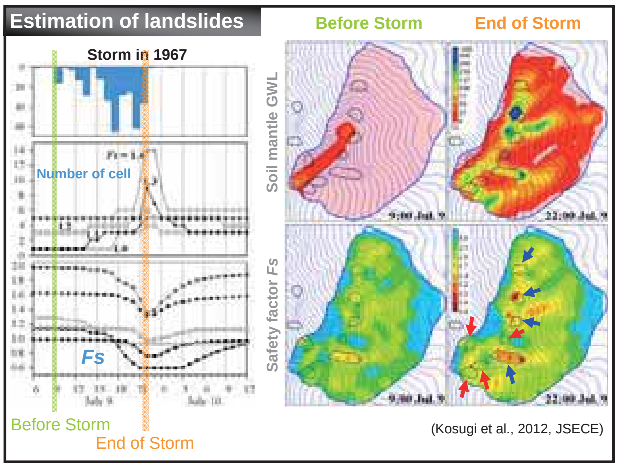
Discharge hydrograph

(Kosugi et al., 2012, JSECE)



Simulation results

(Kosugi et al., 2012, JSECE)

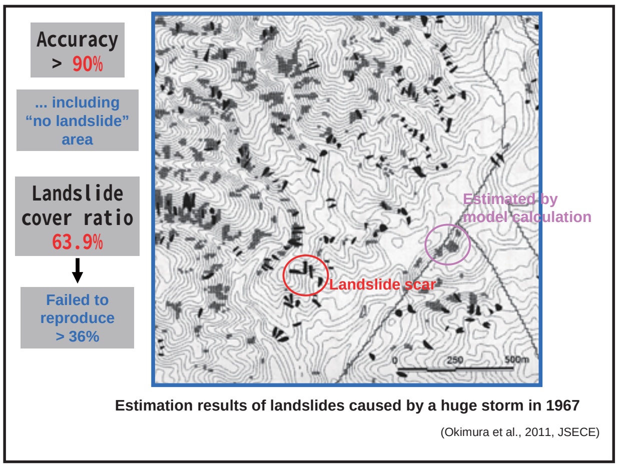


Estimation of landslides

Before Storm

End of Storm

(Kosugi et al., 2012, JSECE)



Accuracy > 90%

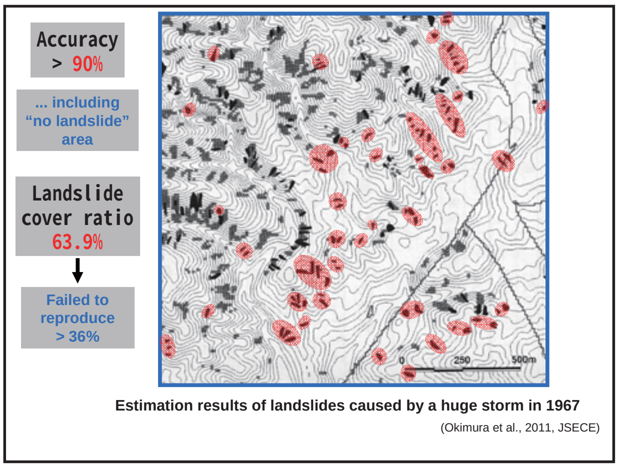
... including "no landslide" area

Landslide cover ratio 63.9%

Failed to reproduce > 36%

Estimation results of landslides caused by a huge storm in 1967

(Okimura et al., 2011, JSECE)



Accuracy > 90%

... including "no landslide" area

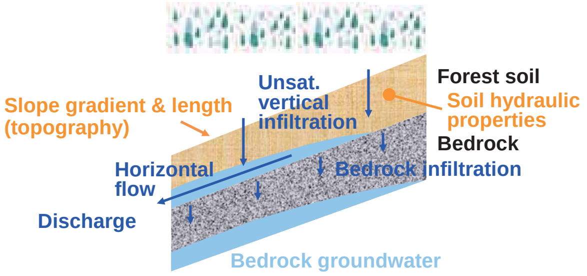
Landslide cover ratio 63.9%

Failed to reproduce > 36%

Estimation results of landslides caused by a huge storm in 1967

(Okimura et al., 2011, JSECE)

Rainwater movement in hillslope



Forest soil

Soil hydraulic properties

Bedrock

Slope gradient & length (topography)

Unsat. vertical infiltration

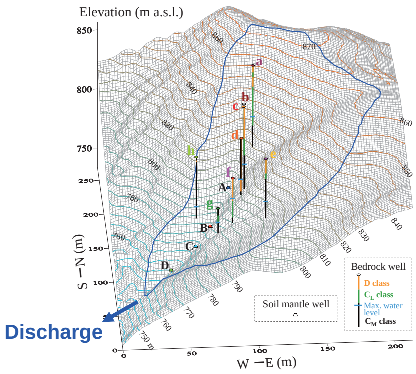
Horizontal flow

Bedrock infiltration

Discharge

Bedrock groundwater

Detailed observation in Q1 watershed

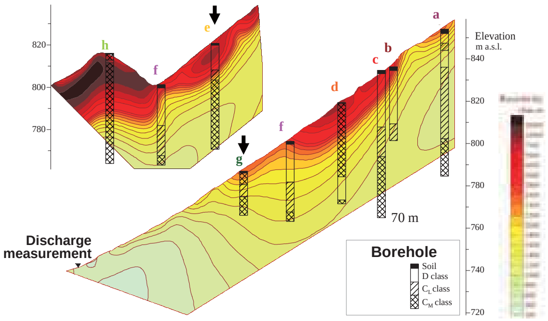


Discharge

(Kosugi et al., 2011, WRR)

Drilling boreholes

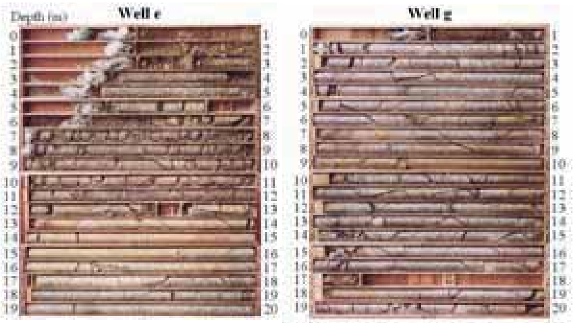
Borehole locations on cross sections



Discharge measurement

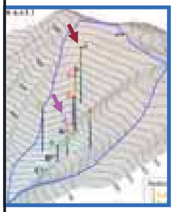
(Kosugi et al., 2011, WRR)

Borehole core samples

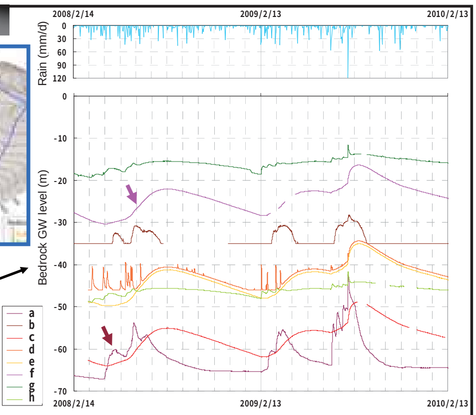


(Kosugi et al., 2011, WRR)

Bedrock GW

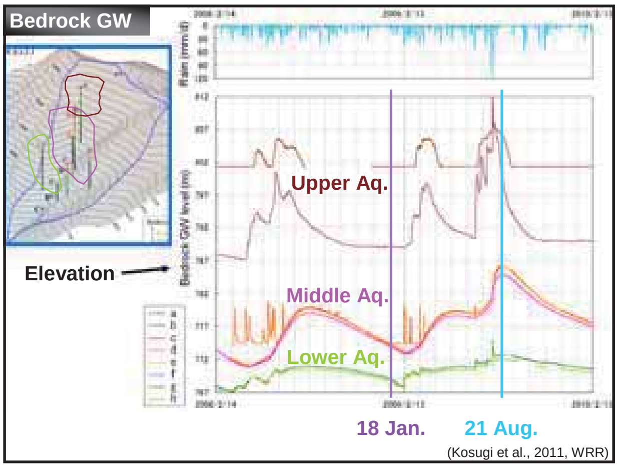


Depth from Soil surface



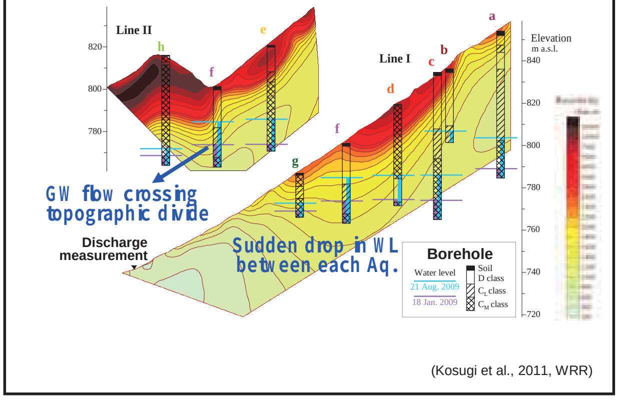
(Kosugi et al., 2011, WRR)

Bedrock GW



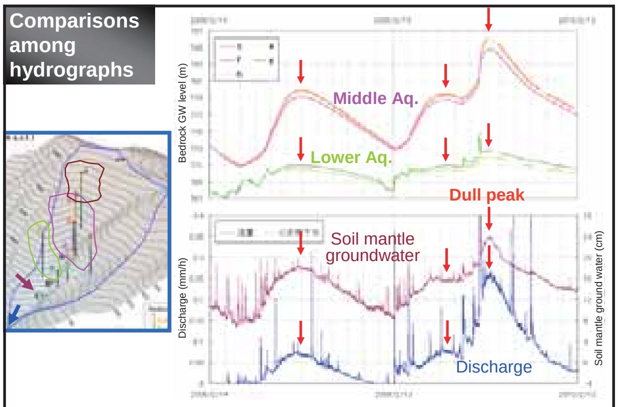
(Kosugi et al., 2011, WRR)

Bedrock GW levels on cross sections



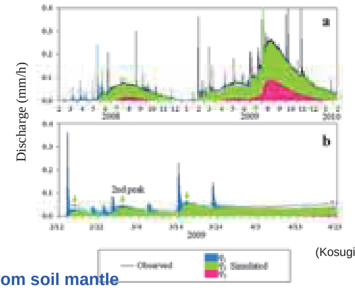
(Kosugi et al., 2011, WRR)

Comparisons among hydrographs



(Kosugi et al., 2011, WRR)

Model calculation

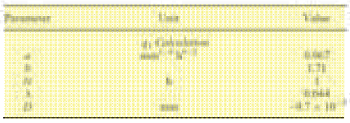


(Kosugi et al., 2011, WRR)

q_1 **Discharge from soil mantle**

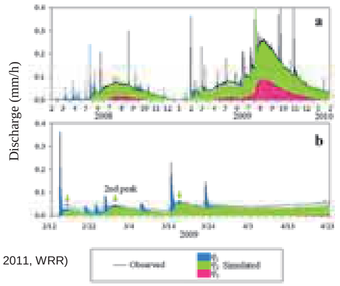
$$q_1 = \left[a(2-b)(S-S_0)\right]^{1/(2-b)} \quad \text{when } S-S_0>0$$
$$q_1 = 0 \quad \text{when } S-S_0\le 0$$

$$\frac{\left(S^{t+\Delta t}-S_0\right)-\left(S^{t}-S_0\right)}{\Delta t}=\lambda\left(P^{t-\delta t+\Delta t/2}-T^{t-\delta t+\Delta t/2}\right)-q_1^{t+\Delta t/2}$$



Parameter	Unit	Value
	q_1 Calculation	
a	$\text{mm}^{1-b}\,\text{h}^{-1}$	0.0467
b		1.71
Δt	h	1
λ		0.0444
D	mm	-8.7×10^{-3}

Model calculation



(Kosugi et al., 2011, WRR)

q_2 **Discharge from lower Aq.**

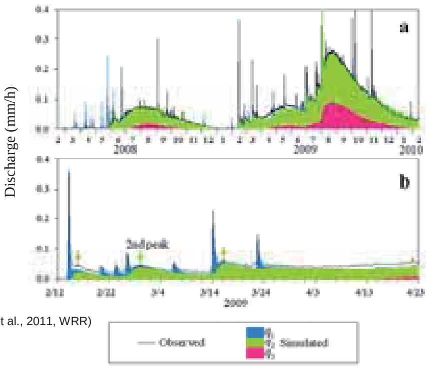
$$q_2=\alpha_2\left(h_2-h_{c,2}\right)^2+q_{c,2} \quad \text{when } h_2>\tilde{h}_2=h_{c,2}+\sqrt{-q_{c,2}/\alpha_2}$$
$$q_2=0 \quad \text{when } h_2\le\tilde{h}_2=h_{c,2}+\sqrt{-q_{c,2}/\alpha_2}$$

q_3 **Discharge from middle Aq.**

$$q_3=\alpha_3\left(h_3-h_{c,3}\right)^2+q_{c,3} \quad \text{when } h_3>\tilde{h}_3=h_{c,3}+\sqrt{-q_{c,3}/\alpha_3}$$
$$q_3=0 \quad \text{when } h_3\le\tilde{h}_3=h_{c,3}+\sqrt{-q_{c,3}/\alpha_3}$$

Dupuit–Forchheimer formula

Model calculation

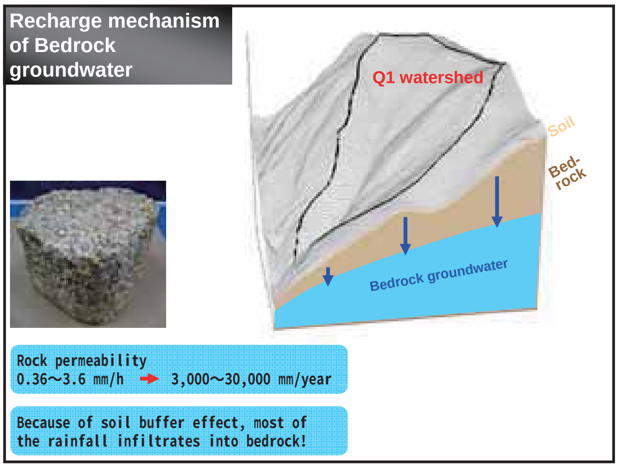


(Kosugi et al., 2011, WRR)

q_1 **Discharge from soil mantle**

7% of annual Dis.

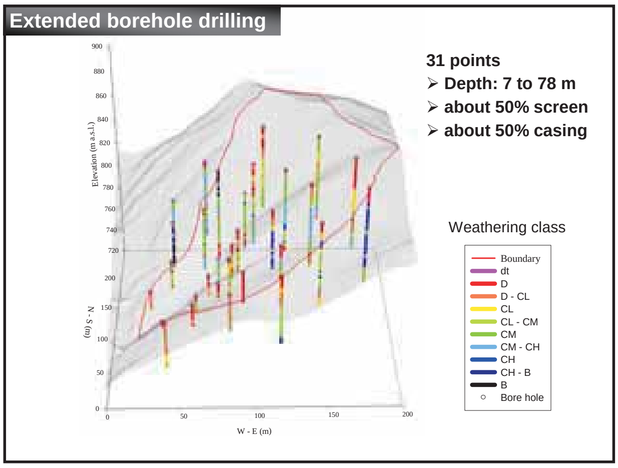
q_2 **Discharge from lower Aq.**
q_3 **Discharge from middle Aq.**
} **93% of annual Dis.**



Recharge mechanism of Bedrock groundwater

Rock permeability
0.36～3.6 mm/h ➡ 3,000～30,000 mm/year

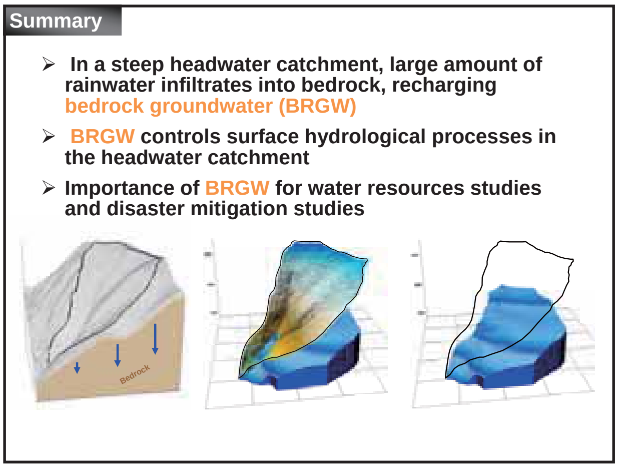
Because of soil buffer effect, most of the rainfall infiltrates into bedrock!



Extended borehole drilling

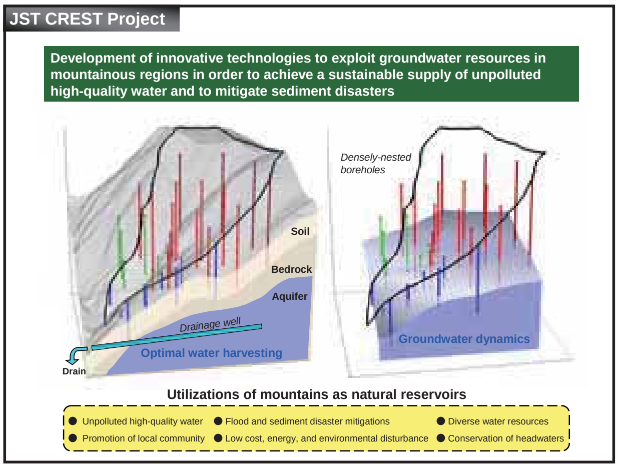
31 points
- Depth: 7 to 78 m
- about 50% screen
- about 50% casing

Weathering class



Summary

- In a steep headwater catchment, large amount of rainwater infiltrates into bedrock, recharging bedrock groundwater (BRGW)
- BRGW controls surface hydrological processes in the headwater catchment
- Importance of BRGW for water resources studies and disaster mitigation studies

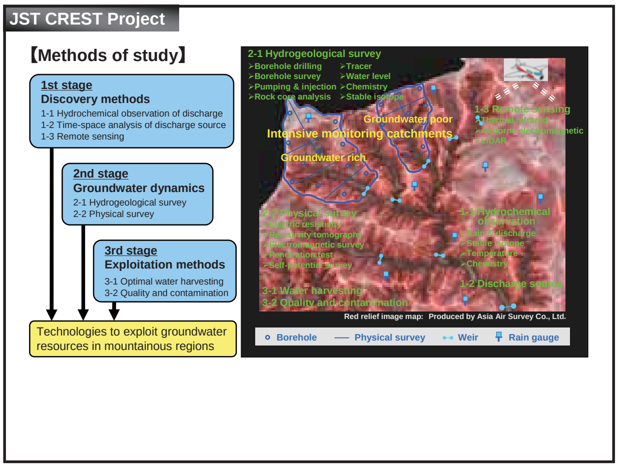


JST CREST Project

Development of innovative technologies to exploit groundwater resources in mountainous regions in order to achieve a sustainable supply of unpolluted high-quality water and to mitigate sediment disasters

Utilizations of mountains as natural reservoirs

- Unpolluted high-quality water
- Flood and sediment disaster mitigations
- Diverse water resources
- Promotion of local community
- Low cost, energy, and environmental disturbance
- Conservation of headwaters



JST CREST Project

【Methods of study】

1st stage
Discovery methods
1-1 Hydrochemical observation of discharge
1-2 Time-space analysis of discharge source
1-3 Remote sensing

2nd stage
Groundwater dynamics
2-1 Hydrogeological survey
2-2 Physical survey

3rd stage
Exploitation methods
3-1 Optimal water harvesting
3-2 Quality and contamination

Technologies to exploit groundwater resources in mountainous regions

2-1 Hydrogeological survey
- Borehole drilling
- Borehole survey
- Pumping & injection
- Rock core analysis
- Tracer
- Water level
- Chemistry
- Stable isotope

1-3 Remote sensing
- Thermal infrared
- Airborne electromagnetic
- LIDAR

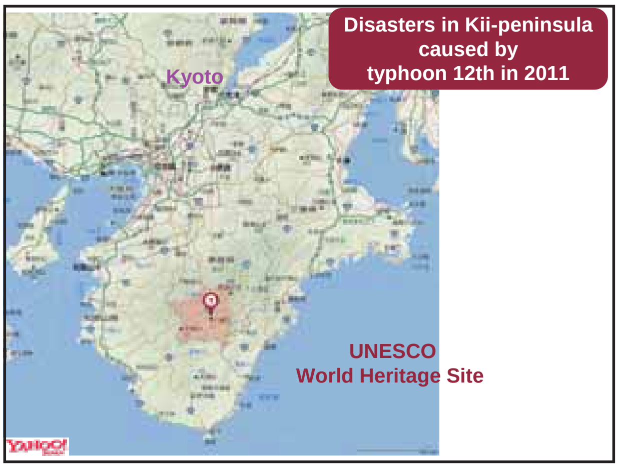
2-2 Physical survey
- Electric resistivity
- Resistivity tomography
- Electromagnetic survey
- Penetration test
- Self-potential survey

1-1 Hydrochemical observation
- Rain & discharge
- Stable isotope
- Temperature
- Chemistry

1-2 Discharge source

3-1 Water harvesting
3-2 Quality and contamination

Red relief image map: Produced by Asia Air Survey Co., Ltd.



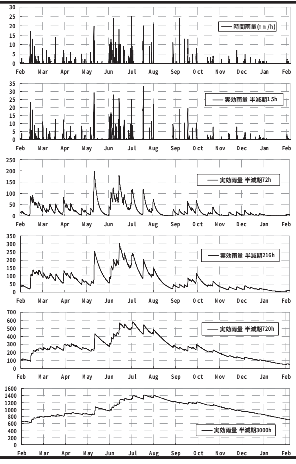
Disasters in Kii-peninsula caused by typhoon 12th in 2011

Damages cause by typhoon 12th

Rain of 1,400 mm triggered a lot of enormous landslides

Landslides: 2000
Casualty: 82
Property loss: > 1 billion US$

“Record of the 2011 Kii Peninsula Typhoon”
Nara. Prefecture, 2013



Hourly rainfall

API with HLT of 1.5 h

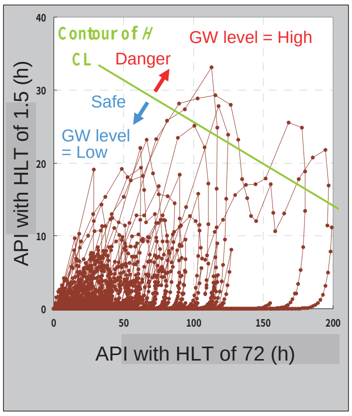
API with HLT of 72 h

API with HLT of 216 h

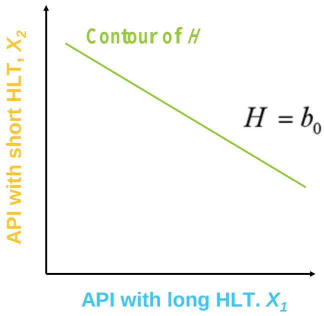
API with HLT of 720 h

API with HLT of 3000 h

Snake line plot

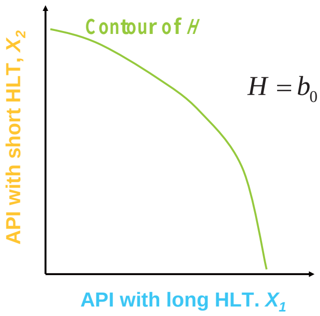


Functional model for Groundwater level



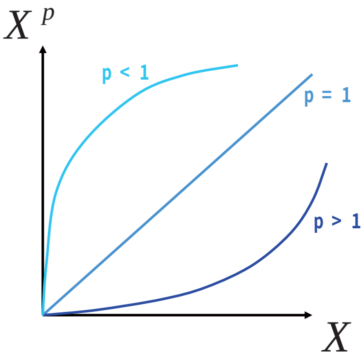
$$H = b_0 + b_1 X_1 + b_2 X_2$$

Functional model for Groundwater level



$$H = b_0 + b_1 X_1{}^{p_1} + b_2 X_2{}^{p_2}$$

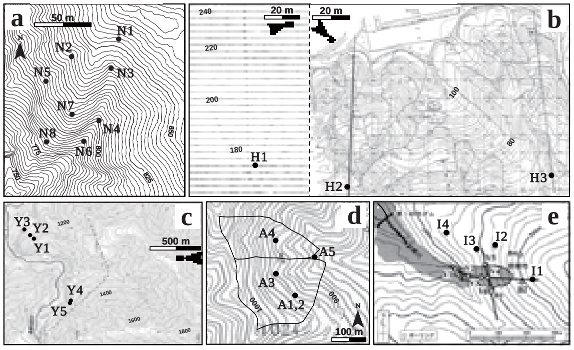
Functional model for Groundwater level



Study site

Rokkou ridge

Rokkou foothill



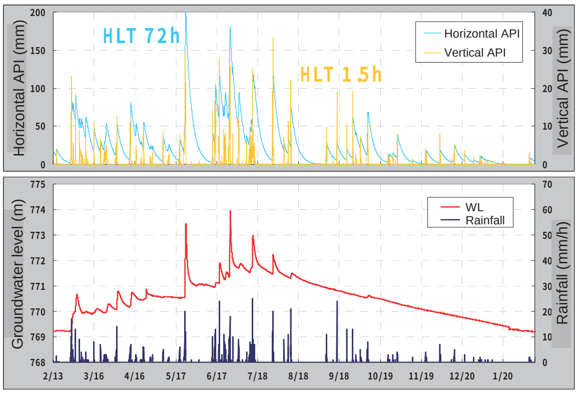
Yotagiri

Asatani

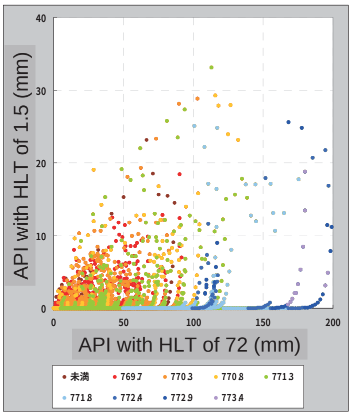
Harihara

(Kosugi et al, 2014, JSECE)

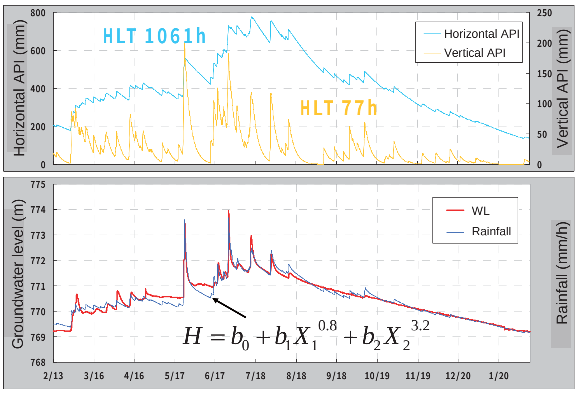
API and Groundwater level (N8)



Snake line plot

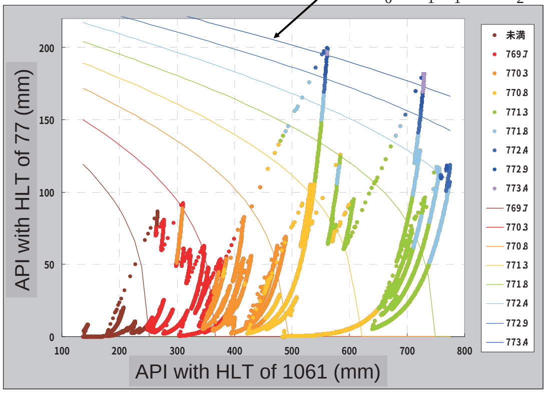


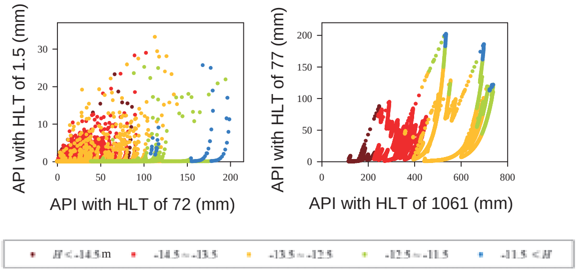
API and Groundwater level (N8)



Snake line plot

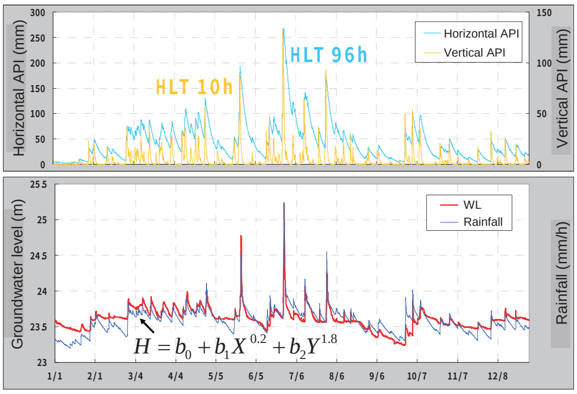
$$H = b_0 + b_1 X_1^{0.8} + b_2 X_2^{3.2}$$



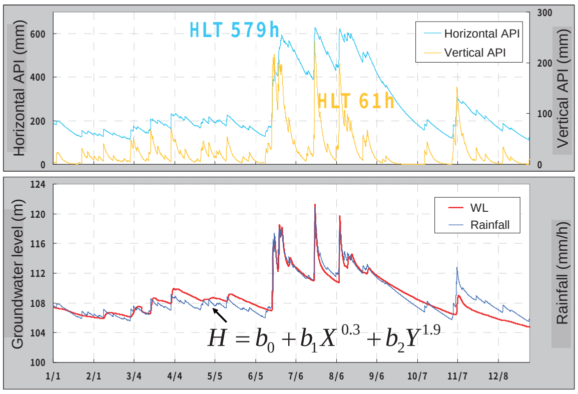


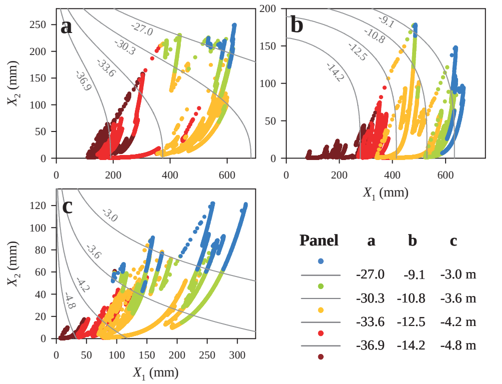
Low ⟵ **Observed groundwater level** ⟶ **High**

API and Groundwater level (A3)

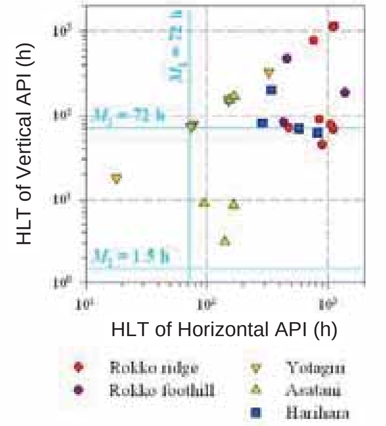


API and Groundwater level (I3)

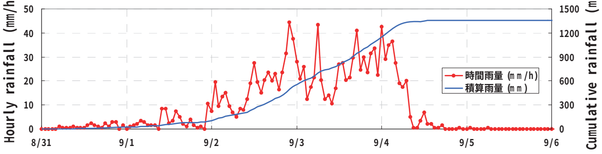


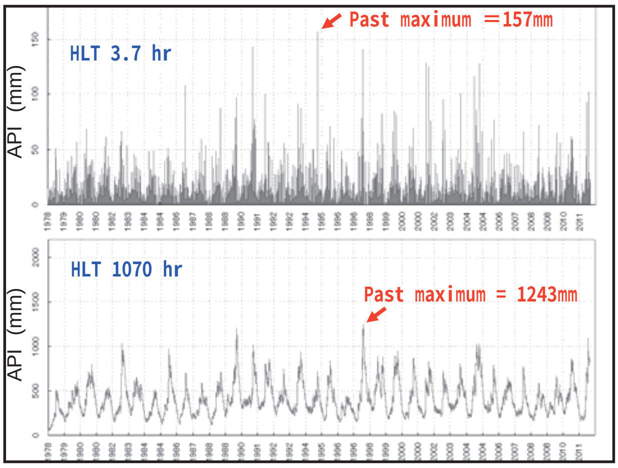


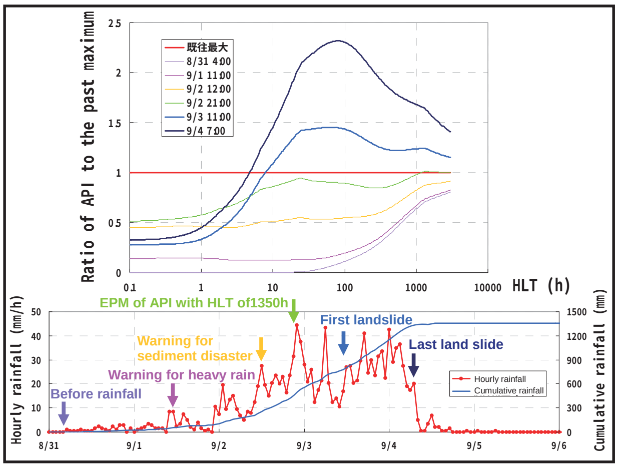
(Kosugi et al, 2014, JSECE)



Hyetograph for Typhoon No. 12



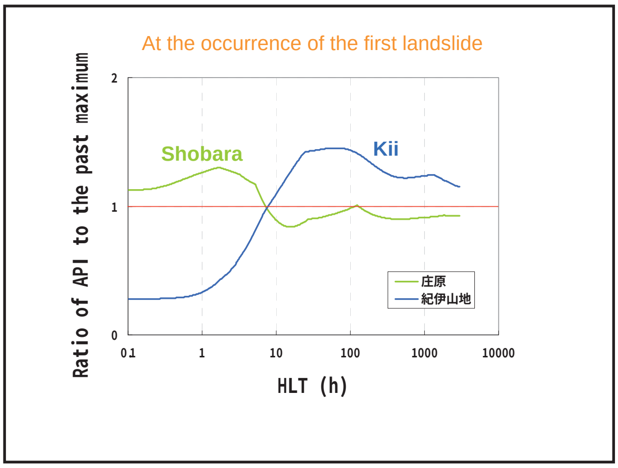


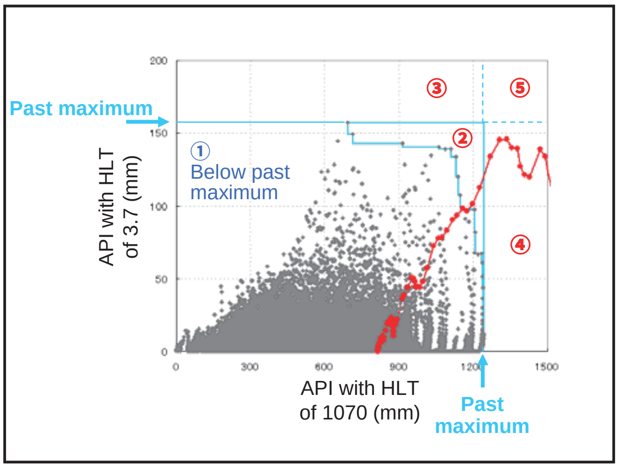


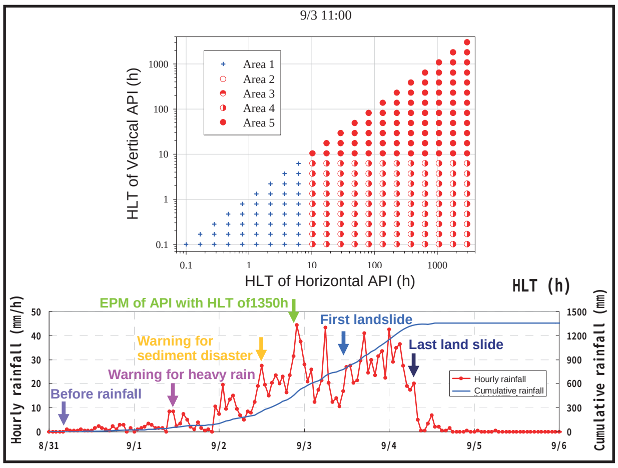
Shallow landslides

Shobara
Hiroshima Pref.

July 16, 2010

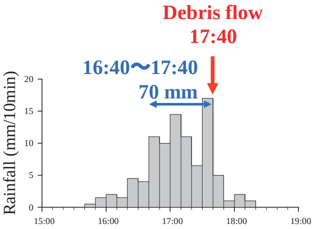


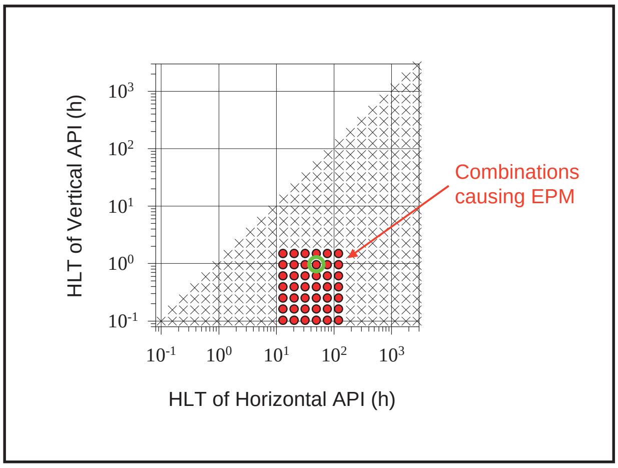


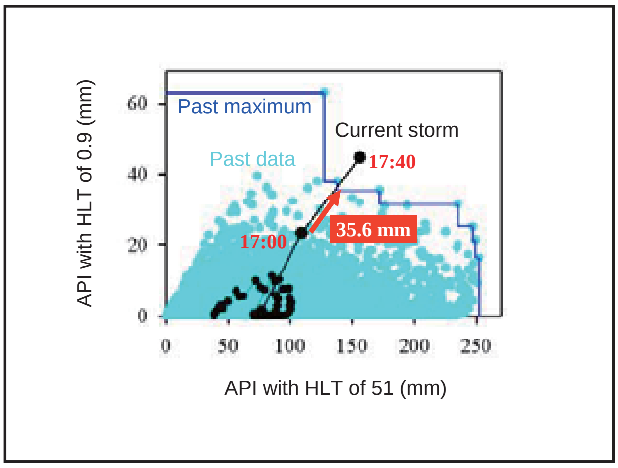


Debris flow

Nagiso
Nagano Pref.
July 9, 2014




10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
HLT of Vertical API (h)
Combinations causing EPM
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
HLT of Horizontal API (h)


API with HLT of 0.9 (mm)
60
40
20
0
Past maximum
Current storm
Past data
17:40
17:00
35.6 mm
0
50
100
150
200
250
API with HLT of 51 (mm)

L4: Effect of vegetation cover on sediment transportation and erosion

Takashi Gomi (*Tokyo University of Agriculture and Technology*)

Abstract

Numerous issues related to land use and vegetation cover changes on soil erosion have been concerns in the wide ranges of regions around the world. “International Year of Soil” in 2015 was announced for increasing awareness and understanding of the importance of soil for food security and essential ecosystem functions. Rapid changes in local economic conditions, population expansion, and shifting resource management policies have been affected planning of land conversion. Rapid shift from old growth forested area to more fragmented second growth and agricultural land have degraded ecological resources and functions. At the degraded land, soil erosion is central concerns for sustainable land use management and productivity of resources. Landscape fragmentation can also be associated with rapid road expansion and other transpiration which links from market centers and rural area in the recent years. Such alternation of landscape induces order of magnitude of soil erosion at various scales from local, watersheds, to regional scales. In steep mountainous terrains, probability for the occurrence of mass movement (e.g., landslide and debris flows) increases due to changes in hydrological flow pathways associated with land use changes and road development. These changes lead to issues for water supply, water quality, soil conservation, agricultural productivity, natural hazard control, and residential conservation.

In this training course, we explore the effects of vegetation condition on soil erosion and sediment transport. Vegetation ground covers have important roles for mitigating and reducing soil degradation while vegetation is often altered by land use changes. Within this class, we cover basic processes of soil erosion including rain splash, sheet and gully erosion, and mass movement. Soil erosion and resultant loss of soil productivity such as nutrient and carbon will also be examined using some examples around the world. We also learn about simple modeling approaches for estimating and predicting soil erosion in a given landscape. Effects of land use changes will also be included for understanding forest cover, land conversion vegetation conversion. We then discuss about hydrological connectivity which is important for understanding sediment transport from hillslopes to rivers and resultant river sedimentation. Scaling effects from plots, headwater, and larger watersheds are also considered for examining how processes related to soil erosion can be altered due to land use changes. We finally learn about specific soil conservation practices for minimizing soil erosion by using structure and vegetation cover in forested and agriculture lands.

Forest Hydrology −Conservation of Forest, Soil, and Water
The Twenty-fourth IHP Training Course

L4

Effect of vegetation cover on soil erosion and sediment transport

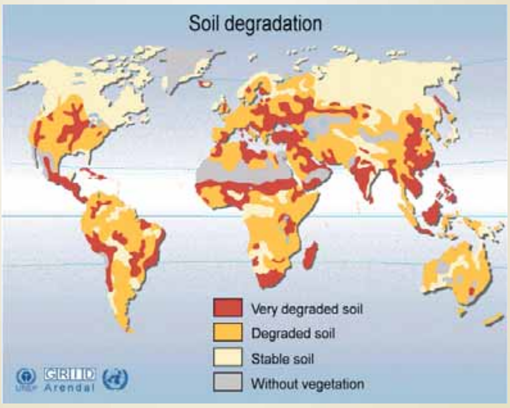
Takashi Gomi

Laboratory for Watershed Hydrology and Ecosystem Management
Tokyo University of Agriculture and Technology

International Year of Soil, 2015

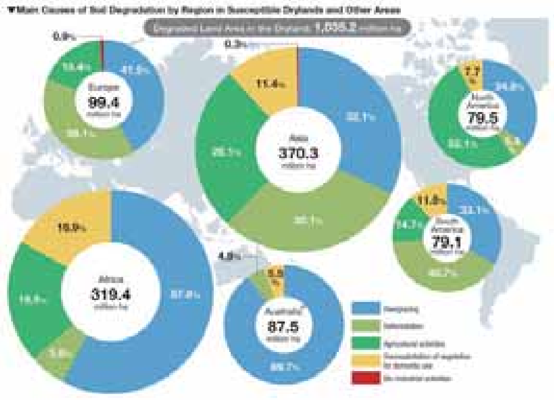
Increase awareness and understanding of the importance of soil for food security and essential ecosystem functions

Global concerns of soil erosion



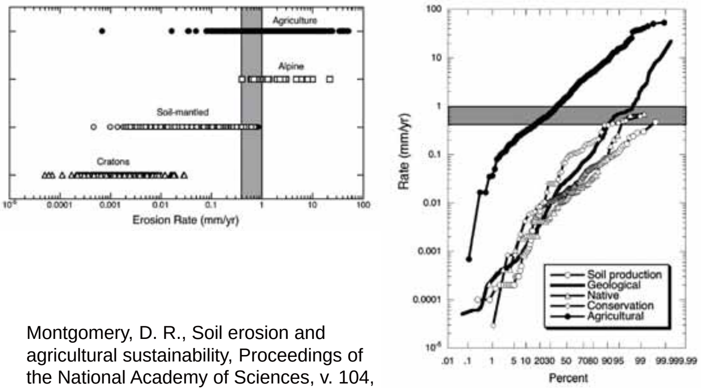
From UNEP

Major concerns for soil erosion

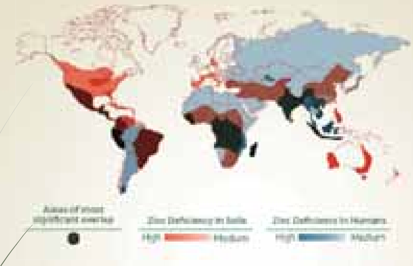


From UNEP

Soil erosion in various landscapes



Montgomery, D. R., Soil erosion and agricultural sustainability, Proceedings of the National Academy of Sciences, v. 104, p. 13,268-13,272, 2007

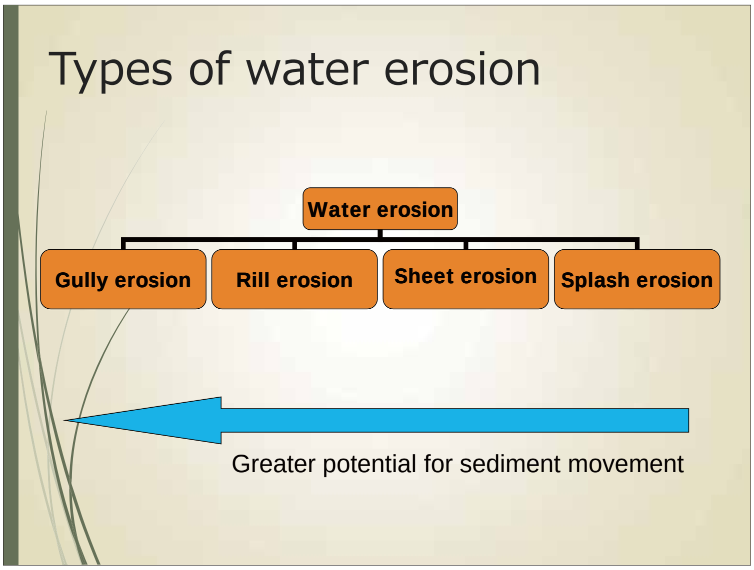


Soil and nutrient loss

http://rootsforgrowth.com/soilhealth/

Erosion Processes

1. Surface Erosion
2. Gully Erosion
3. Mass Movement

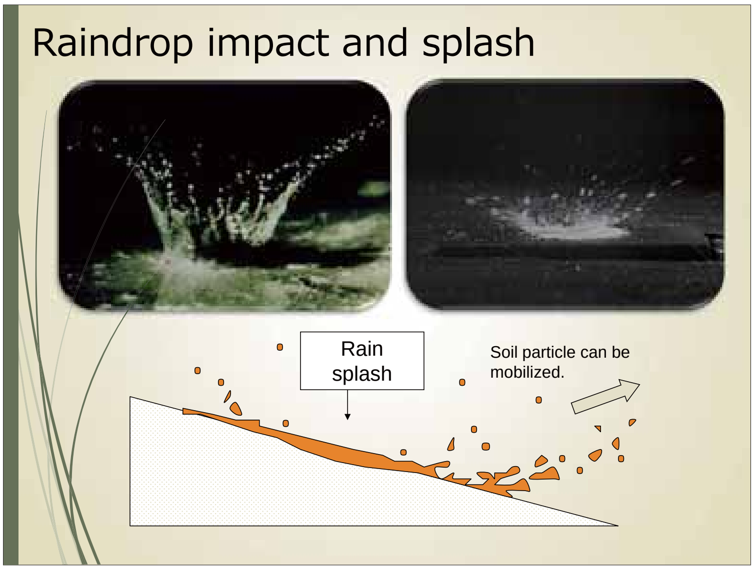


Types of water erosion

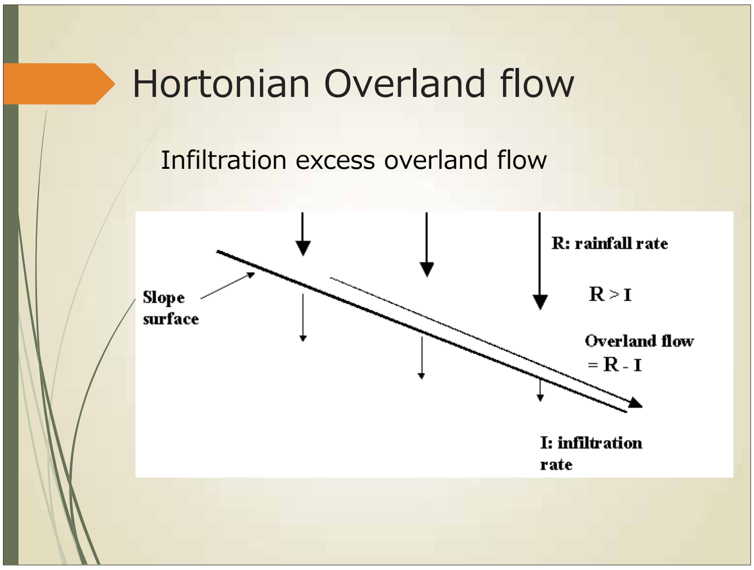
Water erosion

- **Gully erosion**
- **Rill erosion**
- **Sheet erosion**
- **Splash erosion**

Greater potential for sediment movement



Raindrop impact and splash

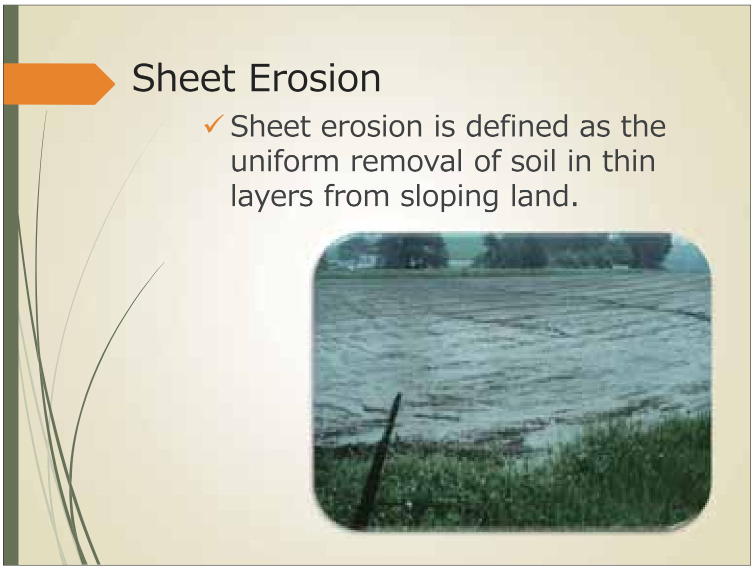


Hortonian Overland flow

Infiltration excess overland flow

Definitions

- **Infiltration** - The downward entry of water into the immediate surface of soil or other materials.
- **Infiltration Capacity** - The maximum rate at which water can infiltrate into a soil under a given set of conditions.
- **Infiltration Rate** - The rate at which water penetrates the surface of the soil and expressed in cm/hr, mm/hr, or inches/hr.
- **Percolation** -**Vertical** and **Lateral** Movement of water through the soil by gravity.

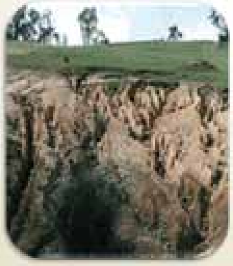


Sheet Erosion

✓ Sheet erosion is defined as the uniform removal of soil in thin layers from sloping land.

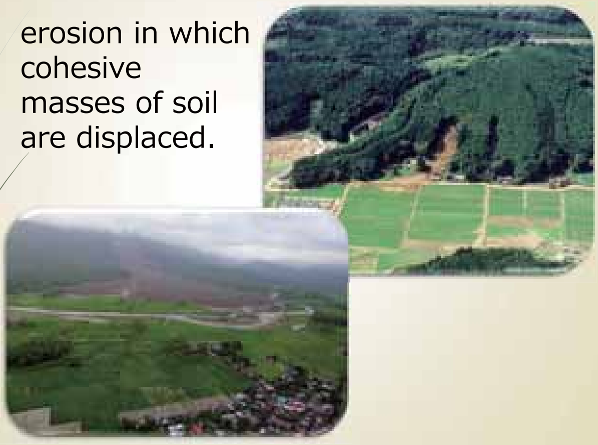
Rill and gully erosion

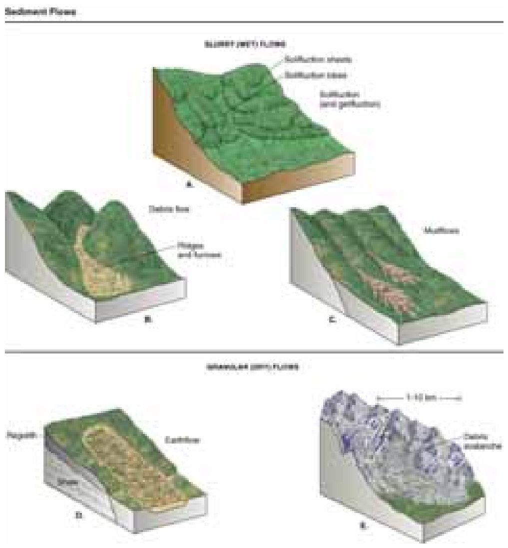
- ✓ detachment and movement of material, either individual soil particles or large aggregates, in a well defined-channel.



Mass Movement

erosion in which cohesive masses of soil are displaced.

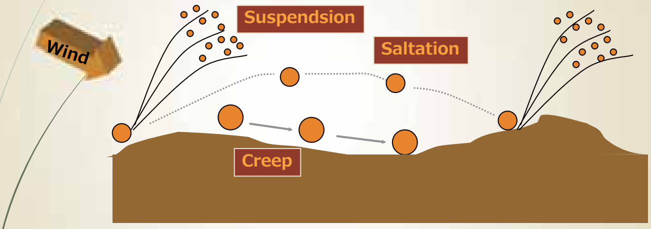




Consequence of soil erosion

- ☐ Splashing of raindrops separates organic matter, silt and clay from sand.
- ☐ These materials are then washed away by surface flow and the heavy sand is left on the field.
- ☐ This sand is turned under at the next plowing of the field or mixed with the surface layer of the soil at the next cultivation.

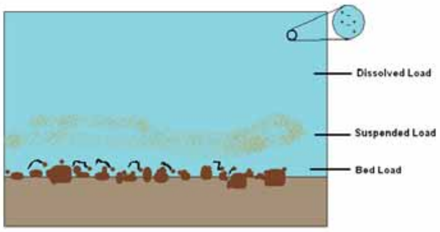
Wind erosion



Bedload and Suspended sediment

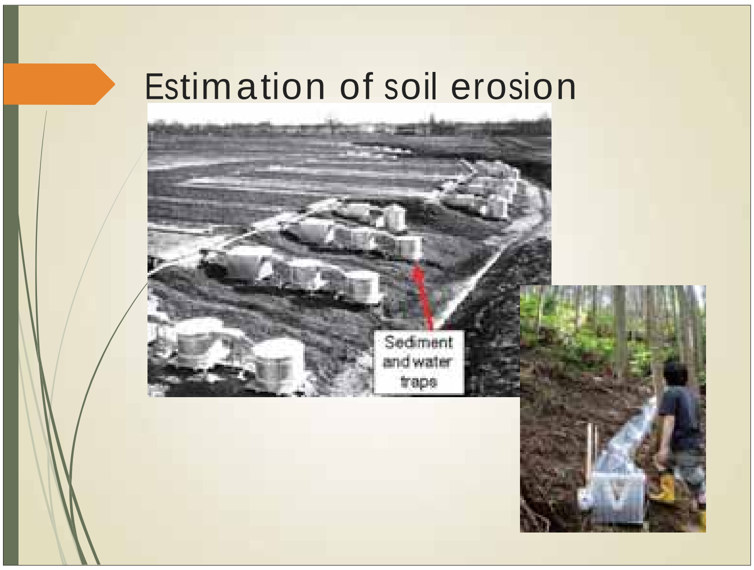
Bedload (≥ 1mm) moves as saltation, creep, and bounding.

Suspended sediment (< 1mm) moved as suspension and floating in water.



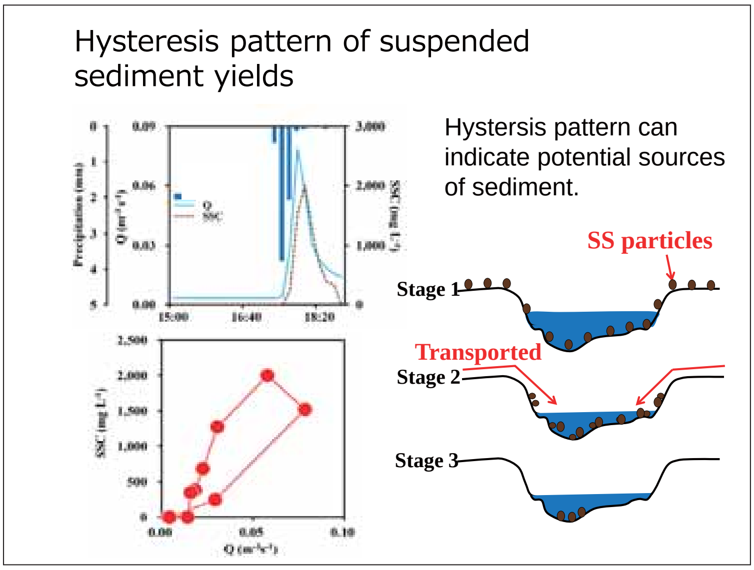
Erosion Impacts on streams

Excess sediment in stream cause water pollution for drinking water and damage freshwater fishes



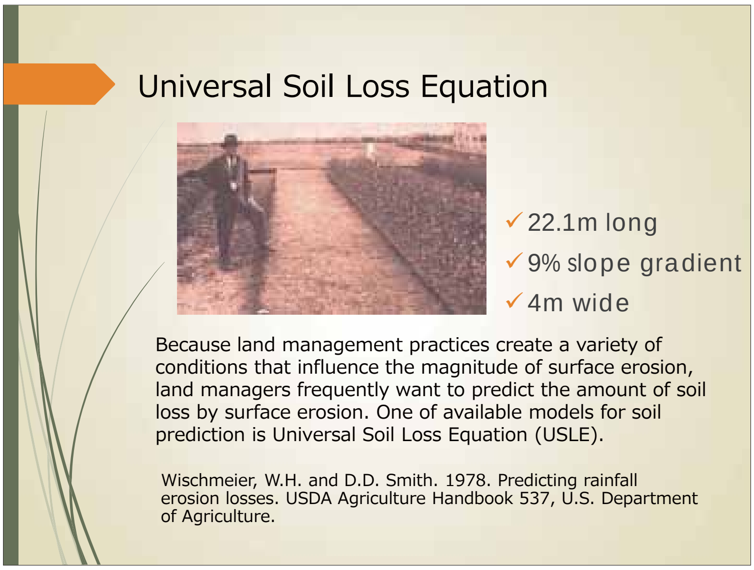
Estimation of soil erosion

Measurement of sediment



Hysteresis pattern of suspended sediment yields

Hystersis pattern can indicate potential sources of sediment.

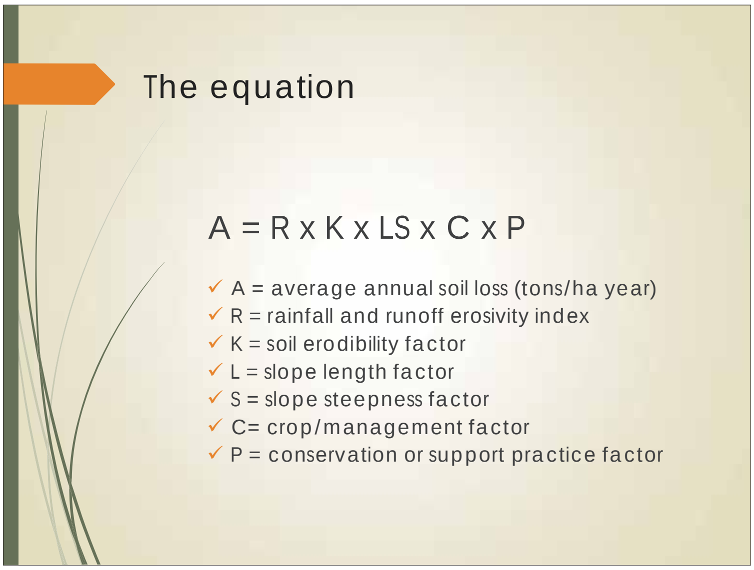


Universal Soil Loss Equation

- ✓ 22.1m long
- ✓ 9% slope gradient
- ✓ 4m wide

Because land management practices create a variety of conditions that influence the magnitude of surface erosion, land managers frequently want to predict the amount of soil loss by surface erosion. One of available models for soil prediction is Universal Soil Loss Equation (USLE).

Wischmeier, W.H. and D.D. Smith. 1978. Predicting rainfall erosion losses. USDA Agriculture Handbook 537, U.S. Department of Agriculture.



The equation

$$A = R \times K \times LS \times C \times P$$

- ✓ A = average annual soil loss (tons/ha year)
- ✓ R = rainfall and runoff erosivity index
- ✓ K = soil erodibility factor
- ✓ L = slope length factor
- ✓ S = slope steepness factor
- ✓ C= crop/management factor
- ✓ P = conservation or support practice factor

Characteristics and assumption

- Empirical model:
  - Analysis of observations
  - Seeks to characterize response from these data.
- Based on:
  - Rainfall pattern, soil type, topography, crop system and management practices.
- Predicts:
  - Long term average annual rate of erosion

R (rainfall and runoff erosivity index)

- Erosion index (EI) for a given storm:
  - Product of the kinetic energy of the falling raindrops and its maximum 30 minute intensity.
- R factor = $\sum$ EI over a year / 100

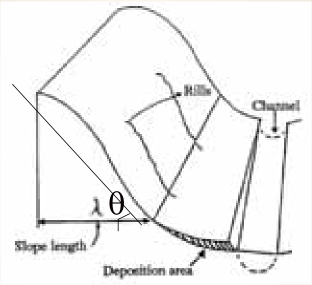
A =R x K x LS x C x P

K (soil erodibility)

- Susceptibility of a given soil to erosion by rainfall and runoff.
- Depend on:
  - Texture, structure, organic matter content, and permeability.

A =R x K x LS x C x P

LS (slope length-gradient)



- Ratio of soil loss under given conditions to that at a site with the "standard" slope and slope length.

C (crop/management)

- Ratio of soil loss from land use under specified conditions to that from continuously fallow and tilled land.

Vegetation cover
Plant litter
Soil surface
Land management

A =R x K x LS x C x P

P (Erosion control conservation practices)

- Ratio of soil loss by a support practice

Practice	P Factor
Up & Down Slope	1.00
Cross Slope	0.75
Contour farming	0.50
Strip cropping, cross slope	0.37
Strip cropping, contour	0.25

A =R x K x LS x C x P

MUSLE
Modified Universal Soil Loss Equation

C (crop management) and p (erosion control practice) factors are replaced by vegetation management (VM) factor.

$$A = R \times K \times LS \times VM$$

- A = average annual soil loss (tons/ha year)
- R = rainfall and runoff erosivity index
- K = soil erodibility factor
- L = slope length factor
- S = slope steepness factor
- VM = vegetation management factor

Vegetation Management (VM) factor

(1)Canopy cover effects

(2)Effects of low-growing vegetation cover

(3)Bare ground with fine root.

Question 1

We are currently working on soil management project in a 12,000 ha Watershed. The area is covered by 30 % ground cover of grass with 25 % canopy of tall weed.
Based on the previous studies in the area, the following values were determined,

- R = 400
- K = 0.15
- LS = 10
- VM = 0.13

Total Erosion rate of the entire watershed = t/yr

Estimated annual Soil loss, A = t/ha/yr

Question 2

Now we are conducting watershed rehabilitation projects. We converted vegetation ground cover as the following

½ watershed area (Area I) = 25 % tree canopy with a 60 % grass cover (VM=0.038)
½ watershed area (Area II) = 25 % short brush cover with 80 % grass cover (VM=0.042)

Estimated annual soil loss of Area I, A1 = t/ha/yr

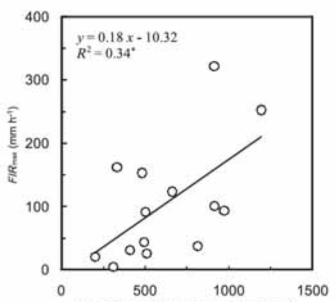
Estimated annual soil loss of Area II, A2 = t/ha/yr

Then estimate percentage of soil loss reduction after the rehabilitation management

Why vegetation is important for preventing soil erosion?

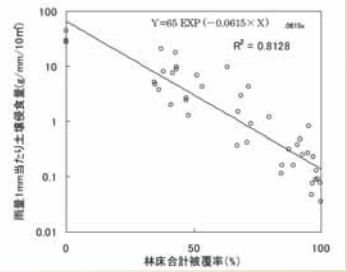
- Reducing soil splash
- Root growth and reinforcement
- Increase infiltration capacity
- Providing surface roughness

Vegetation, infiltration, and soil erosion



Hiraoka et al., 2010

Soil erosion per 1 mm rain

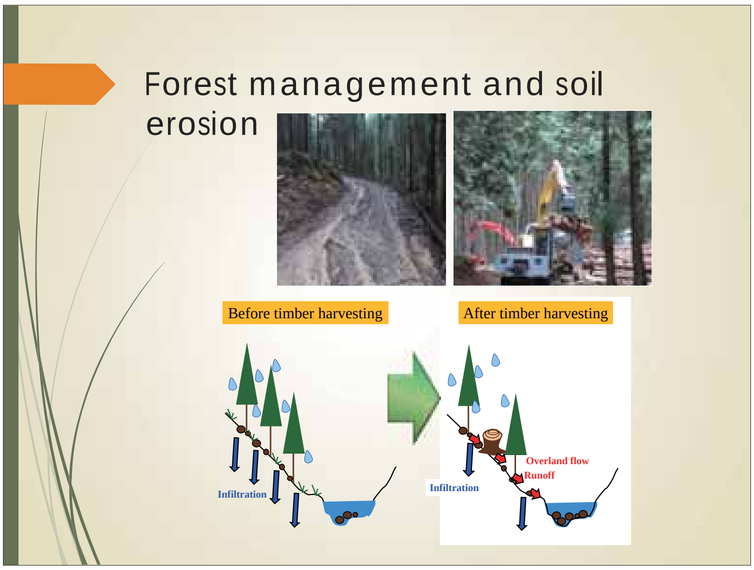


Total ground cover (%)

Chu et al., 2010

Landuse activity and soil erosion

- Removal vegetation decrease interception loss.
- Reducing infiltration capacity due to soil compaction increase runoff.
- Increasing the soil erosion decreases capacity of channel for flow.

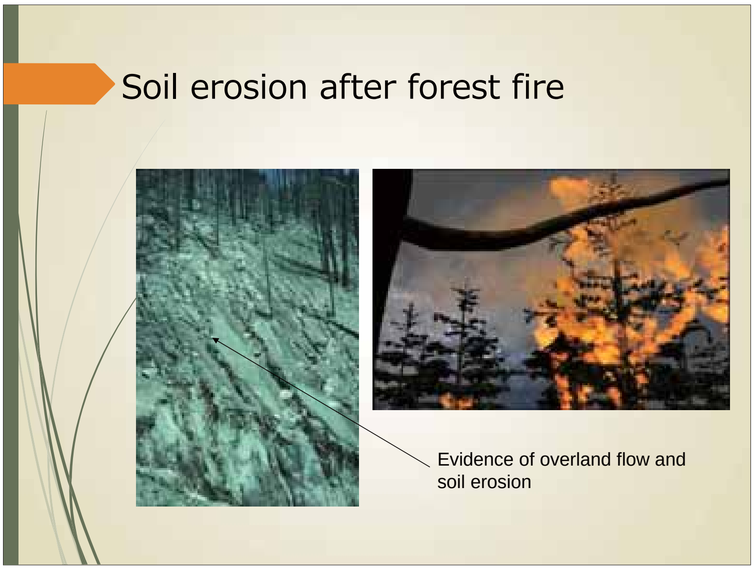


Forest management and soil erosion

Suspended sediment yields after timber harvesting

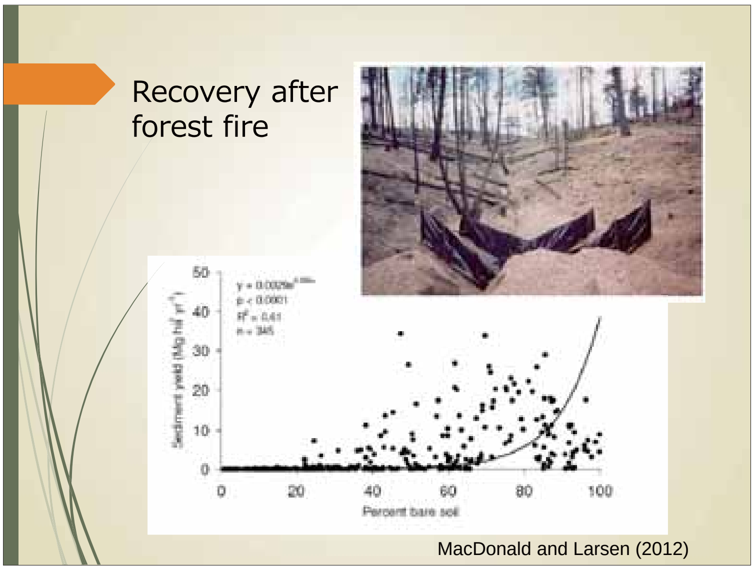
Country	Catchment	Area	Annual precipitation	Thinning treatment	Percentage of treatment (%)	SSY (kg/ha/yr)		Increase in SSY (folds)	Skid trail(road) and/or machinery	Reference
		(ha)	(mm)			Pre	Post			
Nothern America	B3	43.0	500	Clear cut	55.0	N/A	N/A	0.2	Feller–bunchers and skidders	Macdonald et al. (2003)
	B5	150.0	500	Clear cut	53.0	N/A	N/A	0.6	No additional operations	
	Forested catchment	375.5	N/A	Cutting	N/A	N/A	N/A	45.0	Skidding and roads	Megahan (1972)
	Deer Creek	304	2540	Cutting	25.0	161.7	194.3	1.2	Cable yarding and tractor skidding	Brown and Krygier (1971); Beschta (1978)
	Needle Branch	75.0	2540	Clear cut	82.0	75.7	208.6	2.8	Cable yarding and tractor skidding	
	Johnson Gulch research	137.0	N/A	Random thinning	20.0	1.8	13.7	7.7	Tractors and skidder	Aderson and Potts (1987)
	Watershed 1	96.0	2300	Clear cut	100.0	140.0	1700.0	12.1	Burning and cable yarding	Grant and Wolff (1991)
	Watershed 3	101.0	2300	Random thinning	25.0	1500.0	2600.0	1.7	Burning and cable yarding	
	Subbasin EAG	27.0	1200**	Clear cut	100.0	N/A	710.0	2.4	Tractor yarding, burning, and roads	Lewis et al. (2001)
United Kindom	Loch Ard (Catchment 10)	84.0	2000.0	Clear cut	70.0	550.0	835.6	1.5	N/A	Ferguson et al. (1991)
	Hore	308.0	2458.0	Clear cut	N/A	122.0	571.0	4.7	Felling operations	Leeks (1992)
	Kirkton	685.0	2372.0	Clear cut	50.0	141.5	1157.0	8.2	Skylines and tracked vehicle	Johnson (1993)
	Afon Tanllwyth	89.0	N/A	Clear cut	20.0	242.0	438.0	1.8	A single harvester	Stott et al. (2001)
Australia	Catchment I-3	515.0	1183.0	Random thinning	38.7	N/A	N/A	0.3	Roads	Webb et al. (2012)
Asia	Berembun BC1	12.9	2121^{*}	Random thinning	N/A	136.6	269.1	0.7	Tractor or skidder	Kasran (1988)
	Berembun BC3	29.7	2121^{*}	Random thinning	N/A	68.6	117.0	1.0	Tractor or skidder	
	Bukit Berembun Negeri Sembilan	13.0	2126^{*}	Random thinning	40.0	136.0	270.0	2.0	N/A	Zulkifli et al. (1990)
	Ulu Segama Sabah	50.0-100.0	3280^{*}	Random thinning	N/A	600.0	6600.0	11.0	logging trails	Douglas et al. (1992)
	Sipitang Sabah	3.0-18.0	3280^{*}	Clear cut	N/A	240.0	2530.0	10.5	Tractor removal	Malmer (1990)
	Jengka	28.4	2508	Random thinning	25.0	100.0	300.0	2.0	Logging roads and skid trails with tractor	Kasran and Nik (1994)
Japan	Watershed B	1.1	2147	Clear cut	N/A	6.9	9.0	1.3	Skylines and both of no roads and skid trails	Hotta et al. (2007)
	Catchment K2	17.1	1232	Strip thinning	50.0	1.1	9.2	29.3	Cable yarding and skid trail and	This study (2013)

Note: SSY indicates suspended sediment yields. Asterisk (* and **) indicated annual precipitation and mean precipitation during study period. N/A: Not available.



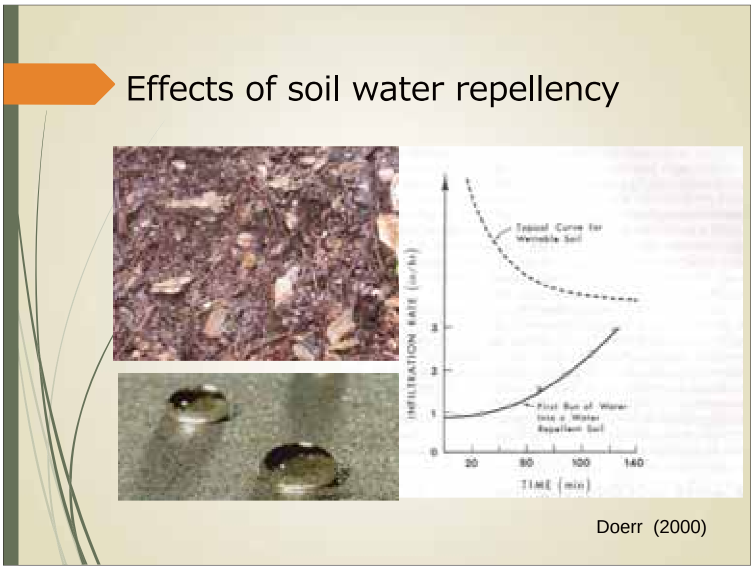
Soil erosion after forest fire

Evidence of overland flow and soil erosion



Recovery after forest fire

MacDonald and Larsen (2012)



Effects of soil water repellency

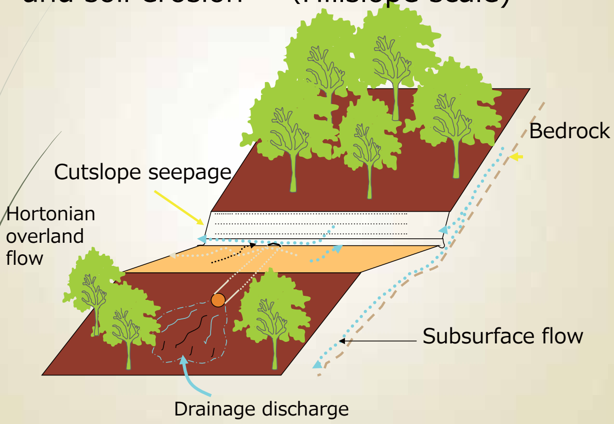
Doerr (2000)

Impact of land use on infiltration capacity

Effects of forest roads on storm flow generation and sediment transport

五味　高志

Effects of forest road on flow generation and soil erosion　(Hillslope scale)



Controlling soil erosion

Reducing rain drop impact	① Soil management, reducing slope ② Providing vegetation Cover
Increase soil resistance	① Improving soil structure ② Organic matter and cohesive properties
Reducing shear strength	① Decreasing runoff velocity

Vegetation practices

1. Vegetarian Cover
2. Contouring
3. Strip Cropping
4. Tillage Operation
   - Increase Infiltration
   - Increase resistance for soil erosion
   - Rough land surface against water and wind erosion
   - Soil moisture retaining capacity

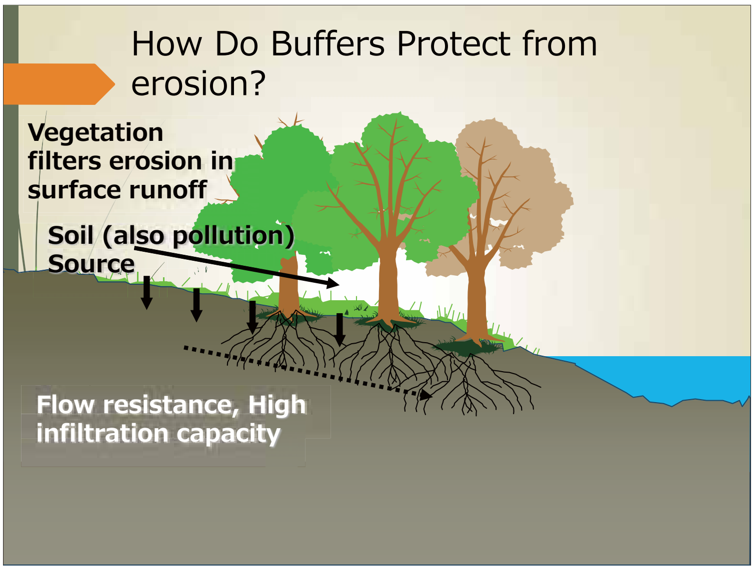
Mechanical practices

1. Terracing
2. Ponds and Dams
3. Vegetated Buffer Strip

A planted or natural vegetative buffer in the area that links to stream channel

SERVES AS:

- Filter
- Transform
- Sink



How Do Buffers Protect from erosion?

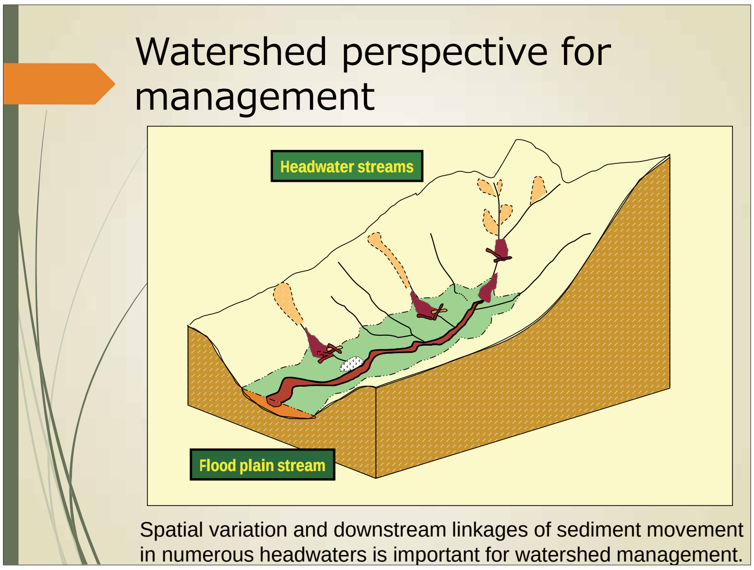
Vegetation filters erosion in surface runoff

Soil (also pollution) Source

Flow resistance, High infiltration capacity

Mountain conservation

Structure for preventing soil surface erosion and sediment movement within channels were introduced.



Watershed perspective for management

Spatial variation and downstream linkages of sediment movement in numerous headwaters is important for watershed management.

L5: Nutrient and organic matter export from forested watershed

Hirokazu Haga (*Faculty of Agriculture, Tottori University*)

Abstract

Forest management is not limited to the forest industry any more. It is one of the important pillars of the national land control, because it is considered that water and substances supplied from forests to streams are transported in the channel to have large influences on the water resources and environments in the downstream basins.

The matters that receive special attention in recent years in Japan are the delay of tree thinning in artificial forests expanded by the forestation policy after World War II and the loss of the original mountain stream environments caused by afforestation and sediment control works. In the case of the cypress artificial forest, the delay of tree thinning can be cause the deterioration of infiltration capacity of soil to generate overland flow and muddy stream water. Previously, the only purpose of tree thinning was lumber production. In late years, however, tree thinning is expected to be an important land control technique for supplying water resources stably through deterring of the overland flow generation and improving the stream water quality. In fact, Forestry Agency in Japan has widely promoted the effective tree thinning by supporting large subsidies as a national growth strategy.

However, although proposals and trials of forest management are ongoing under such a new framework, there are lots of unclear points regarding whether the expected results can be actually obtained. What kind of change is caused to the rainwater flow paths, streamflow and geomorphic features of streams by intense tree thinning? What kind of influence is exerted on the water resources and environments in downstream basins? Such information and knowledge are extremely insufficient. The verification of results and sophistication of assessment techniques are needed in the near future.

In this lecture, the following points will be introduced: (1) close relationships between rain water flow paths in hillslope and dissolved substances (nitrogen and organic carbon) in stream water; (2) a variety of export properties of solid substances (sediment and particulate phosphorous; (3) dynamics of in-stream wood (fallen tree and thinning residues supplied from riparian area to stream); and (4) specific methods of their investigations. In addition, this lecture will include a short practice of field survey using a highly accurate surveying instrument which employs electro-optical distance metering method. These topics could help participants enhance their imagination necessary to understand linkage between forest management and stream water in their country.

upstream

Nutrient and Organic Matter Export from Forested Watershed

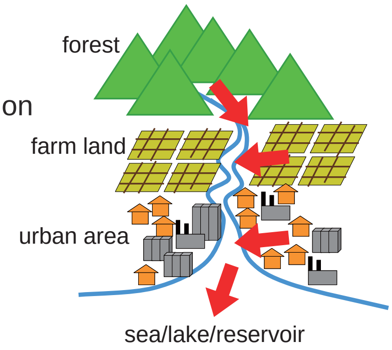
Faculty of Agriculture, Tottori University
Hirokazu Haga

downstream

Nutrient production

- Nitrogen
- Phosphorus
- Carbon

etc...



Large contribution of headwater areas to downstream nutrient

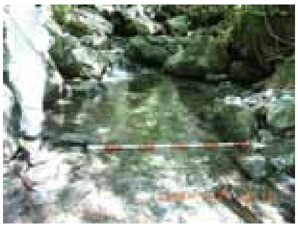
Our life and headwater areas

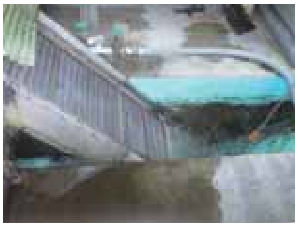
Water as resources for…

- Agricultural use
- Industrial use
- Electric power generation
- Drinking water

High-quality water

- little of organic matter
- unpolluted
- low cost purification
- easy to use and apply





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in humid regions like Japan, headwater areas = forested areas

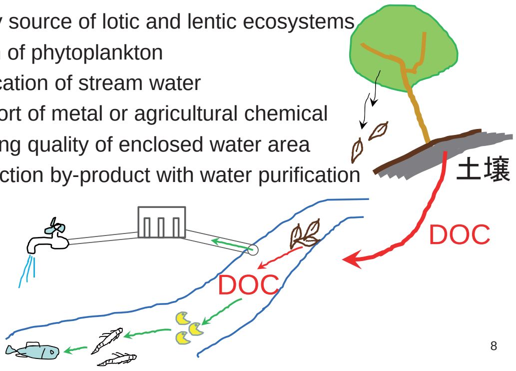
Positive aspect

➔ Supply of timber, mushroom, fuel wood, charcoal
Keeping of biodiversity, ecosystem service

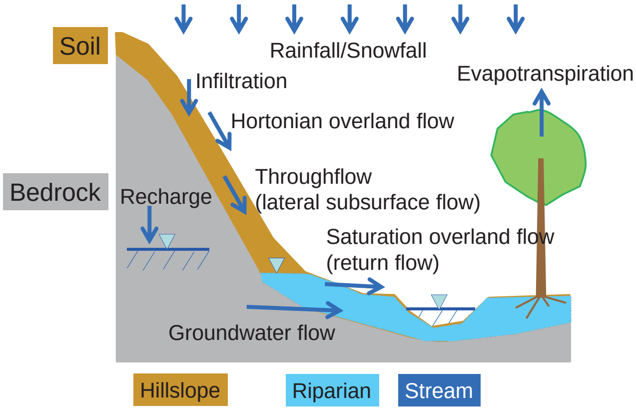
Reserved water surface covered by floating wood
➔ trouble of water intake, decline of water quality

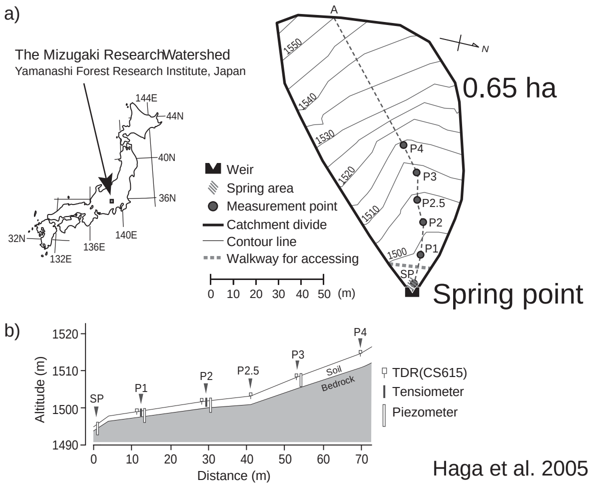
Dissolved Organic Carbon (DOC)

- soil- and litter-derived
- energy source of lotic and lentic ecosystems
- growth of phytoplankton
- acidification of stream water
- transport of metal or agricultural chemical
- declining quality of enclosed water area
- disinfection by-product with water purification



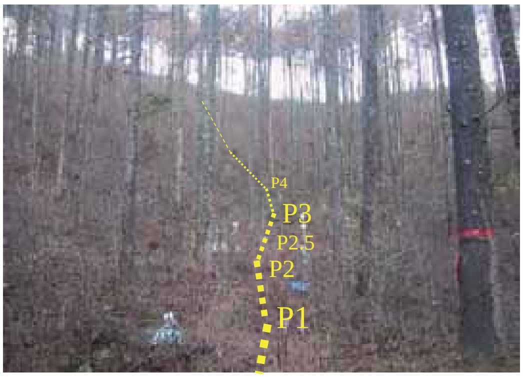
Hydrological flow paths





Haga et al. 2005

Observation points of soil water and groundwater along the bottom of unchanneled catchment



Spring area and V-notch weir

Hydrological measurements

Rainfall

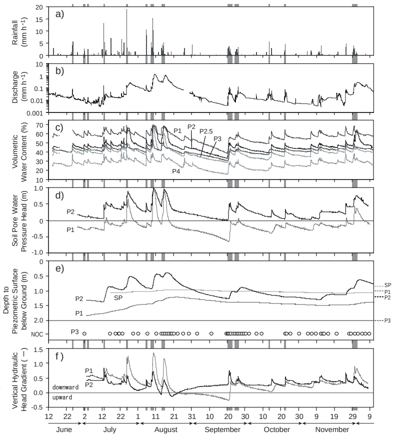
Spring discharge

Soil moisture

Soil pore
water pressure

Groundwater level

Hydraulic gradient

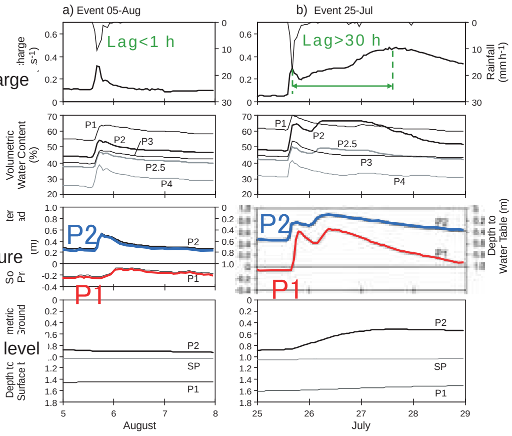


Rainfall
Spring discharge

Soil moisture

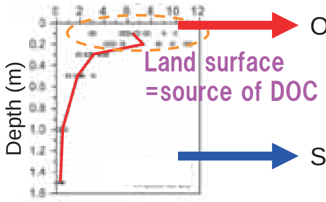
Soil pore
water pressure

Groundwater level



DOC concentration of soil water

Soil water DOC (mg/L)

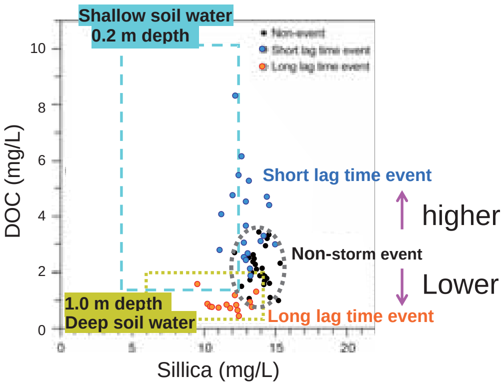


Overland flow＝high conc.

Subsurface flow＝low conc.

Hypothesis

- Overland flow-dominated event
  quick response hydrograph → high concentration
- Subsurface flow-dominated event
  delayed response hydrograph → low concentration



Short lag time → Overland flow → High DOC
Long lag time → Subsurface flow → Low DOC

Loading (kg/year)

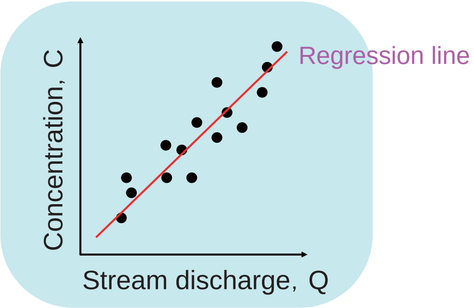
continuous monitoring → OK

Export loading = Stream discharge x Concentration

Estimation ← unrealistic ← continuous monitoring

Convenient method for estimation of concentration

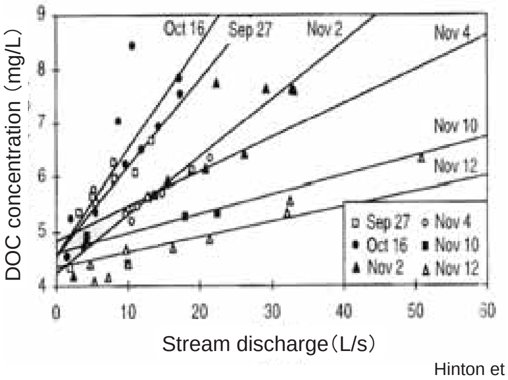
Regression line method



C-Q plot → C-Q relation

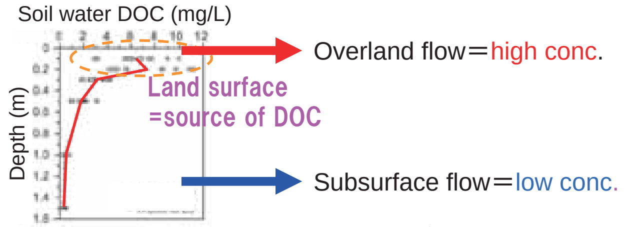
Using the C-Q relation, concentration is estimated from discharge

a broad range of data on C-Q plot



Hinton et al.1997

DOC concentration of soil water



Overland flow＝high conc.

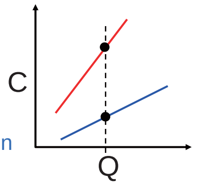
Subsurface flow＝low conc.

Hypothesis

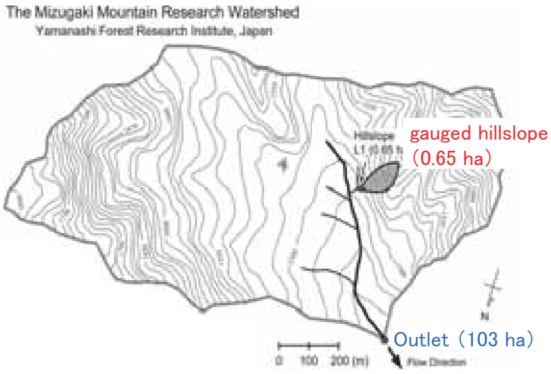
Even the same stream discharge,

Overland flow → high concentration

Subsurface flow → low concentration

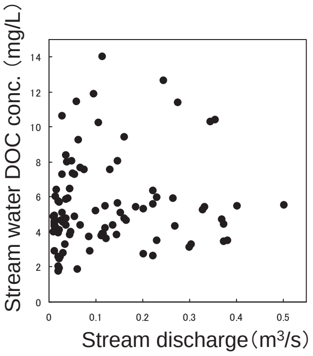


Study site

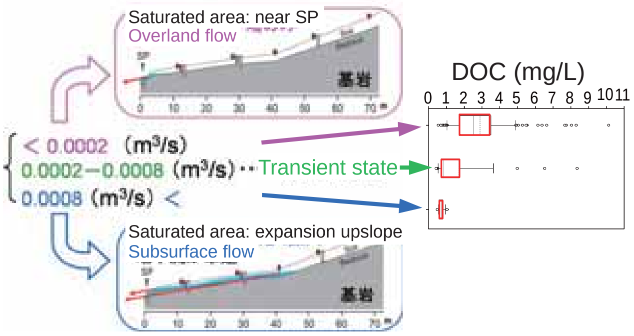


Outlet of the catchment (106 ha)

C-Q plot



Flow path and DOC concentration

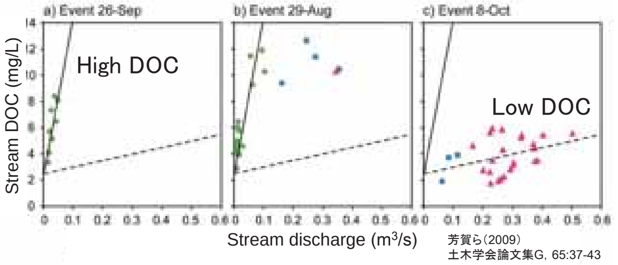


Flow paths in a hillslope were identified using spring discharge

Flow paths in a hillslope and C-Q in a catchment

Hillslope = 0.65 ha, Catchment outlet = 103 ha

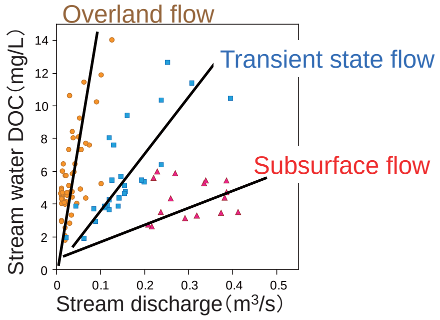
Overland flow-dominated | Transient state | Subsurface flow-dominated



芳賀ら（2009）
土木学会論文集G, 65:37-43

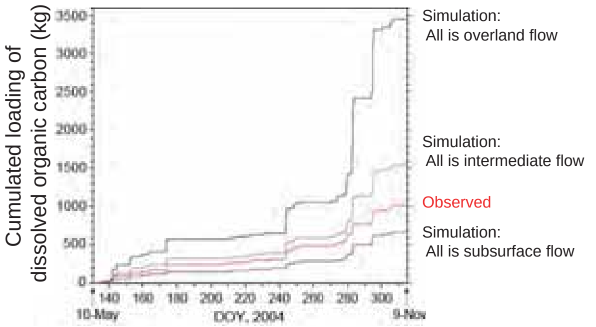
Shifting of flow path in a hillslope
→ Changes in concentration in a catchment

Contribution of saturated subsurface flow to DOC concentration of stream water



Increase of contribution of subsurface flow
➔ dilution of stream water DOC

Flow paths strongly control export loading



toward good countermeasures to lake eutrophication
➔ flow path-based estimation of loading exported from forests
➔ importance of rainfall-runoff mechanisms

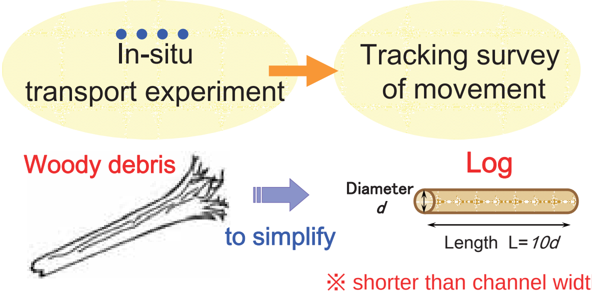
Woody debris in dam lake and salvage operation

Step formation associated with woody debris

Sediment trap / energy loss of flowing water caused by step

Investigation of woody debris movement

Haga et al. 2002



In-situ transport experiment → Tracking survey of movement

Woody debris → to simplify → Log

※ shorter than channel width
d = 0.14 m, L = 1.7 m

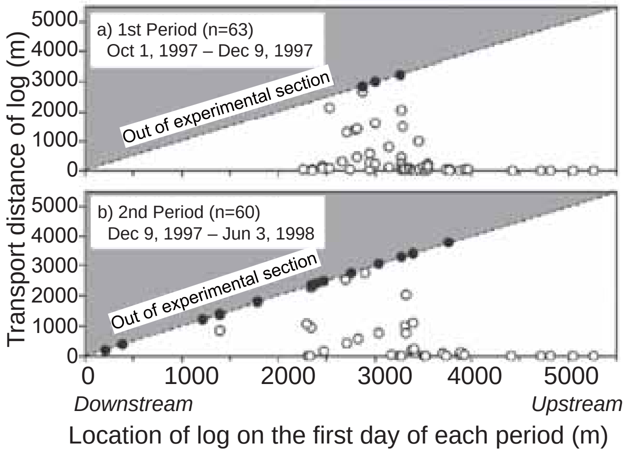
Experiment stream
catchment area 530 ha, reach length 5500 m, width 9 m, gradient 4%

Experimental log deposited after flood

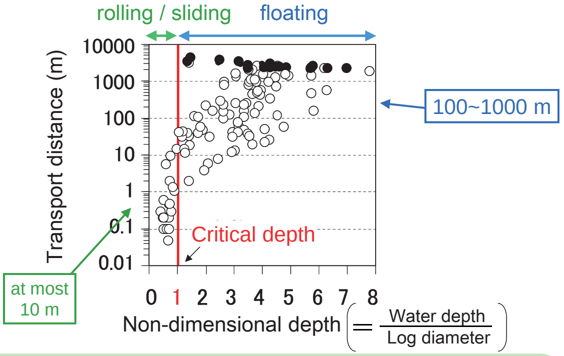
depositional form “grounded”

Other example of “grounded”

logs moved from a different site to deposit at the same site

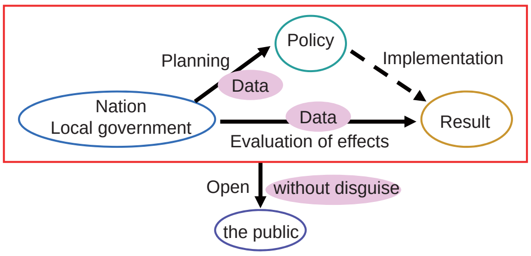


Theoretical consideration



Critical depth for floating → transport pattern
→ several orders of magnitude of transport distance

Scientific data as information for decision-making



Data is necessary and powerful for planning of policy,
but in case of issue related to natural environment…

- Data is not always correct
- Our knowledge about nature should be tested in each case
- People want information to judge the quality of policy whether government officials or general public

---

Japan ⇔ Your country

humid temperate — tropics / steppe / arid

Natural environmental conditions → large difference
but…..
Basic concept to deal with forest and water resources issues
→ little difference

- Understanding water balance (rainfall-runoff), flow path, quality based on objective data and scientific approach
- Planning of water resources policy and evaluating its effects based on scientific evidence and fact

L6: Evapotranspiration from forest

Yoshiko Kosugi (*Graduate School of Agriculture, Kyoto University*)

Abstract

With regard to the water cycle in terrestrial ecosystems, approximately 65% of precipitation reaching the land surface returns to the atmosphere as evapotranspiration, with the remainder running off to rivers and oceans. The partitioning of precipitation into evapotranspiration and runoff has been a significant concern for human societies from ancient times. Evapotranspiration is the main driver of the water cycle, and it governs the Earth’s climate system through control of the water cycle, energy budget, and greenhouse effect. It also has a huge influence on the carbon cycle, which is driven by photosynthesis, because transpiration occurs simultaneously with the uptake of CO_2 by plants via stomata. Thus evapotranspiration has an important role in many environmental processes. Studies in many environmental fields, including forest hydrology, have attempted to understand the bio-physical mechanism of evapotranspiration as a primary aim.

In this lecture, the significance of evapotranspiration is introduced, and two basic physical concepts, the energy balance and Penman-Monteith equation, that are commonly used to investigate the environmental and physiological control of evapotranspiration from vegetation, are described. Methods for estimating evapotranspiration based on field measurements are also outlined. In forest ecosystems, evapotranspiration can be divided into three components: transpiration of plant leaves from a dry canopy, evaporation from a wet canopy during and after rain, and evaporation from the soil surface. I also briefly explain how these components can be measured separately to investigate the factors that control them.

1. Basics of evapotranspiration
  1.1 Evapotranspiration and forest hydrology
  1.2 Energy balance
  1.3 Penman-Monteith equation
(Exercise)
2. Measurement of evapotranspiration
  2.1 Water budget method
  2.2 Micrometeorological methods
  2.3 Methods used to measure each components of evapotranspiration

International Hydrological Programme

Forest Hydrology –Conservation of Forest, Soil, and Water Resources

The Twenty-fourth IHP Training Course
23 November - 7 December, 2014

L6 : Evapotranspiration from forest

Yoshiko Kosugi, Kyoto Univ.

Contents

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   2.2 Micrometeorological methods
   2.3 Methods to measure each components of evapotranspiration

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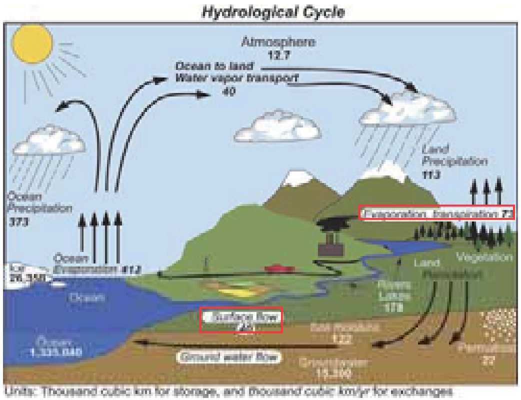
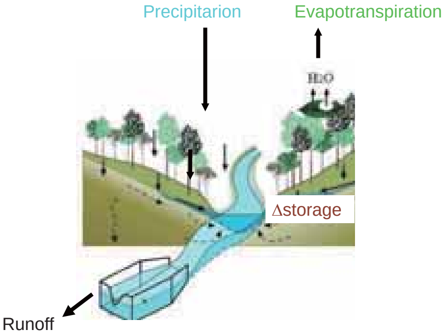
1.1 Evapotranspiration and forest hydrology



Trenberth et al, 2007, J. Hydrometeor, 8, 758-769

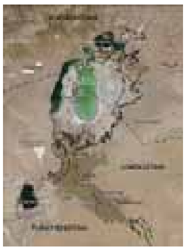
1.1 Evapotranspiration and forest hydrology

Runoff = Precipitation - Evapotranspiration - Δstorage



1.1 Evapotranspiration and forest hydrology

The partitioning of precipitation into evapotranspiration and runoff has been a significant concern for human societies.

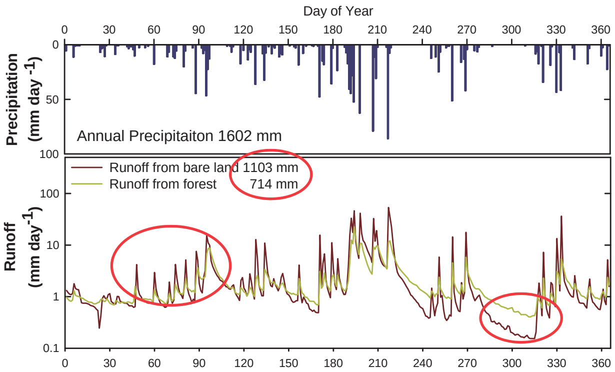


Aral Sea In 2004

In 1989 (left) In 2008 (right)

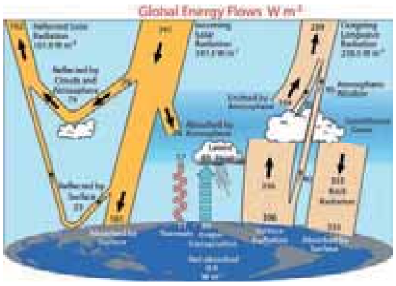
1.1 Evapotranspiration and forest hydrology

Water budget of forest vs. bare land

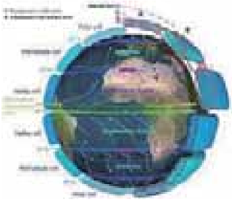


1.1 Evapotranspiration and forest hydrology

Evapotranspiration governs the Earth’s climate system through control of the water cycle, energy budget, and greenhouse effect.



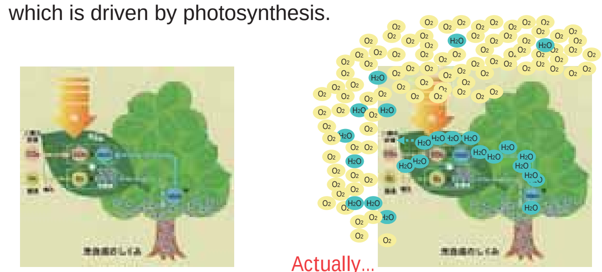
The atmosphere’s energy budget
(Trenberth et al. 2009)



The atmospheric circulation
(NASA illustration)

1.1 Evapotranspiration and forest hydrology

Evapotranspiration has a huge influence on the carbon cycle, which is driven by photosynthesis.



http://www.rinya.maff.go.jp/j/sin_riyou/ondanka/con_2.html

Actually…

In atmosphere

O_2:H_2O:CO_2 =550:100-25:1

Exchange through stomata

O_2:H_2O:CO_2 = 0.3:1000-10:-1

1.1 Evapotranspiration and forest hydrology

‘Evapotranspiration’

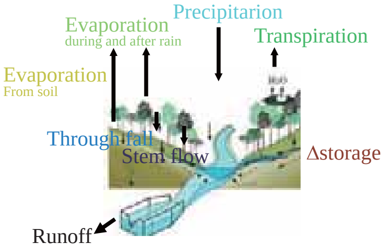
The process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants.

(Oxford Dictionary)

1.1 Evapotranspiration and forest hydrology

Three components of Evapotranspiration

✓Runoff = Precipitation - Evapotranspiration - Δstorage
✓Evapotranspiration = Transpiration + Evaporation during and after rain + Evaporation from soil
✓Evaporation during and after rain = Interception = Precipitation - Through fall - Stem flow

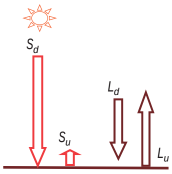


1.2 Energy budget

Energy Budget Equations

$R_n = S_d - S_u + L_d - L_u$

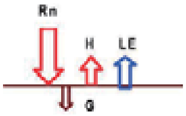
R_n : Net Radiation
S_d : Downward Shortwave (Solar) Radiation
S_u : Upward Shortwave Radiation
L_d : Downward Longwave Radiation
L_u : Upward Longwave Radiation



$R_n = H + \lambda E + G\ (+ S + M)$

R_n: Net Radiation
H : Sensible Heat Flux
λE : Latent Heat Flux
G : Soil Heat Flux
S : Physical Storage Flux
M : Metabolic Storage Flux

✓Unit W m^{-2}

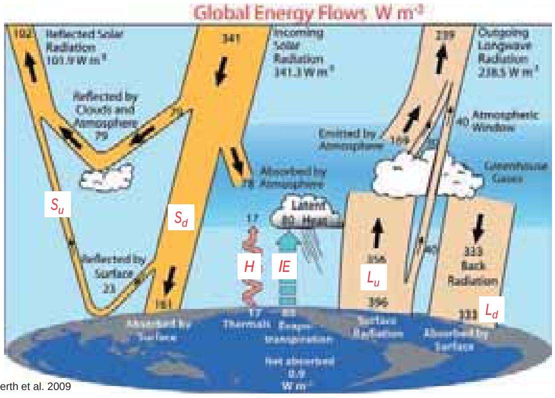


✓Flux : The rate of flow of a fluid, radiant energy, or particles across a given area

---

1.2 Energy budget

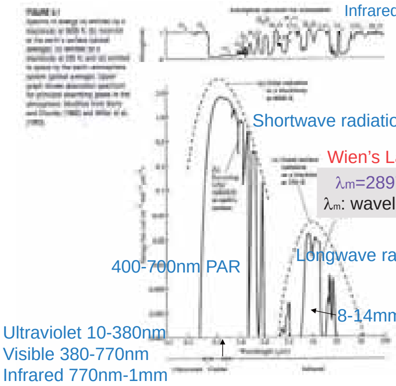
The Atmosphere’s Energy Budget



Trenberth et al. 2009

1.2 Energy budget

Wien's Law and greenhouse effect



Infrared absorbed by greenhouse gases

H_2O, CO_2

Shortwave radiation from the Sun (K=6000)

Wien's Law

λ_m=2897.769/T (mm)

λ_m: wavelength at max radiation (mm)

400-700nm PAR

Longwave radiation from the Earth (K=290)

8-14mm 'atmospheric window'

Ultraviolet 10-380nm
Visible 380-770nm
Infrared 770nm-1mm

1.2 Energy budget

Stefan-Boltzmann Law and Planetary temperature

Stefan-Boltzmann Law

$L_T = \varepsilon\sigma T^4$

L_T: radiation emitted per unit area per unit time by a material
ε: emittance (black body = 1)
σ: Stefan-Boltzmann constant (5.67*10^{-8} W m^{-2} K^{-4})
T : the Kelvin temperature of the material

Planetary temperature

$T_{planetary}=(L_t/\varepsilon\sigma)^{1/4}$ if L_t = 239 W m^{-2}, $T_{planetary}$ = 255K (-18C) too cold!

Nevertheless, because of the water vapor's greenhouse effect, actual temperature at the land surface is,

$T_{landsurface}$ = 288K (15C) suitable for the most living things

---

1.2 Energy budget

Energy budget, Earth vs Moon

EARTH

atmosphere => ***H***
L_d (greenhouse effect)
water => ***λE***

$R_n = H + \lambda E + G$

T = 17 C

MOON

no atmosphere => no ***H***
no L_d
no water => no ***λE***

$R_n = G$

Daytime : T = 130 C

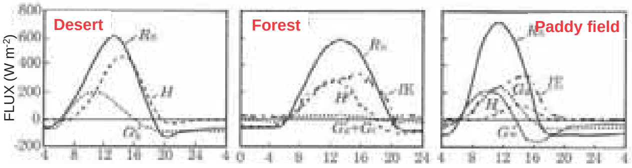
Nighttime : T = -170 C

Energy budget is a primary concept to understand the Earth's environment

---

1.2 Energy budget

Energy budget of various land surfaces



Desert : Vehrencamp 1953, Coniferous forest : Mcnaughton & Black 1973, Paddy field : Yabuki 1957

「農学·生態学のための気象環境学」より転写

What makes the difference in partitioning of net radiation ?

1.3 Penman-Monteith Equation

Transport Equation (Mass)

'Under steady state, the flux goes from regions of high concentration to regions of low concentration, with a magnitude that is proportional to the concentration gradient.' (Fick's First Law of Diffusion)

$J = -D(\delta c/\delta x)$

flux = diffusion coefficient × concentration gradient

J: flux [kg m^{-2} s^{-1}], D: diffusion coefficient [m^2 s^{-1}]
c: concentration [kg m^{-3}], x: distance [m]

↓(integrated form)

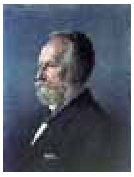
$J = D\Delta c/l$

Δc: concentration difference [kg m^{-3}] , l: length, thickness [m]

↓(use an analogy of Ohm's Law, $D/l = g = 1/r$)

$J = g\Delta c = \frac{1}{r}\Delta c$

g: conductance [m s^{-1}], r: resistance [s m^{-1}]



Adolf Eugen Fick (1829-1901)

1.3 Penman-Monteith Equation

Transport Equation (Heat)

'The rate of heat transfer is proportional to the temperature gradient present in a solid.' (Fourier's Law)

$C = -k(\delta T/\delta x) = -D_H \rho c_p(\delta T/\delta x)$

flux = diffusion coefficient × temperature gradient

C: heat flux [J m^{-2} s^{-1}], k: thermal conductivity [J m^{-1} s^{-1} K^{-1}]
T: temperature [K], x: distance [m], D_H: thermal diffusion coefficient [m^2 s^{-1}]
ρ: density [kg m^{-3}], c_p: specific heat capacity [J kg^{-1} K^{-1}]

↓(integrated form)

$C = D_H\rho c_p\Delta T/l$

ΔT: temperature difference [K] , l: length, thickness [m]

↓(using an analogy of Ohm's Law, $D_H/l=g_H=1/r_H$)

$C = g_H\rho c_p\Delta T = \frac{1}{r_H}\rho c_p\Delta T$

Joseph Fourier (1768-1830)

g_H: conductance for heat [m s^{-1}], r_H: resistance for heat [s m^{-1}]

1.3 Penman-Monteith Equation

Evaporation (*E*) and Latent Heat Flux (*λE*)

(from Fick's law for mass transfer)

$$E=g_W \Delta c_W$$

E: evaporation [kg m^{-2} s^{-1}], g_W: total conductance for water vapor [m s^{-1}], c_W: concentration of water vapor, absolute humidity [kg m^{-3}]

$$c_W=\rho_a (M_W/M_A)[e/(P-e)] \approx \rho_a (M_W/M_A)(e/P)$$
$$\gamma = P c_p \, M_A/M_W \lambda$$

ρ_a: density of dry air [kg m^{-3}], M_W: molecular mass of water, M_A: effective molecular mass of dry air, M_W/M_A=0.622, *P*: atmospheric pressure [Pa], γ: psychrometer constant [Pa K^{-1}], λ: latent heat of vaporization of water [J kg^{-1}], c_p: specific heat capacity [1012, J kg^{-1} K^{-1}], *e*: vapor pressure [Pa]

$$E = g_W (\rho_a (M_W/M_A)/P)\left(e_{s(Ts)} - e_a\right) = g_W \frac{\rho_a c_p}{\lambda \gamma}\left(e_{s(Ts)} - e_a\right)$$

$$\lambda E = g_W \frac{\rho_a c_p}{\gamma}\left(e_{s(Ts)} - e_a\right) = \frac{1}{r_W}\frac{\rho_a c_p}{\gamma}\left(e_{s(Ts)} - e_a\right)$$

$e_{s(Ts)}$: saturated vapor pressure at T_s [Pa], e_a: air vapor pressure [Pa]

1.3 Penman-Monteith Equation

Sensible Heat Flux (*H*)

(from Fourier's law for heat conduction)

$$H = g_H \rho_a c_p (T_s - T_a) = \frac{1}{r_H} \rho_a c_p (T_s - T_a)$$

H: sensible heat flux [W m^{-2}], g_H: total conductance for heat [m s^{-1}], ρ_a: density of dry air [kg m^{-3}], c_p: specific heat capacity [J kg^{-1} K^{-1}], T_s: surface temperature [K], T_a: air temperature [K]

1.3 Penman-Monteith Equation

Penman Equation (for evaporation from wet surface, 1948)

↓(if we don't know the surface temperature…..)

$$\lambda E = \frac{1}{r_W}\frac{\rho_a c_p}{\gamma}\left(e_{s(Ts)} - e_a\right) = \frac{1}{r_W}\frac{\rho_a c_p}{\gamma}\underbrace{\left[\left(e_{s(Ta)} - e_a\right) + \Delta(T_s - T_a)\right]}_{\text{Penman linearisation}}$$

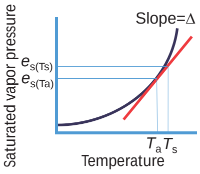
$$H = \frac{1}{r_H}\rho_a c_p (T_s - T_a)$$

$$r_H = r_W \quad \leftarrow \text{Assumption for wet surface}$$

$$H = (R_n - G) - \lambda E$$

↓(combining equations to solve *λE* without T_s)

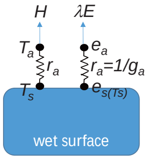
$$\lambda E = \frac{\Delta(R_n - G) + \rho_a c_p \left(e_{s(Ta)} - e_a\right)/r_H}{\Delta + \gamma}$$



To evaluate the potential evaporation rate from wet surface

1.3 Penman-Monteith Equation

Introduction of canopy resistance/conductance by J. Monteith



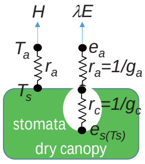
Howard Penman 1909-1984

[wet surface]
$r_H = r_W = r_a = 1/g_a$

[dry canopy]
$r_H = r_a = 1/g_a$
$r_W = r_a + r_c = 1/g_a + 1/g_c = (g_a + g_c)/g_a \, g_c$

r_a: aerodynamic resistance
r_c: canopy resistance

g_a: aerodynamic conductance
g_c: canopy conductance



John Monteith 1929-2012

1.3 Penman-Monteith Equation

Penman-Monteith Equation (for evapotranspiration from vegetation, 1965)

[Penman Equation for potential evaporation rate]

$$\lambda E = \frac{\Delta(R_n - G) + \rho_a c_p \left(e_{s(Ta)} - e_a\right)/r_a}{\Delta + \gamma}$$

[Penman-Monteith Equation for dry canopy]

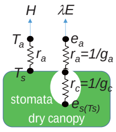
$$\lambda E = \frac{\Delta(R_n - G) + \rho_a c_p \left(e_{s(Ta)} - e_a\right)/r_a}{\Delta + \gamma(1 + r_c/r_a)}$$

Determining factors of evapotranspiration related to vegetation = aerodynamic resistance (r_a), canopy resistance (r_c)

1.3 Penman-Monteith Equation

Aerodynamic conductance vs Canopy conductance

forest



grass land, crop field

g_a: 50 – 1000 mm s^{-1}
g_c: 1 – 20 mm s^{-1}

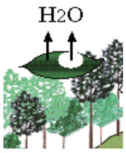
<u>g_c governs *E*</u>

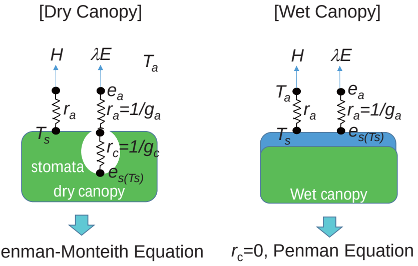
g_a: 5 – 100 mm s^{-1}
g_c: 1 – 40 mm s^{-1}

<u>Both g_c and g_a govern *E*</u>

1.3 Penman-Monteith Equation

Big Leaf Model





Penman-Monteith Equation

r_c=0, Penman Equation

Exercise

Q: Using the Penman-Monteith equation, calculate the evapotranspiration rate (E) and latent heat flux (λE) from a forest (g_a = 200 mm s^{-1}) or from short grass (g_a = 10 mm s^{-1}) for $\boldsymbol{R_n\text{-}G}$ = 400 W m^{-2}, T_a = 20C, $e_{s(Ta)}$ - e_s = 1kPa ; (a) when the surface is wet, (b) when g_c = 30 mm s^{-1}.
(Δ = 145 [20C, Pa K^{-1}], ρ_a = 1.204 [20C, kg m^{-3}], c_p = 1012 [J kg^{-1} K^{-1}],
γ = 66.1 [20C, 145 Pa K^{-1}], λ = 2.454 [20C, MJ kg^{-1}])

Caution! UNIT (mm s^{-1} -> m s^{-1}, kPa -> Pa, MJ kg^{-1} -> J kg^{-1})

A: (a) forest: E = 0.000581 kg m^{-2} s^{-1} λE = 1426 W m^{-2}
short grass: E = 0.000135 kg m^{-2} s^{-1} λE = 331 W m^{-2}

(b) forest: E = 0.000188 kg m^{-2} s^{-1} λE = 461 W m^{-2}
short grass: E = 0.000123 kg m^{-2} s^{-1} λE = 302 W m^{-2}

('Plants and Microclimate7 3rd Eddition, H.G. Jones, 2014)

Contents

1. Basics of evapotranspiration
   1.1 Evapotranspiration and forest hydrology
   1.2 Energy balance
   1.3 Penman-Monteith equation

(Exercise)

2. Measurement of evapotranspiration
   2.1 Water budget methods
   2.2 Micrometeorological methods
   2.3 Methods to measure each components of evapotranspiration

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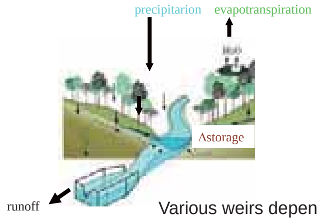
2.1 Water budget method

Runoff = Precipitation - Evapotranspiration - Δstorage



Various weirs depending on runoff range

2.1 Water budget method

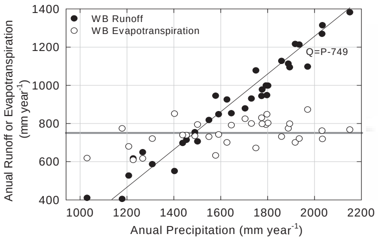
At KEW (Japanese cypress forest)

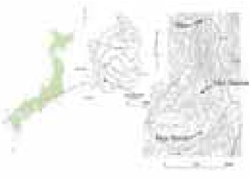
Precipitation : 1645mm

Runoff : 873mm

Evapotranspiration : 772mm

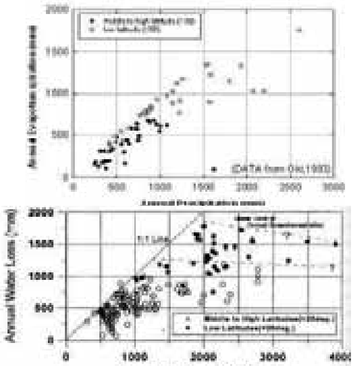
40 years average (1972-2011)





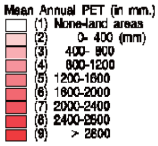
2.1 Water budget method

Water budget over the world



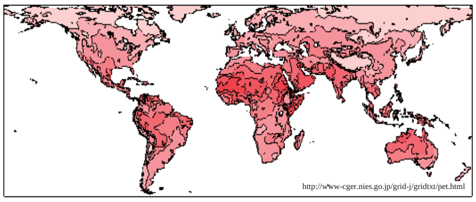
(Kondo, 1999)

2.2 Micrometeorological methods



Estimation of Potential Evaporation Rate

[using air temperature data]
Thornthwaite Eq., Hamon Eq.
[using more precise met data]
Penman Eq., Penman-Monteith Eq.



http://www-cger.nies.go.jp/grid-j/gridtxt/pet.html

How is the actual evapotranspiration from various vegetation ?

2.2 Micrometeorological methods

Micrometeorological methods for evaluating evapotranspiration

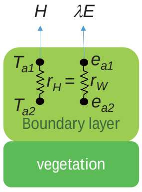
- ☐ Bowen ratio–energy balance (BREB) method
- ☐ Eddy covariance (EC) method

$$\boldsymbol{\lambda E}=(\boldsymbol{R_n}-\boldsymbol{G})/(1-\beta)$$

$$\beta=\frac{\boldsymbol{H}}{\boldsymbol{\lambda E}}=\left(\frac{P\rho_a c_p}{0.622\rho_a}\right)\frac{\Delta T}{\lambda\Delta e}$$

$$\Delta T=(T_{a2}-T_{a1})$$

$$\Delta e=(e_{a2}-e_{a1})$$



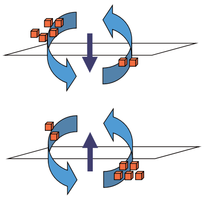
β : Bowen ratio

IS Bowen, 1926, The ratio of heat losses by conduction and by evaporation from any water surface, *Phys. Rev.*, 27, 779-787

2.2 Micrometeorological methods

Micrometeorological methods for evaluating evapotranspiration

- ☐ Bowen ratio–energy balance (BREB) method
- ☐ Eddy covariance (EC) method



✓If H_2O concentration is high when vertical wind go down, and low when wind go up,
net H_2O molecules were absorbed into vegetation.
(=condensation)

✓If H_2O concentration is low when vertical wind go down, and high when wind go up,
net H_2O molecules were emitted from vegetation.
(=evapotranspiration)

$$\lambda E=\lambda\overline{w'\rho_v{}'}$$

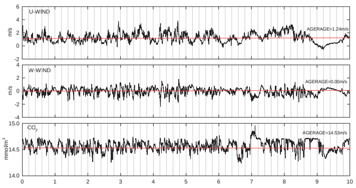
$$H=\rho_a c_p\overline{w'T'}$$

▣ H_2O molecule , ρ_v [kg m^{-3}]

Vertical wind, w [m s^{-1}]

2.2 Micrometeorological methods

Ecosystem flux observation with eddy covariance method

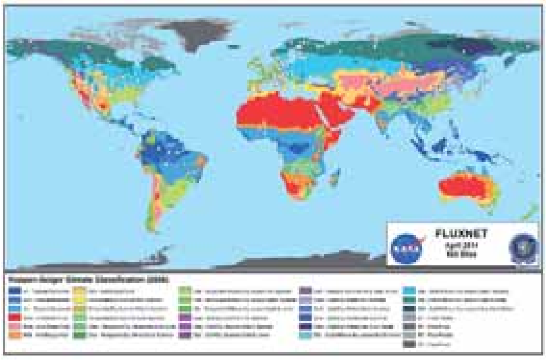


Ultra sonic anemometer
For x, y, z wind and T at 10Hz

Ultra sonic anemometer
For x, y, z wind and T at 10Hz

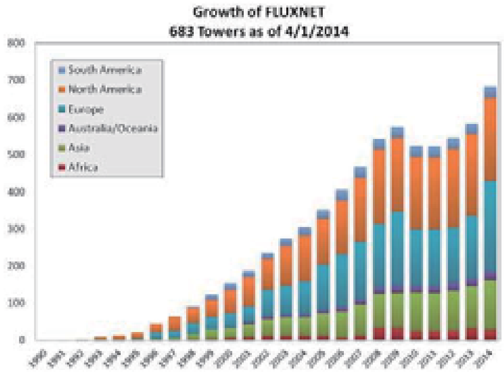
2.2 Micrometeorological methods

Ecosystem flux observation with eddy covariance method



2.2 Micrometeorological methods

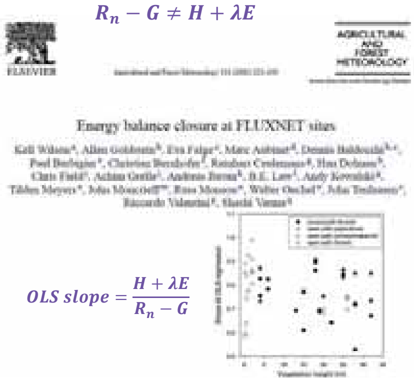
Ecosystem flux observation with eddy covariance method



2.2 Micrometeorological methods

Imbalance Problem

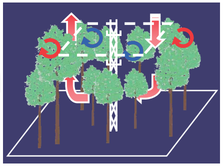
$$R_n - G \neq H + \lambda E$$


AGRICULTURAL AND FOREST METEOROLOGY

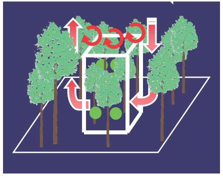
Energy balance closure at FLUXNET sites

$$OLS\ slope = \frac{H + \lambda E}{R_n - G}$$

Flux measured with EC =

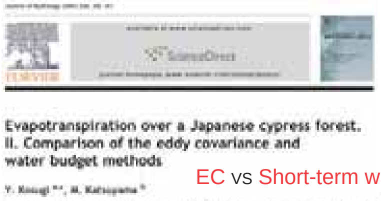


Total Flux = + +



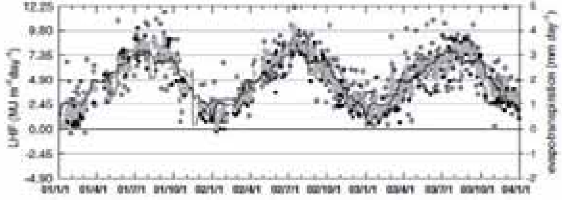
2.2 Micrometeorological methods

Cross check with water budget method


Evapotranspiration over a Japanese cypress forest.
II. Comparison of the eddy covariance and
water budget methods

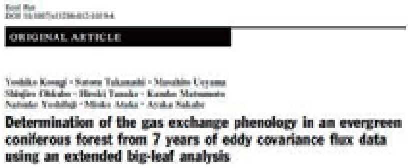
Y. Kosugi, M. Katsuyama

EC vs Short-term water budget

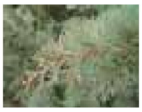


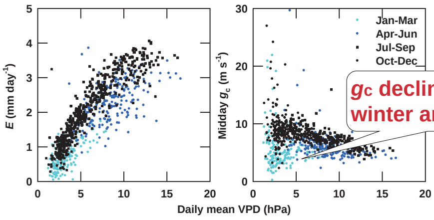
2.2 Micrometeorological methods

Big-leaf model analysis of canopy conductance


ORIGINAL ARTICLE

Determination of the gas exchange phenology in an evergreen coniferous forest from 7 years of eddy covariance flux data using an extended big-leaf analysis





g_c declined in winter and spring.

2.3 Methods to measure each components of evapotranspiration

Leaf-scale gas exchange

[Advantage]
- ✓ stomatal behavior
- ✓ link with photosynthesis
- ✓ control factors of gas exchange

Stomatal conductance model
- ☐ Jarvis type model
  (Jarvis 1976 Phil. Trans. R. Soc. Lond. B)
  + Lohammer function for *f*(*D*)
  (Lohammer 1980 Ecol. Bull.)
- ☐ Ball type model
  (Ball et al 1987Progress in Photosynthesis Res.)
  (Leuning 1995 Plant, Cell & Environment)

2.3 Methods to measure each components of evapotranspiration

Sap flow

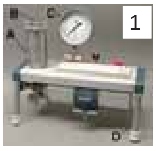
[Advantage]
- ✓ stand-scale continuous transpiration
- ✓ timing of the onset of transpiration
- ✓ scale up to the canopy transpiration

Sap flow measurements
- ☐ Heat pulse method (1)
  (Swanson & Whitfield 1981J. Exp. Botany)
- ☐ Thermal dissipation probe method (2)
  (Granier 1987 Tree Physiol.)
- ☐ Stem heat balance method (3)
  (Sakuratani 1981 J. Agric. Meteorol.)

etc..

2.3 Methods to measure each components of evapotranspiration

Plant water potential



[Advantage]
- ✓ Plant water status
- ✓ Pressure-volume curve
- ✓ SPAC water movement
  (Soil-Plant-Atmosphere Continuum)

Water potential measurements
- ☐ Pressure chamber (1)
  (Scholander et al 1964 Proc Na Aca Sci USA)
- ☐ Psychrometer (2)
- ☐ Stem Psychrometer (3)

2.3 Methods to measure each components of evapotranspiration

Interception (throughfall, stemflow, fog)


1


1

[Advantage]
- ✓ Evaporation during and after rain
- ✓ Water budget components

Interception measurements
- ☐ Throughfall (1)
- ☐ Stemflow (2)
- ☐ Fog (3)


1


2


3

2.3 Methods to measure each components of evapotranspiration

Leaf wetness

[Advantage]
- ✓ Transition between evaporation and transpiration at rainfall event
- ✓ gas exchanges during and after rain

Measurements
- ☐ Wetness sensors

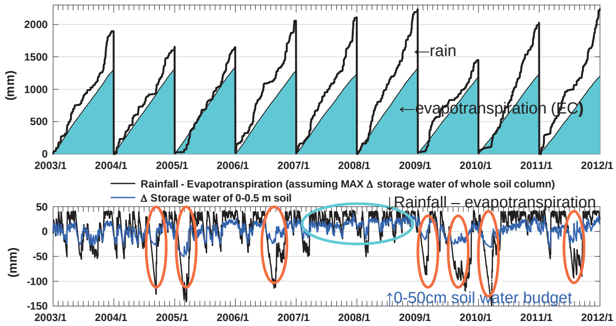
2.3 Methods to measure each components of evapotranspiration

Lysimeter

[Advantage]
- ✓ Soil evaporation
- ✓ Snow evaporation
- ✓ Evapotranspiration from crop/grass field
- ✓ Whole-plant transpiration

2.3 Methods to measure each components of evapotranspiration

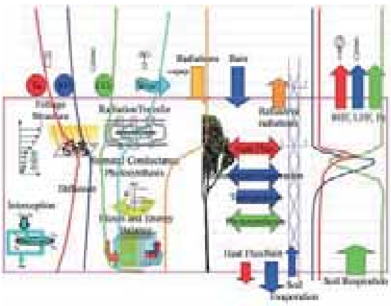
Combination of EC flux and soil water budget method



Data based on Kosugi et al 2011 JFR

2.3 Methods to measure each components of evapotranspiration

Multi-layer model parameterized with field observations



[Advantage]
- ✓ Control factor analysis
- ✓ Scale up
- ✓ Ecosystem modelling

etc..

L7: Water resources in forested watershed

Hikaru Komatsu (*The Hakubi Center for Advanced Research, Kyoto University, Japan*)

Abstract

This class will be held on the last day of the series of lectures. You will have learned basic knowledge of forest hydrology before this day. In this class, we will apply the knowledge to think about practical problems.

This class focuses on the relationship between forests (or, more generally, vegetation) and water resources (WR). Specifically, we will study two questions, i.e., (1) whether deforestation/afforestation reduces WR and (2) whether converting native forests to plantations reduces WR.

First of all, we will think about why these problems are important. Many factors, other than vegetation, affect WR (e.g., topography, geology, and meteorology). What is the difference between the vegetation factor and other factors? Also, we will discuss how to represent WR. The meaning of "WR" is vague, as that of "intelligence" is. What kinds of indices do we use to represent "WR"?

To study the two problems raised above, there are two steps. First, changes in WR with changes in vegetation (e.g., deforestation) are evaluated using data recorded at a site. Second, applicability of the results to other sites/regions are examined. We will see methods (e.g., time-trend analysis and the paired-catchments method) used in the first step and discuss advantages and disadvantages of each method. We will see methods used in the second step and learn a lesson that although Asia has been learning from results obtained in advanced countries such as Europe and America, the results are not always applicable to Asia. Namely, we have to consider indigenous conditions of the target region to propose a WR policy, instead of directly adopting policies developed in Europe and America. I am looking forward to seeing and talking with you all.

Water Resources in Forested Watershed

Hikaru Komatsu

The Hakubi Center for Advanced Research, Kyoto University

Personal History

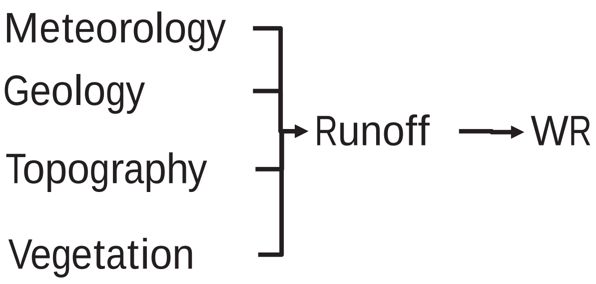
Sameura dam reservoir in Shikoku

Today’s questions

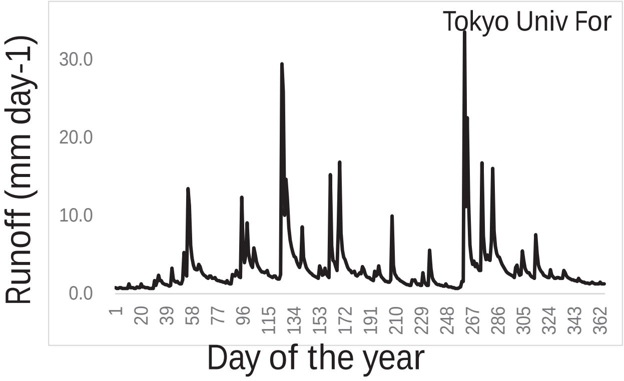
1. Deforestation/Afforestation reduces water resources (WR)?

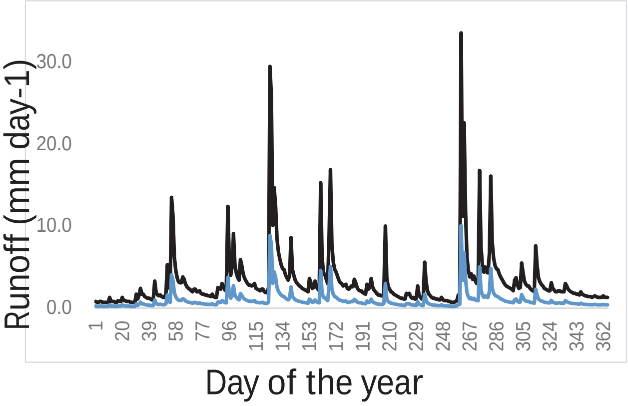
2. Converting native forests to plantations reduces WR?

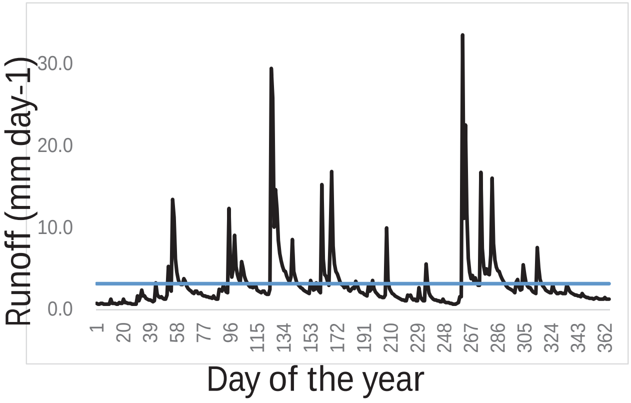
Why is vegetation important?



How to represent water resources?







Two steps

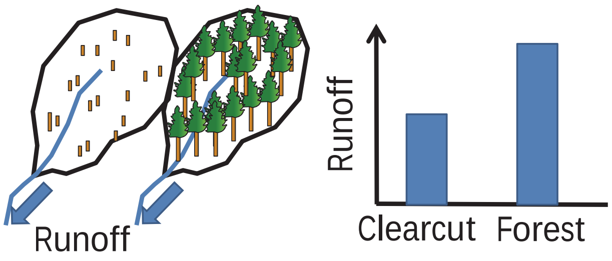
1. Examine changes in WR at a site

2. Assess applicability of the results to other sites/regions

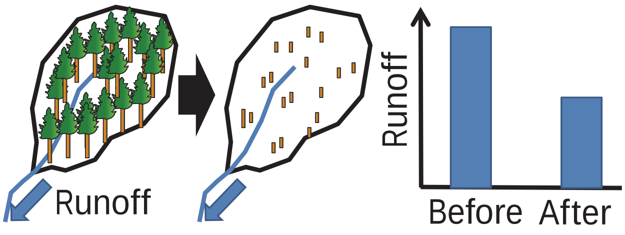
---

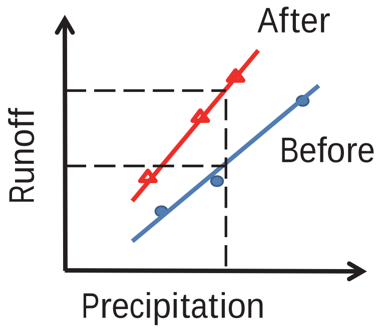
Examination at a site

Simple comparison

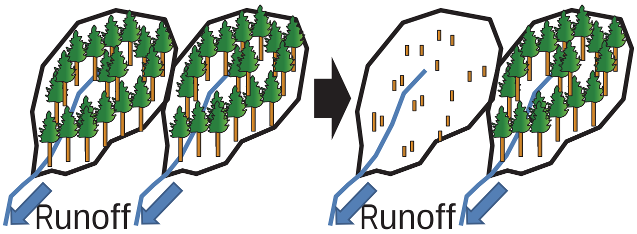


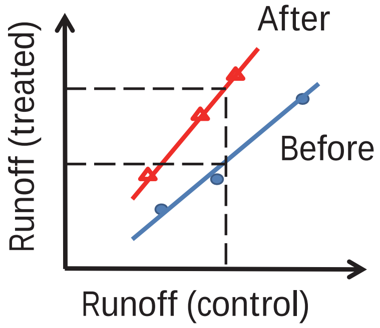
Time-trend analysis





Paired-catchments method



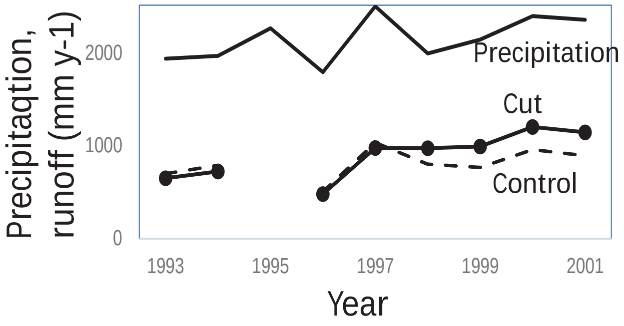


Deforestation/Afforestation

Tokyo University Forests

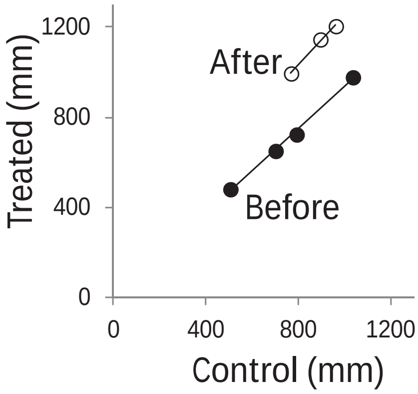
Raw data

Maita et al. (2005)



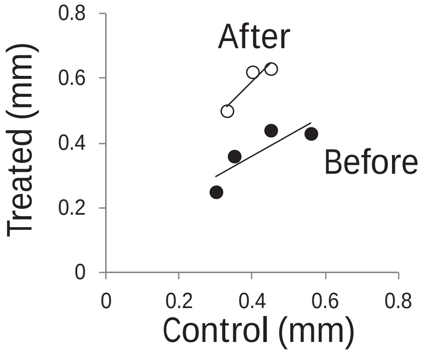
Annual runoff

Maita et al. (2005)

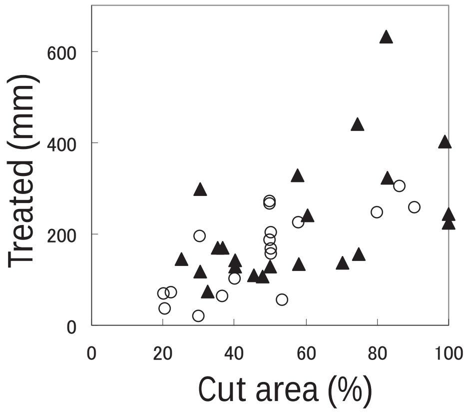


Low flow

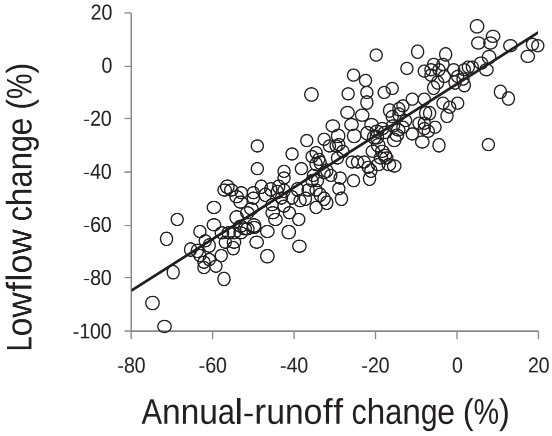
Maita et al. (2005)



Bosch and Hewlett (1982)

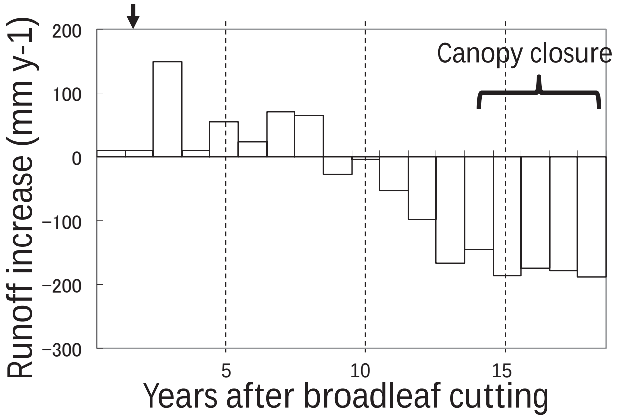


Farley et al. (2005)

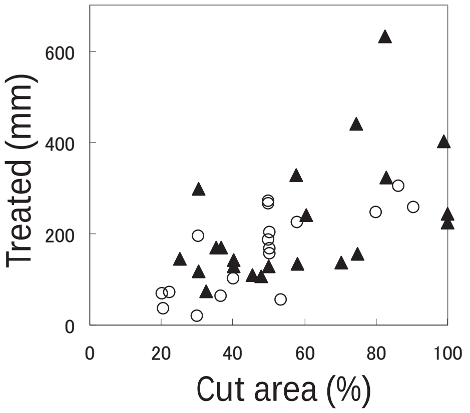


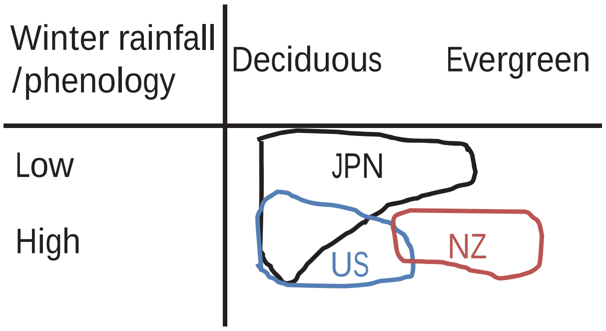
Native forests/plantations

Swank and Douglass (1974)

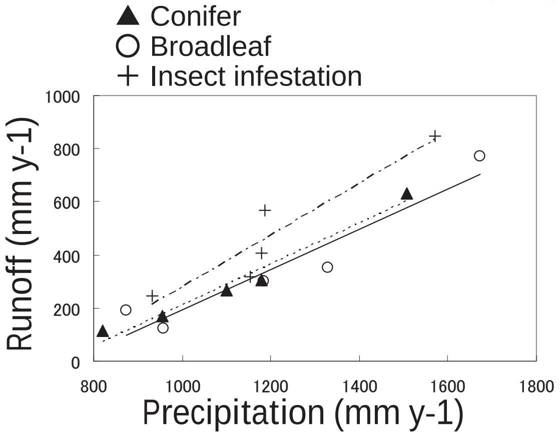


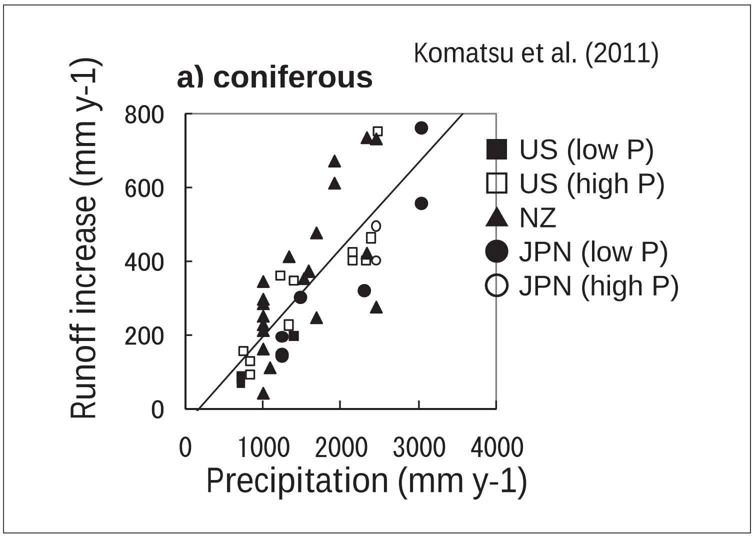
Bosch and Hewlett (1982)



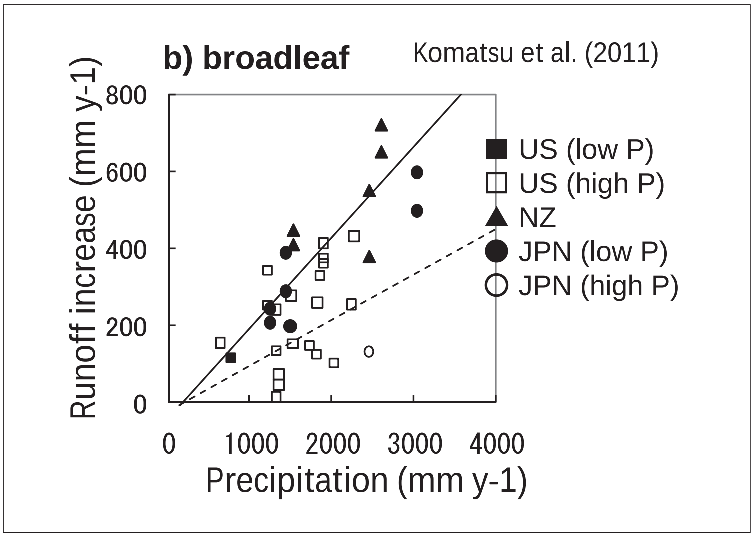


Komatsu et al. (2009)





Komatsu et al. (2011)



Komatsu et al. (2011)

L8: Basics of forest dynamics

Hisashi SATO (*Japan Agency for Marine-Earth Sciences and Technology, JAMSTEC*)

Abstract

Vegetation is the most crucial component affecting water and energy cycles on the land surface. Indeed, between 80% and 90% of the total evapotranspiration from the land surface is estimated to be caused by transpiration, and the process consumes almost half of the solar energy absorbed by the land-surface. The impact of vegetation on the climatic environment is evident in our everyday experience. For example, the temperatures of land surface in urban areas covered in concrete and asphalt are typically higher than those in areas covered in vegetation.

Therefore, around middle of the 1980's, simulation models used for predicting long-term climate changes have embedded Land Surface Model (LSMs) that consider such interactions between terrestrial surface and atmosphere. Initially, these models only treated the water and radiation balances on the land surface. Around the end of the 20th century, they gradually incorporated carbon balances to predict changes in atmospheric CO_2 concentration. Subsequently, the changes in vegetation distribution caused by climate change were also taken into consideration.

In this lecture, I present a brief explanation of the various land-atmosphere interactions and how such interactions have been modeled. Subsequently, we will look into detail for forest dynamics and plant geography, both of which constitute recent LSMs. We will allot enough time for learning forest dynamics, and how it interacts with local environment. Finally, we will discuss how such LSMs can be utilize for planning forest and landscape managements under trend of rapid climatic change.

The Twenty-fourth IHP Training Course
Forest Hydrology
Conservation of Forest, Soil, and Water Resources
23 Nov.~7 Dec., 2014 @ Nagoya, Japan

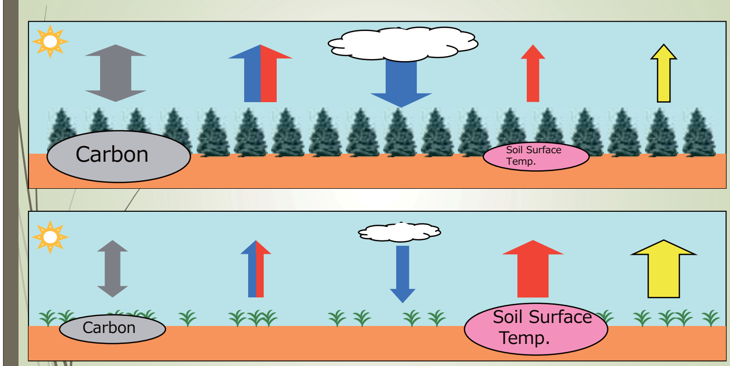
Forest Dynamics
~basis and modelling~

26 Dec 09:30-12:00, Lecture
26 Dec 14:00-16:30, Exercise

Lecturer
Hisashi SATO
(Japan Agency for Marine-Earth Sciences and Technology)

Interactions between Vegetation and Atmosphere

How vegetation affects interactions between terrestrial surface and atmosphere



Carbon cycle | Transpiration/ Latent heat | Precipitation | Sensible heat | Shortwave reflection

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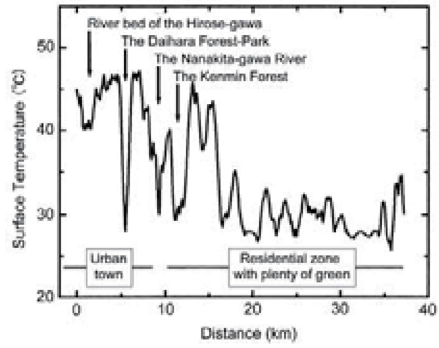
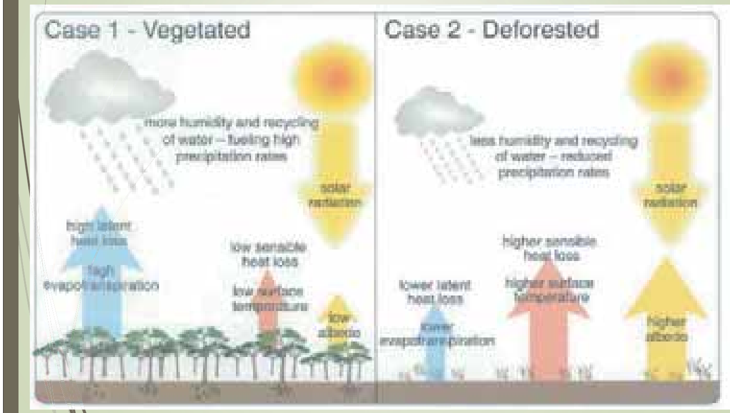
[Example] Vegetation impact on surface temperature

Geographical distribution of surface temperature observed at Sendai city during daytime on a mid-summer day



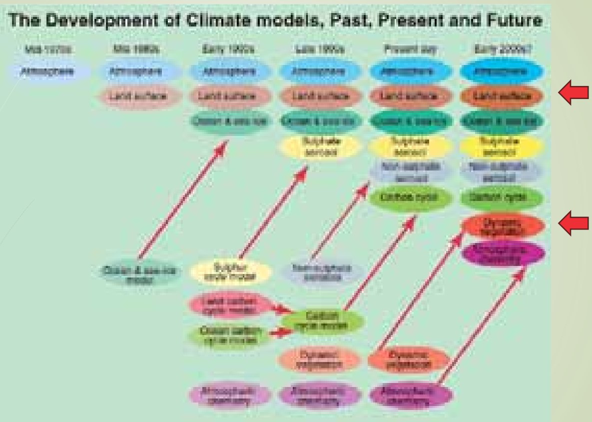
Observations were made in the air using a helicopter-based radiation thermometer (Observed by Hirofumi SUGAWARA). From Kondo (2000), modified by Sato et al. (2014)

[Example] Climatic effects of Tropical deforestation



Foley et al. (2003)

The Development of Climate models



Box 3, Figure 1: The development of climate models over the last 25 years showing how the different components are first developed separately and later coupled into comprehensive climate models.

From: Climate Change 2001 (IPCC) Technical Summary of the Working Group I Report

Timescales of land-ecosystem processes

PHYSIOLOGICAL

Photosynthesis

Stomatal Opening

Leaf Phenology

ECOLOGICAL

Demography
(Changes in growth, mortality, & recruitment rates)

Biome Shift
(Changes in distribution of biome)

Succession
(Changes in canopy structure & composition)

Hours | Months | Years | Decades | Centuries

Weather Prediction

Inter-annual Variability

Anthropogenic Climate Change

Incorporating ecological Processes is critical to forecast the responses of land-ecosystems to anthropogenic climate change

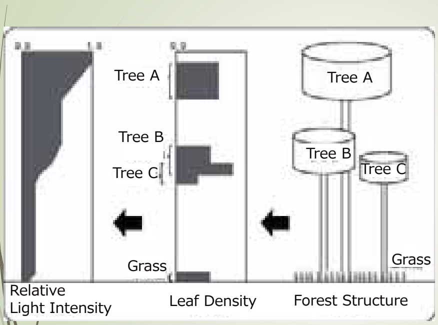
Original Figure: Prof. Moorcroft, P.R.

Basis for plant population dynamics

Topics:

- One-sided competition for light
- Self-thinning rule & Three-halves law
- Succession
- Gap-dynamics
- Wild fire as a major disturbance scheme

One-sided competition for light



A Light attenuation formulation based on the Lambert-Beer law

$$I = LAI^{\,k}$$

I Relative Sun-Light Intensity

LAI Leaf Area Index above the mentioned layer (m^2)

K Light Attenuation Factor (Typically around -0.5)

Local vertical structure prominently controls competition for light among trees

---

The Self-thinning & Three-halves law

In a dense plant population, the "Self-thinning" occurs with growth of mean plant size. This process generally results in the "Three-halves law".

Theory

$W \backsim L^{3}$ $A \backsim L^{2}$

$W \backsim A^{3/2}$ $A \backsim D^{-1}$

Tree-halves law

$W \backsim D^{-3/2}$

Example (Obs.)

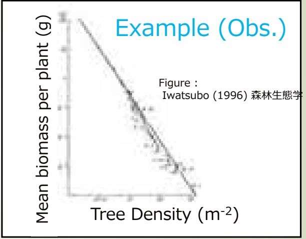


Figure :
Iwatsubo (1996) 森林生態学

L : Length of side of a plant
W : Mean biomass per plant
A : Area per a plant
D : Plant density

Primary Succession

Succession: Sequential changes of physiognomy, those are mediated by plant induced environmental changes (such as soil formation and sun light interception)

[Example] Temperate forest in North America

If it begins in barren area where soil was not formed, it is called **Primary Succession**

Source of this figure:
tree: primary succession. [Art]. In Britannica Online for Kids. Retrieved from http://kids.britannica.com/comptons/art-90129

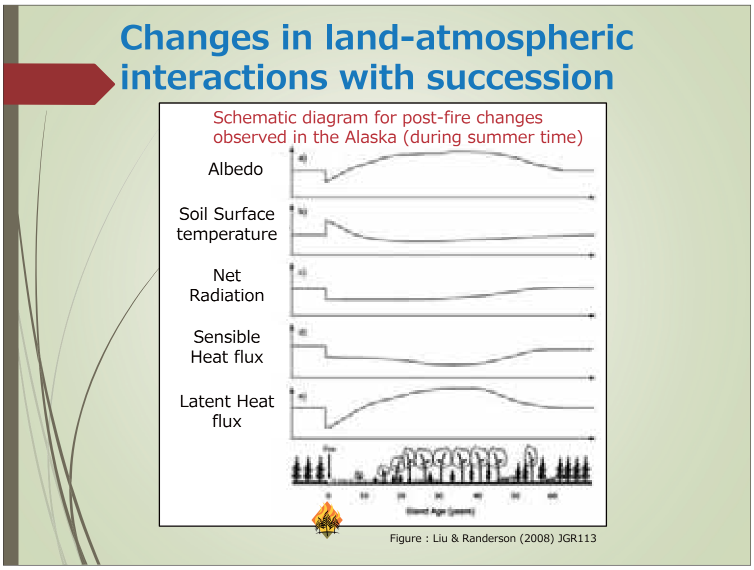
Secondary Succession

If succession occurs on a disturbed site with soil, it is called **Secondary Succession**

[Example] Temperate forest in North America

Secondary succession is a much faster process than to the primary succession

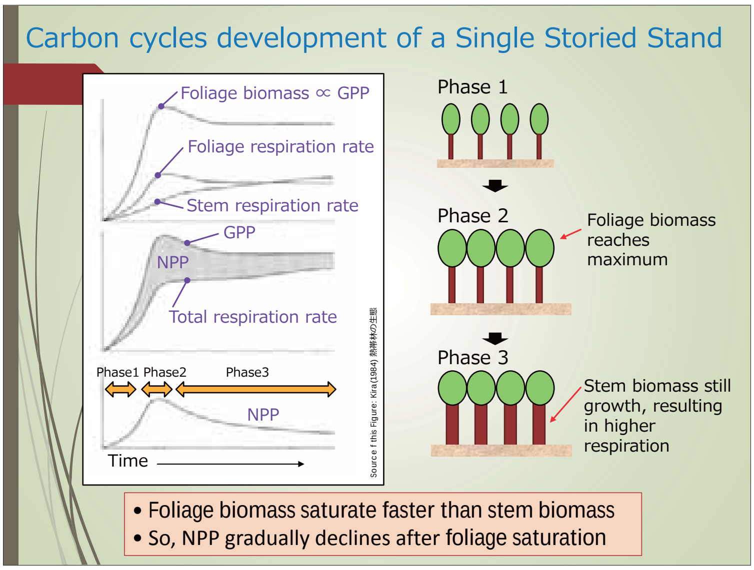
Source of this figure:
forest fire: secondary succession. Art. Britannica Online for Kids. Web. 9 Sept. 2014. <http://kids.britannica.com/comptons/art-90130>.



Changes in land-atmospheric interactions with succession

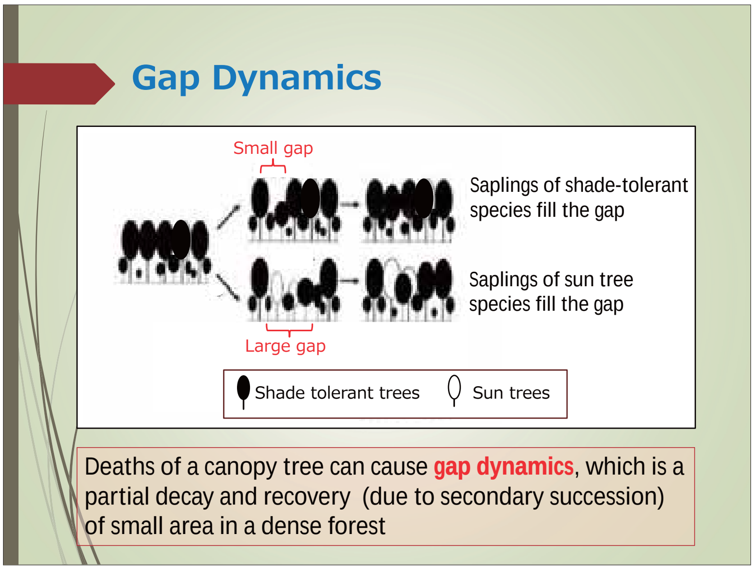
Schematic diagram for post-fire changes observed in the Alaska (during summer time)

Figure : Liu & Randerson (2008) JGR113



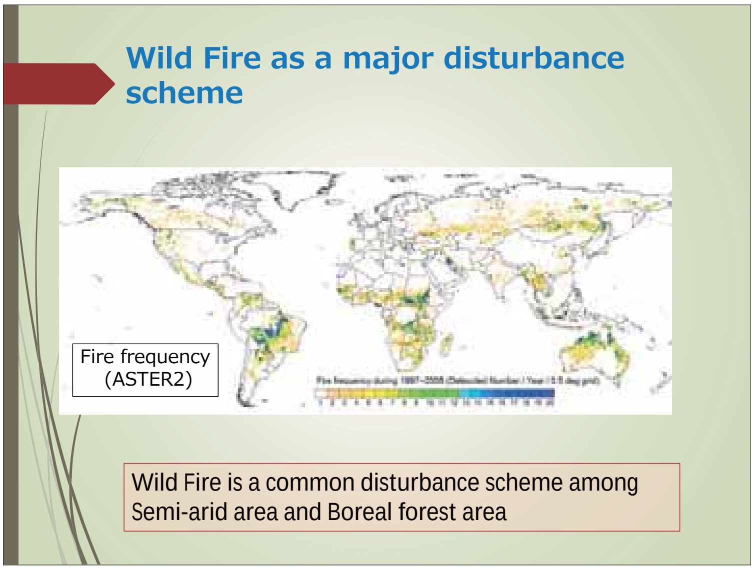
Carbon cycles development of a Single Storied Stand

- Foliage biomass saturate faster than stem biomass
- So, NPP gradually declines after foliage saturation



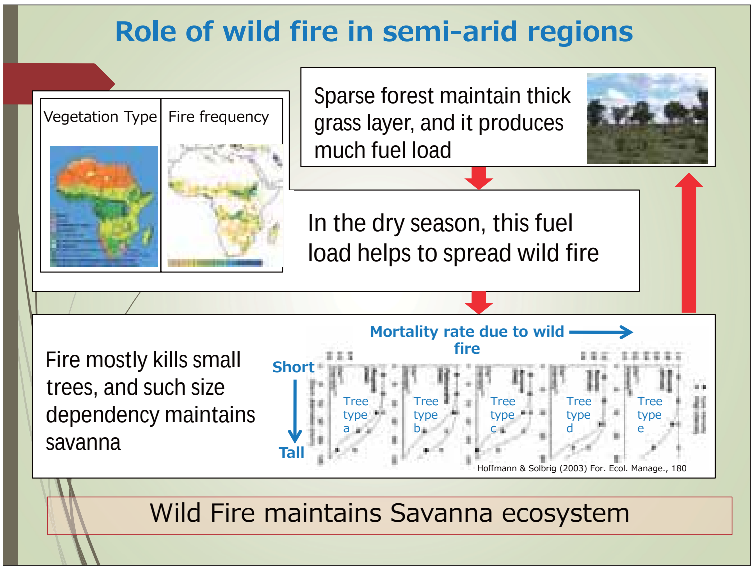
Gap Dynamics

Deaths of a canopy tree can cause **gap dynamics**, which is a partial decay and recovery (due to secondary succession) of small area in a dense forest



Wild Fire as a major disturbance scheme

Wild Fire is a common disturbance scheme among Semi-arid area and Boreal forest area



Role of wild fire in semi-arid regions

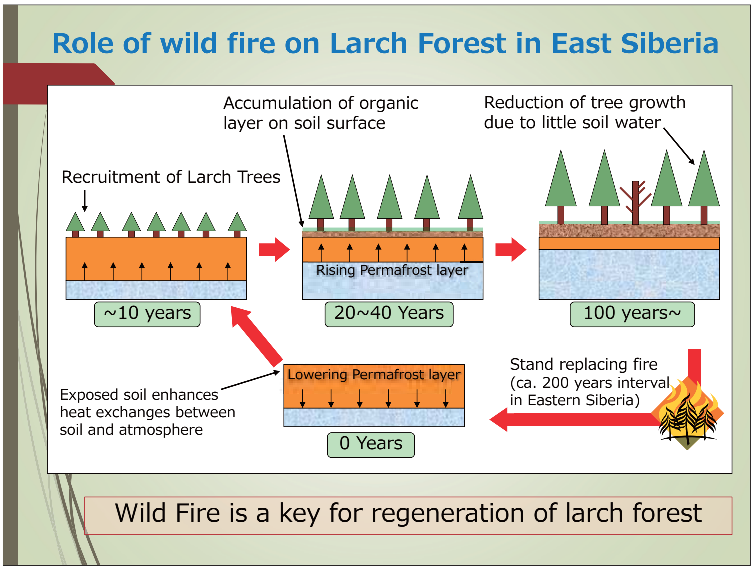
Sparse forest maintain thick grass layer, and it produces much fuel load

In the dry season, this fuel load helps to spread wild fire

Fire mostly kills small trees, and such size dependency maintains savanna

Hoffmann & Solbrig (2003) For. Ecol. Manage., 180

Wild Fire maintains Savanna ecosystem



Role of wild fire on Larch Forest in East Siberia

Exposed soil enhances heat exchanges between soil and atmosphere

Stand replacing fire (ca. 200 years interval in Eastern Siberia)

Wild Fire is a key for regeneration of larch forest

Land Surface Models (LSMs) those treat plant population dynamics

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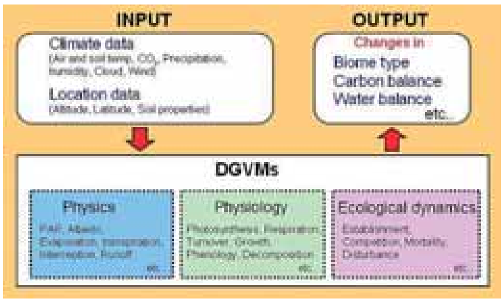
About SEIB-DGVM

I/O and Composition of SEIB-DGVM



Vegetation Representation

A simulation result for Temperate forest

Individual trees compete for light and space within a virtual forest

---

Sub-models that compose SEIB-DGVM

	Process	Approach	Source
Physical process	Radiation	Beer's law	
	Evapotranspiration	Penman-Monteith transpiration + interception + evaporation from soil surface	Monteith & Unsworth (1990)
	Soil water process	Simple bucket model	Manabe (1969)
Physiology	Photosynthesis	Michaelis-type function	
	Maintenance respiration	respiration rate is in proportion to nitrate contents for each organ	Ryan (1991)
	Growth respiration	based on chemical composition of each organ	Poorter(1994)
	Stomatal conductance	a semi-empirical model as a function of VPD	Leuning et al. (1995)
	Phenology	a set of semi-empirical models of which parameters were estimated from satellite NDVI data	Botta et al. (2000)
	Decomposition	2 carbon source of decomposition: labile part of litter and passive part in mineral soil	Sitch et al. (2003)
Ecologocal Dynamics	Establishment	climatically favored PFTs establish as small individuals	Sitch et al. (2003)
	Mortality	function of "annual NPP per leaf area", "heat stress", "bioclimitic limit", and "fire"	Sitch et al. (2003)
	Disturbance (fire)	an empirical function of soil moisture and fuel load	Kirsten et al (2001)

Plant species were summarized into Plant Functional Types (PFTs)

Woody PFTs (8 types)

Tropical	broad-leaved	evergreen
Tropical	broad-leaved	raingreen
Temperate	needle-leaved	evergreen
Temperate	broad-leaved	evergreen
Temperate	broad-leaved	summergreen
Boreal	needle-leaved	evergreen
Boreal	needle-leaved	summergreen
Boreal	broad-leaved	summergreen

Grass PFTs (2 types)

C3 - grass
C4 - grass

Herbaceous species are represented by average biomass per unit area

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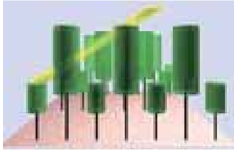
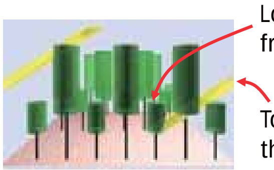
Photosynthesis condition for woody PFTs (Direct radiation)



Midday radiation is calculated
for each individual tree
for each 10cm-interval crown layer.

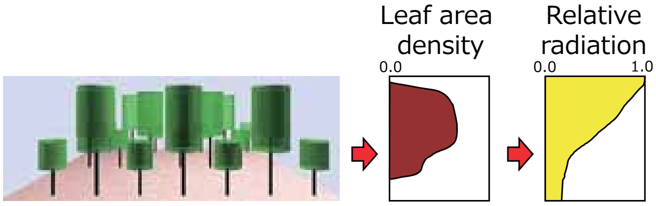


Lower crown layer suffers from self-shading

To avoid 'edge effect', it is assumed that virtual forest repeats

---

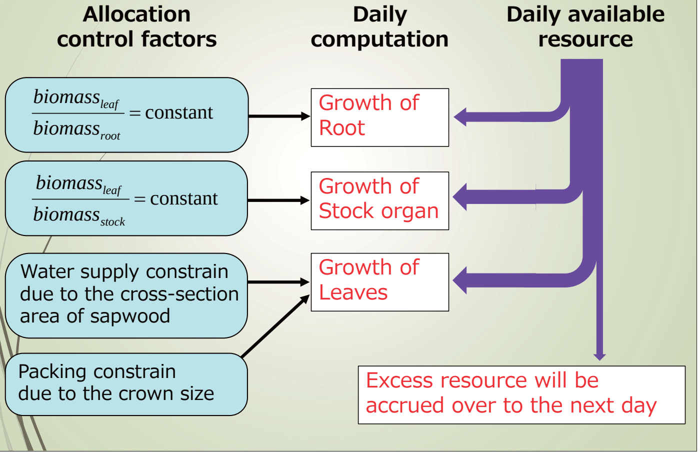
Photosynthesis condition for woody PFTs (Diffused radiation)



Based on average leaf-area-density for each crown layer, mean intensity of diffused radiation was calculated for each crown layer

Horizontal structure was ignored

Growth procedure for woody PFTs (1)



Allocation control factors

Daily computation

Daily available resource

$\frac{biomass_{leaf}}{biomass_{root}} = \text{constant}$ → Growth of Root

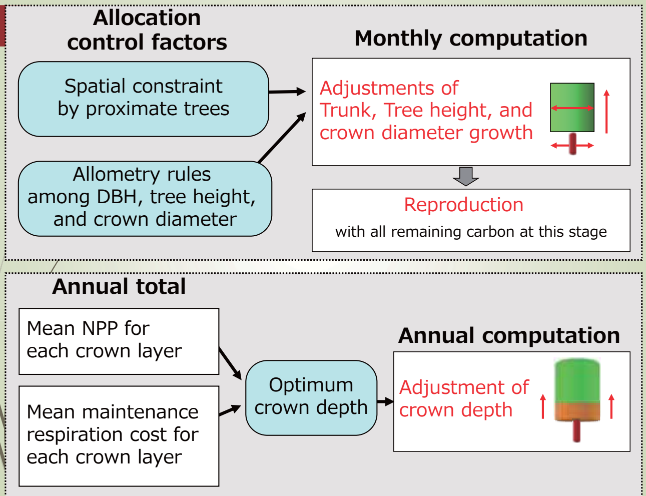
$\frac{biomass_{leaf}}{biomass_{stock}} = \text{constant}$ → Growth of Stock organ

Water supply constrain due to the cross-section area of sapwood → Growth of Leaves

Packing constrain due to the crown size → Growth of Leaves

Excess resource will be accrued over to the next day

Growth procedure for woody PFTs (2)



Allocation control factors

Monthly computation

Spatial constraint by proximate trees

Allometry rules among DBH, tree height, and crown diameter

Adjustments of Trunk, Tree height, and crown diameter growth

Reproduction

with all remaining carbon at this stage

Annual total

Annual computation

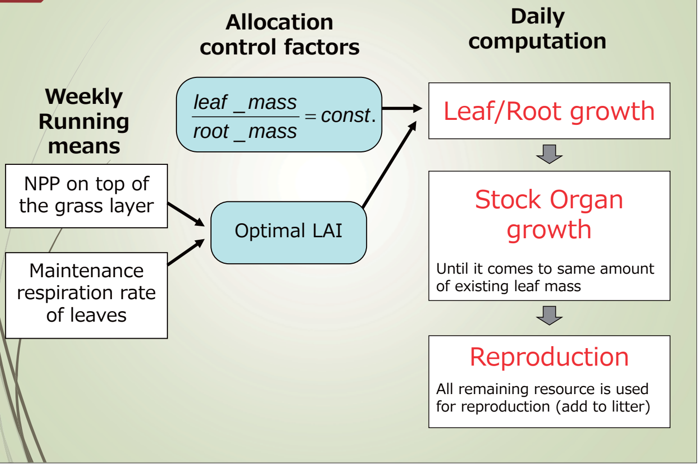
Mean NPP for each crown layer

Mean maintenance respiration cost for each crown layer

Optimum crown depth

Adjustment of crown depth

Growth procedure for Grass PFTs



Weekly Running means

Allocation control factors

Daily computation

NPP on top of the grass layer

Maintenance respiration rate of leaves

$\frac{leaf\_mass}{root\_mass} = const.$

Optimal LAI

Leaf/Root growth

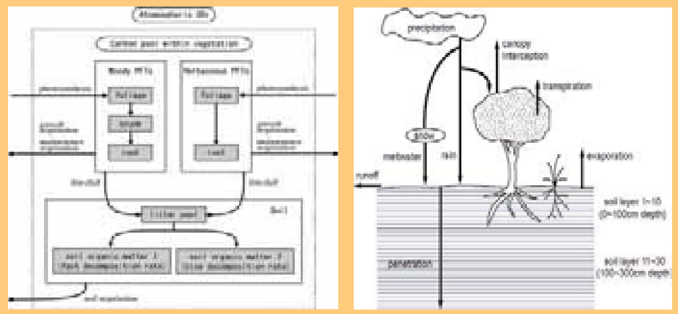
Stock Organ growth

Until it comes to same amount of existing leaf mass

Reproduction

All remaining resource is used for reproduction (add to litter)

Carbon and Water cycles



Carbon cycles

Water cycles

From Sato et al. (2007)

Class Discussion

How Dynamic Vegetation Models can be utilized for Forest Management

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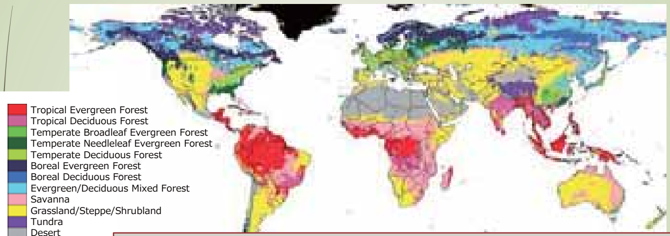
Supplements

Plant geography and Biome

Topics:
- Global distribution of natural vegetation
- Biomes (Definition, Distribution, and Boundary)
- Bioclimatic limits

Global Distribution of Natural Vegetation[1]



Biome:

A major regional ecological community characterized by distinctive life forms and principal plant species[2].

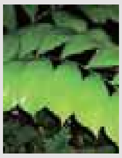
Terrestrial ecosystems are typically classified into 5~20 biomes, those are mostly determined by climate.

[1] ISLSCP2
[2] A Dictionary of Ecology, Evolution and Systematics

An example of Biome: Tropical rain forest

Common characteristics

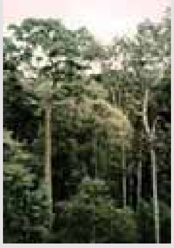
Drip tips



Buttress root

Epiphytic plants

Dense and stratified forest structure



Photos are gathered from the Web

These characteristics are commonly observed in Tropical rain forests, although species composition much differs among regions

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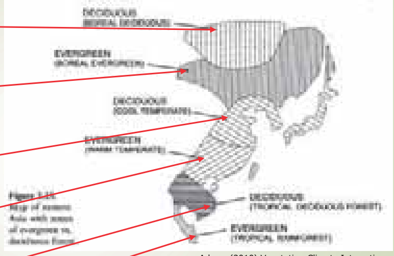
Biome distribution in eastern Asia



Adams (2010) Vegetation-Climate Interaction

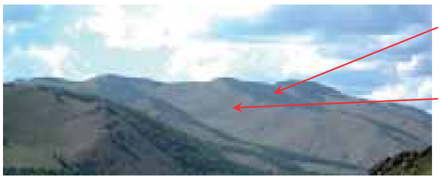
- Very short summer, and very cold winter
- Needle leaves are tolerant for frost damage and dehydration
- Winter is not suitable for photosynthesis
- Moderate climate throughout the year
- Warm and Humid throughout the year
- Warm throughout the year, but dry season exist

In eastern Asia, alternative band of Evergreen and Deciduous forest exists along latitude

---

Biome boundary

[Example] Northern part of Mongolia



North-faced slope: Larch forest

South-faced slope: Steppe

Photo: Forests of Northern Mongolia - FCA Today (www.fca-today.com/page13.html)

Biome boundaries generally transit gradually, but topographic heterogeneity produces mosaic-structured transition zone

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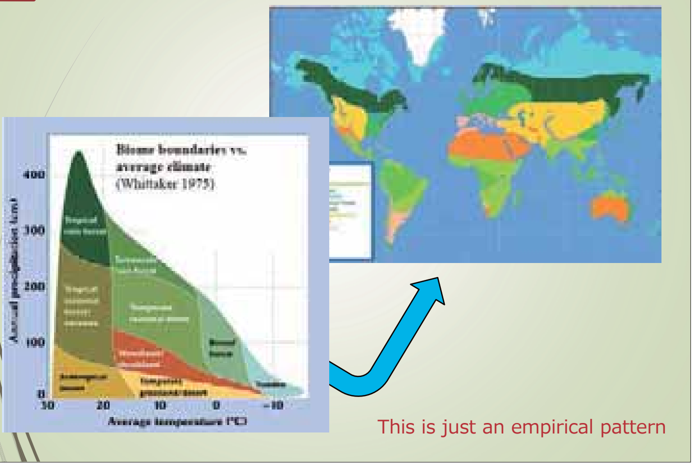
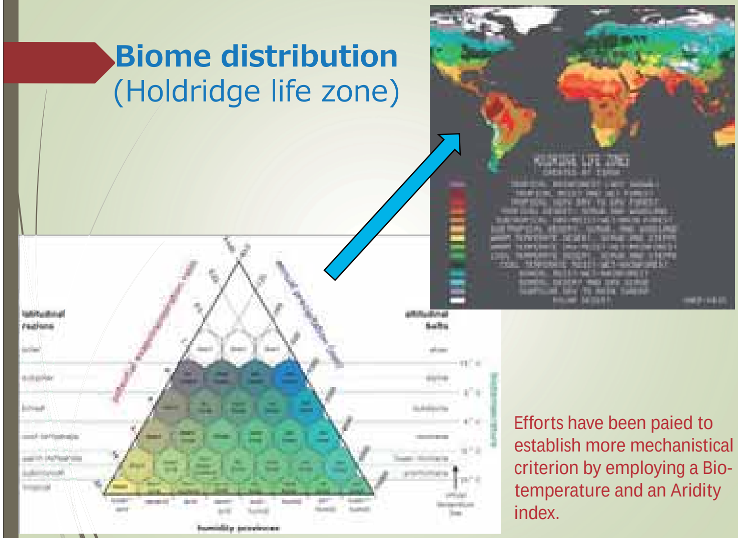
Biome distribution (Whittaker)



This is just an empirical pattern

Biome distribution
(Holdridge life zone)



Efforts have been paied to establish more mechanistical criterion by employing a Bio-temperature and an Aridity index.

Bioclimatic limits 1: Physiological Requirements[†]

Biome distribution was actually controlled by <u>Bioclimatic limits</u> for each Plant Functional Types (PFTs)

[Example] High-temperature injury

49 ° C : For most plant species
64 ° C : For some succulent species

[Example] Frost damage

-15 °C < T : Evergreen Broad Leaved Species
-40 ° C < T : Deciduous Broad Leaved Species
No limits[‡] : Boreal Conifer Species

PFTs: a classification of plant species in terms of their responses to environmental changes such as higher air-temperature and CO_2

[†] : Beerling & Woodesrd (2001) Vegetation and the Terrestrial Carbon Cycle: "植生と大気の4億年(及川武久 監修)“
[‡] For the Minimum Air temperature in the nature of the earth surface

---

Bioclimatic limits 2:
Requirements for satisfying Life Cycle

[Example] Temperature requirements for Woody Species

Koppen (1936)

$T > -5$
$T < 42 \times \log P - 106$

Ojima (1991)

$P > 100$
$P > 20.0 \times T$

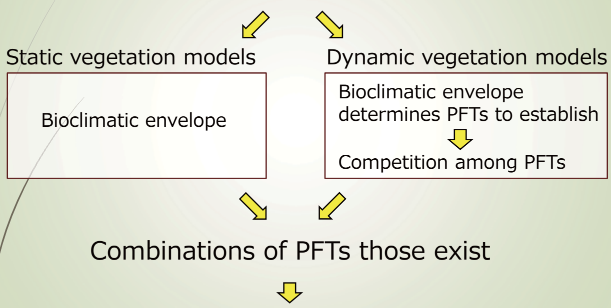
T : annual mean temperature (in °C)
P : annual precipitation (in mm)

[Example] Growth Degree Day (GDD)* requirements for woody PFTs in the LPJ-DGVM

GDD> 1200 : Temperate broad-leaved (evergreen/summergreen)
GDD> 900 : Temperate needle-leaved evergreen
GDD> 600 : Boreal needle-leaved evergreen
GDD> 350 : Boreal summer greeen (neelde/broad-leaved)

* Annual sum of daily air temperature above which 5 °C.

How to determine Biome in vegetation models



Climate data

Static vegetation models

Bioclimatic envelope

Dynamic vegetation models

Bioclimatic envelope determines PFTs to establish

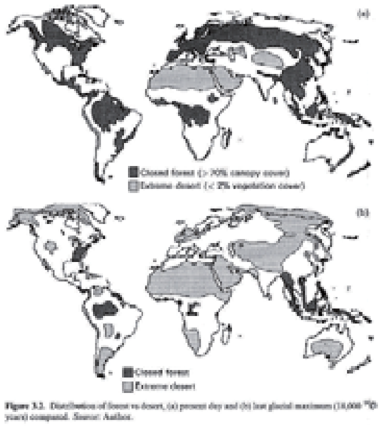
Competition among PFTs

Combinations of PFTs those exist

Biome was determined with some criteria

Biome Shift

Geographical Distribution of Closed-Forest and Desert

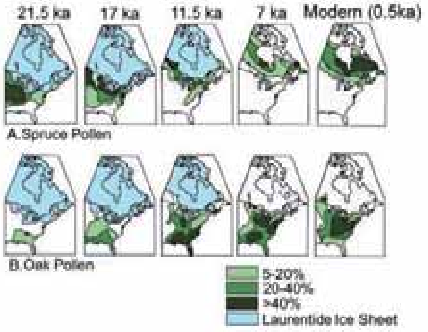


@Present Day

@18000 yrs ago

Source of the Figure:
Adams (2007) Vegetation-Climate Interaction 2nd edition

Ranges, as indicated by pollen percentages in sediment, of spruce and oak in eastern North America



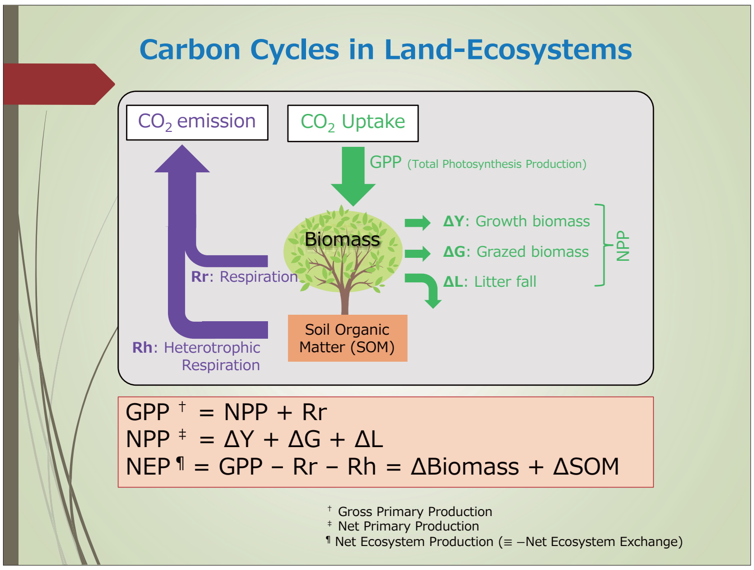
Davis & Shaw (2001)

Species of trees, not communities of forests, tracked their climatic niches at their own rates and along their own trajectories

Carbon cycles in vegetation

Topics:

- GPP, NPP, NEE
- Estimation methods for carbon cycles
- General patterns of carbon cycles



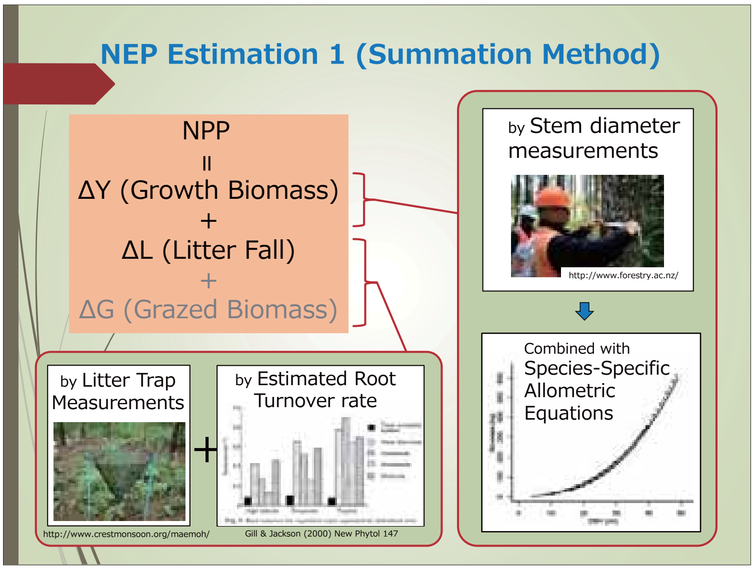
Carbon Cycles in Land-Ecosystems

$\mathrm{GPP}^{\dagger} = \mathrm{NPP} + \mathrm{Rr}$

$\mathrm{NPP}^{\ddagger} = \Delta Y + \Delta G + \Delta L$

$\mathrm{NEP}^{\P} = \mathrm{GPP} - \mathrm{Rr} - \mathrm{Rh} = \Delta\mathrm{Biomass} + \Delta\mathrm{SOM}$

[†] Gross Primary Production
[‡] Net Primary Production
[¶] Net Ecosystem Production (≡ −Net Ecosystem Exchange)



NEP Estimation 1 (Summation Method)

NPP
=
ΔY (Growth Biomass)
+
ΔL (Litter Fall)
+
ΔG (Grazed Biomass)

by Stem diameter measurements

http://www.forestry.ac.nz/

Combined with Species-Specific Allometric Equations

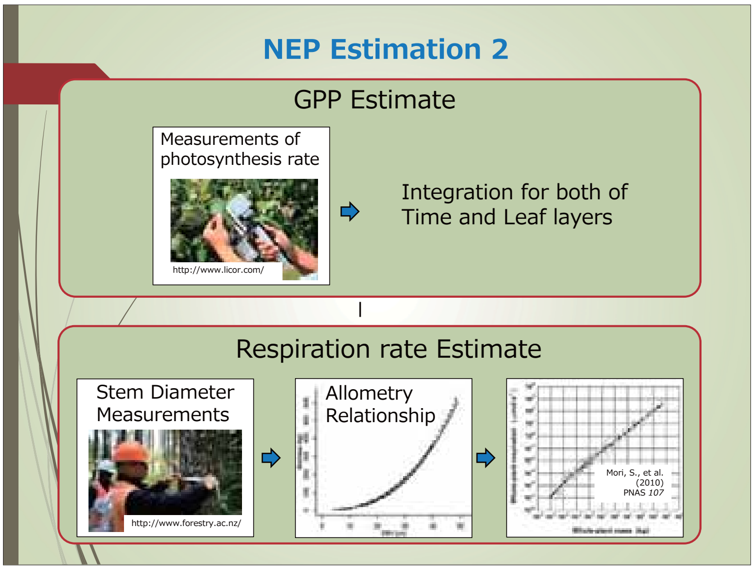
by Litter Trap Measurements

+

by Estimated Root Turnover rate

http://www.crestmonsoon.org/maemoh/

Gill & Jackson (2000) New Phytol 147



NEP Estimation 2

GPP Estimate

Measurements of photosynthesis rate

http://www.licor.com/

Integration for both of Time and Leaf layers

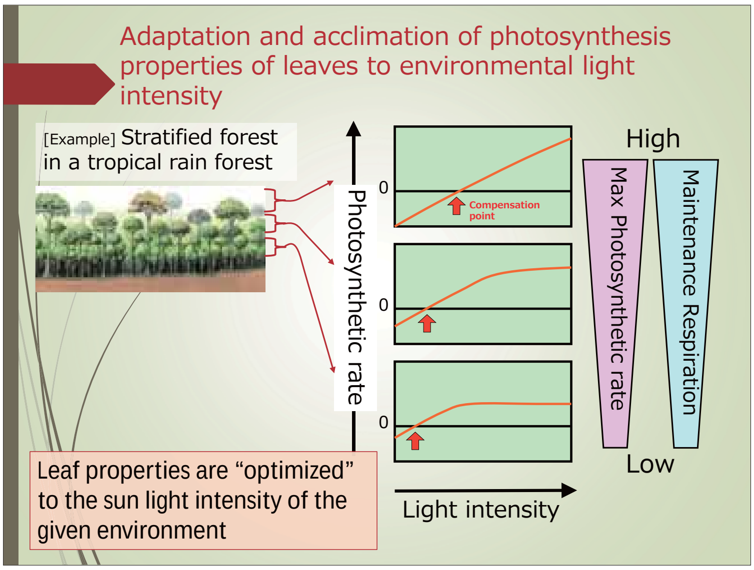
−

Respiration rate Estimate

Stem Diameter Measurements

http://www.forestry.ac.nz/

Allometry Relationship



Adaptation and acclimation of photosynthesis properties of leaves to environmental light intensity

[Example] Stratified forest in a tropical rain forest

Leaf properties are “optimized” to the sun light intensity of the given environment

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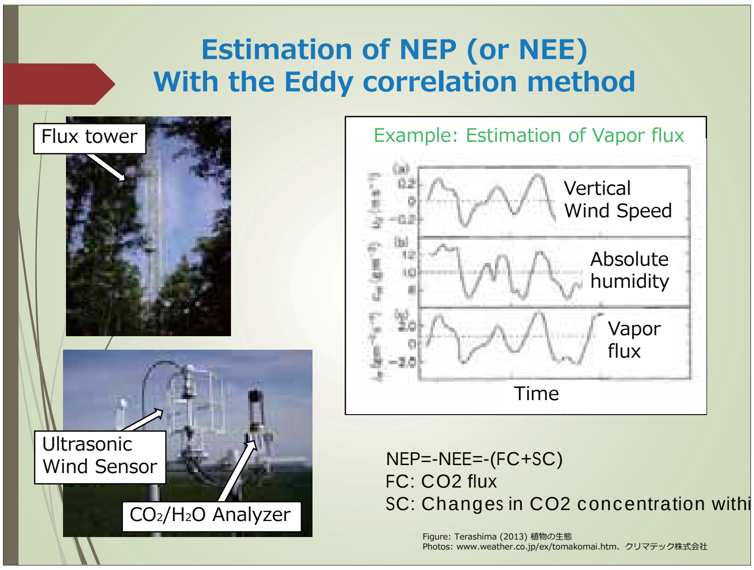


Estimation of NEP (or NEE) With the Eddy correlation method

Example: Estimation of Vapor flux

NEP=-NEE=-(FC+SC)
FC: CO2 flux
SC: Changes in CO2 concentration withi

Figure: Terashima (2013) 植物の生態
Photos: www.weather.co.jp/ex/tomakomai.htm、クリマテック株式会社

Estimated carbon cycles of key biomes (1)

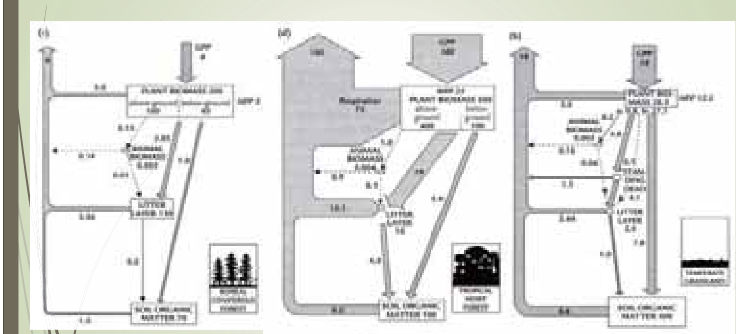
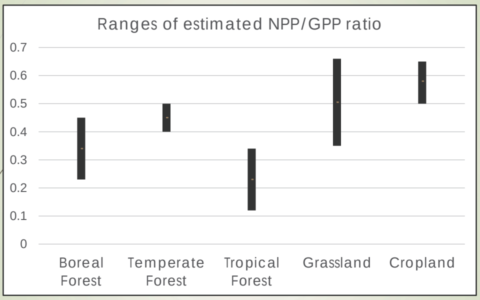


Figure: Eddy van der Maarel (2005) Vegetation Ecology

Estimated carbon cycles of key biomes (2)



Amthor & Boldocchi (2001): Terrestrial higher plant respiration and net primary production *In*: Terrestrial global productivity

- Biomes without stem biomass have lower ratio
- Tropical Forest has the lowest ratio among the key biomes

L9: Global/local hydrometeorology and forest (1)

Tetsuya Hiyama (*Hydrospheric Atmospheric Research Center, Nagoya University*)

Abstract

In this lecture, ecohydrological research results obtained from an interdisciplinary research project No.C-07 of the Research Institute for Humanity and Nature (RIHN), entitled ‘Global Warming and the Human–Nature Dimension in Siberia: Social Adaptation to the Changes of the Terrestrial Ecosystem, with an Emphasis on Water Environments’ (P.I.: T.H.) are shown. Main contents of this lecture are summarized below.

The extent of Arctic summer sea ice, especially in the Eurasian continent side, has been decreasing. Global warming is a partial cause. Cyclones have appeared frequently in summer in the region, bringing much precipitation to Siberia and its forest ecosystems. Because water-logging and humidification severely damaged to our monitoring forest in eastern Siberia, evapotranspiration and photosynthesis properties changed drastically after 2007.

Meteorological data revealed high rates of summer precipitation in the upper and middle parts of the Lena River Basin from 2005 to 2008 and in 2012. Thus summer river flooding around Yakutsk, capital city of the Sakha Republic of the Russian Federation, has become a problem, severely damaging local agriculture and pastoralism. On the contrary, the spring thaw along the Lena River typically causes river ice flooding, which can be severe when low winter temperatures are followed by gradually increasing spring temperatures. Such spring floods have caused severe damages to local residents living along the river in almost every year since 1998.

We investigated local people's perceptions and local governmental adaptation strategies for both spring- and summer-river flooding. Interestingly, spring flooding has been recognized as beneficial except when it causes damages to villages along the river. This is because spring floods bring nutrient-rich water to the river islands on which the farmers cultivate pastures for cattle and horses. Summer river flooding, on the contrary is seen as a hazard, because it submerges the pasture completely in summer, and prevents getting of hay for cattle and horses.

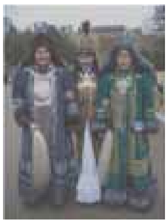
Village relocations were adopted as one of the adaptation strategies to prevent damages from spring floods. Because local people prefer to live along the river on which their subsistence depends, they agreed, with government support, to migrate seasonally. There have been no similar adaptations to summer flooding, however. Based on our observations and analysis, we intend to promote sustainable subsistence activities in the region by proposing strategies to facilitate information transmission and improvement of feed-hay distribution networks that can aid in adaptation to spring and summer river flooding.

The Twenty-fourth IHP Training Course 2014.12.01

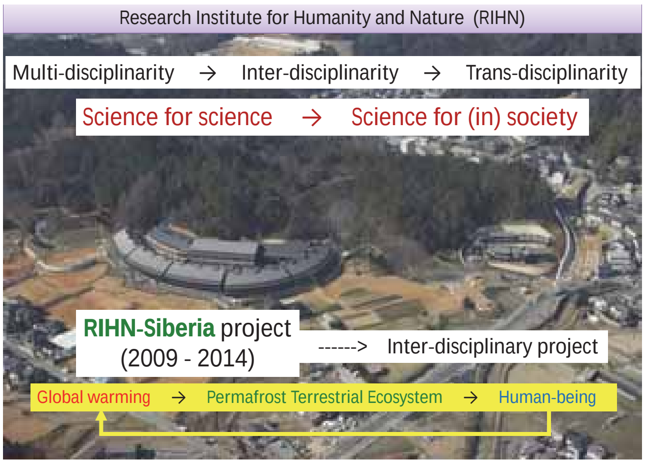
Forest Hydrology –Conservation of Forest, Soil, and Water Resources

L9 :

Global/local hydrometeorology and forest (1)



HIYAMA Tetsuya
(HyARC, Nagoya University)



Research Institute for Humanity and Nature (RIHN)

Multi-disciplinarity → Inter-disciplinarity → Trans-disciplinarity

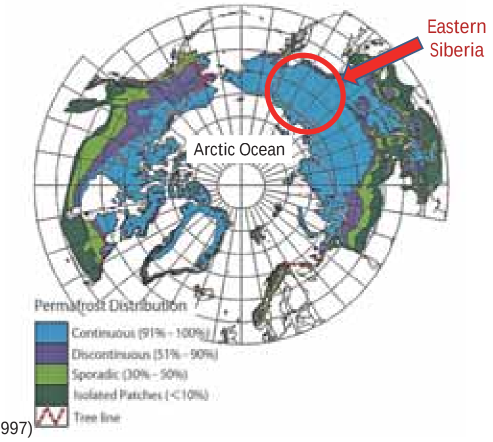
Science for science → Science for (in) society

RIHN-Siberia project (2009 - 2014) ------> Inter-disciplinary project

Global warming → Permafrost Terrestrial Ecosystem → Human-being

---

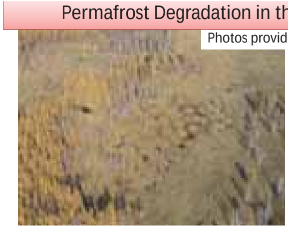
Permafrost Distribution



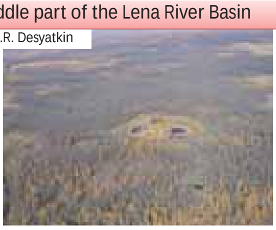
(Brown et al., 1997)

Permafrost Degradation in the middle part of the Lena River Basin

Photos provided by A.R. Desyatkin



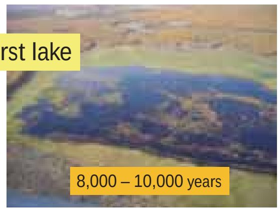
Stage 1 (bullar)



Stage 2 (dyede)

Thermokarst lake

Stage 3 (tuumpu)

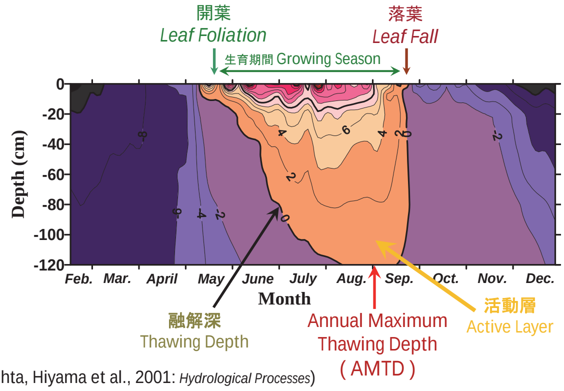


8,000 – 10,000 years

Stage 4 (alas)

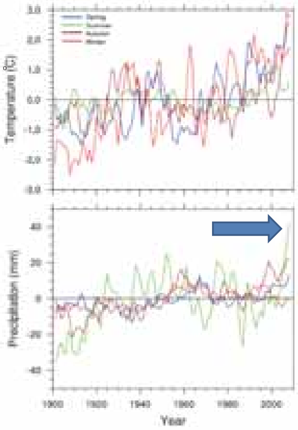
Basics of the Permafrost

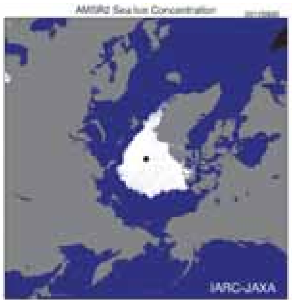
Seasonal Variation in Soil Temperature



(Ohta, Hiyama et al., 2001: *Hydrological Processes*)

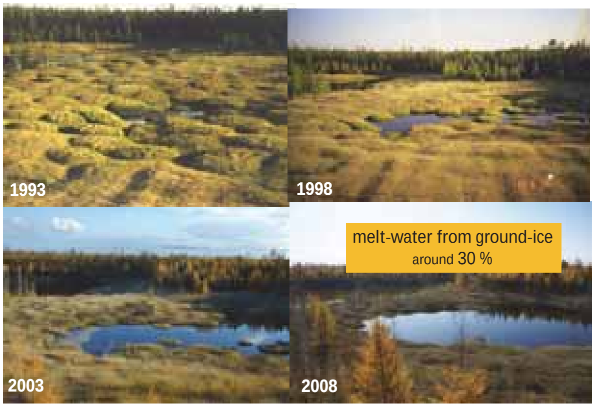
Climate Change in the Lena River Basin





(http://www.ijis.iarc.uaf.edu/jp/seaice/extent.htm)

Permafrost Degradation in the middle part of the Lena River Basin



melt-water from ground-ice
around 30 %

(Fedorov, Hiyama et al., 2014: *Ecohydrology*)

Research Objectives and Hypothesis

- Objectives :

1) To understand the **changes** of environment in Siberia caused by Global Warming (GW).
2) To understand the **impacts** of GW on the society (the life of local resident) through humidification, floods, and permafrost-forest degradation.
3) To suggest suitable **adaptation strategies**.

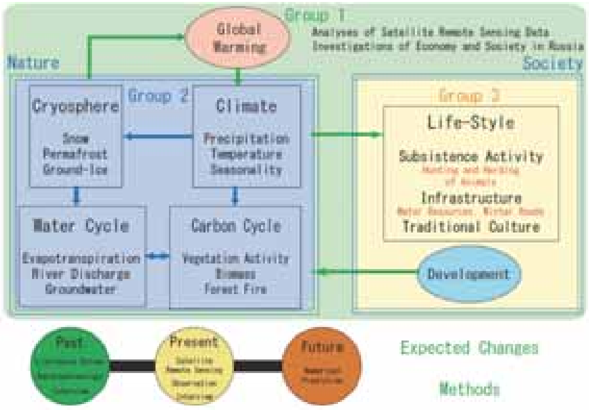
- Hypothesis :

Siberia will be **humidified** in a warmer climate
(at least in decadal ～ half century scale)

- Main Research Region :

Lena River Basin (Sakha Republic, Russia) of Eastern Siberia

Research Group Structure



Main Research Topics

Climate Change

- High Precipitation → Permafrost Ecosystems

Waterlogging → Changes in H_2O, CO_2 and CH_4 fluxes

- Flood Impacts → Cattle-horse Pastoralism

Local Residents

River Floods → Benefits or Hazards ?

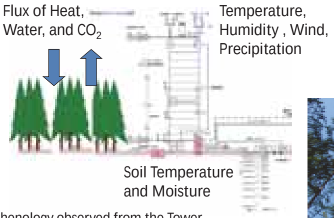
- Flora and Fauna → Reindeer Herding

Degradation → Adaptation to ecosystem changes

Social Changes

→ Foci : not only global warming but also social changes

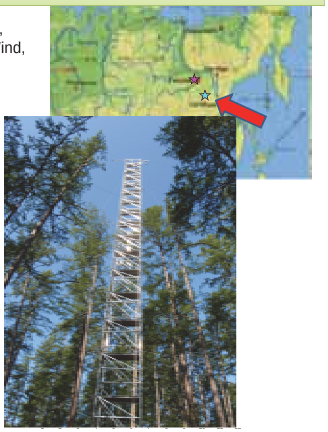
Flux Observation at Two Sites with Different Precipitation



Flux of Heat, Water, and CO_2

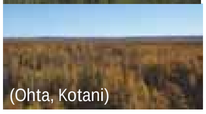
Temperature, Humidity , Wind, Precipitation

Soil Temperature and Moisture



Phenology observed from the Tower

(summer)

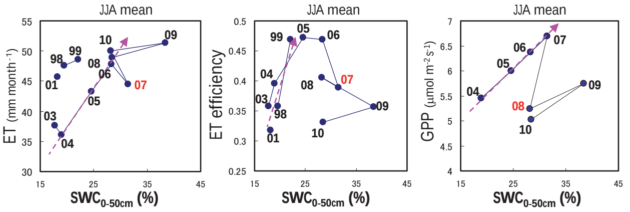


(autumn)

(Ohta, Kotani)

Canopy-scale Fluxes of H_2O & CO_2 at Larch Forest in Eastern Siberia

Over-humidification → Canopy-scale Fluxes

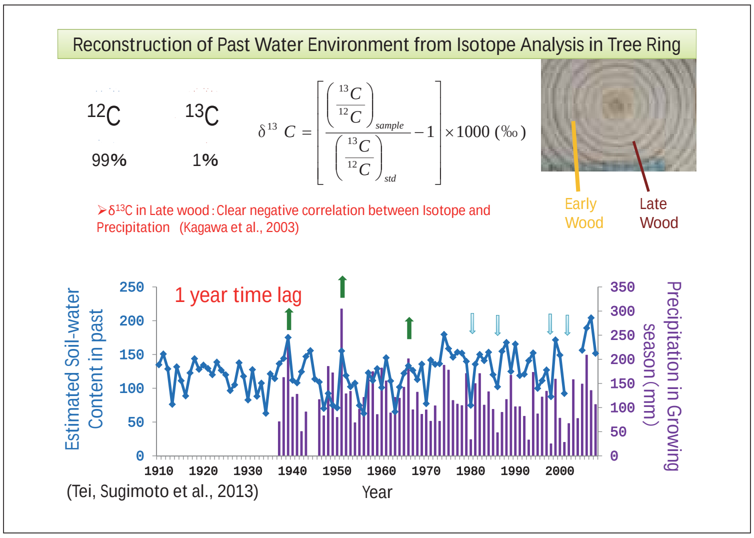


(ET & ET efficiency) ⇔ (SWC)
Change response after 2007

(GPP) ⇔ (SWC)
Change response after 2008

- Clear relationships between (SWC) and (ET, ET efficiency, GPP)
- After 2007 - 2008, the relationships have changed.

(Ohta, Kotani et al., 2014: *Agric. For. Meteorol.*)

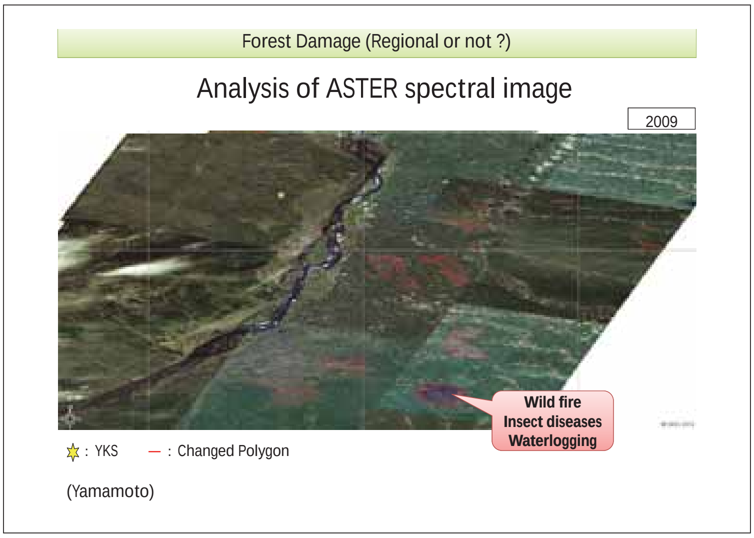


Reconstruction of Past Water Environment from Isotope Analysis in Tree Ring

$$\delta^{13}C = \left[\frac{\left(\frac{^{13}C}{^{12}C}\right)_{sample}}{\left(\frac{^{13}C}{^{12}C}\right)_{std}} - 1 \right] \times 1000\ (‰)$$

➢δ^{13}C in Late wood : Clear negative correlation between Isotope and Precipitation (Kagawa et al., 2003)

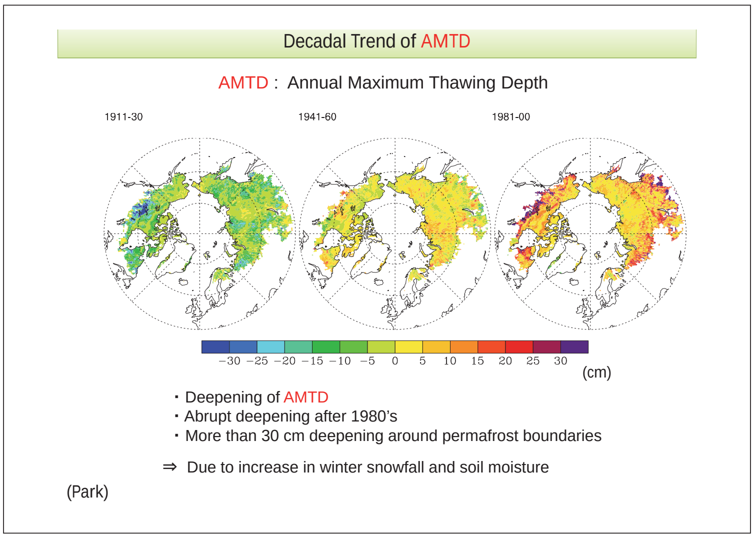
(Tei, Sugimoto et al., 2013)



Forest Damage (Regional or not ?)

Analysis of ASTER spectral image

(Yamamoto)



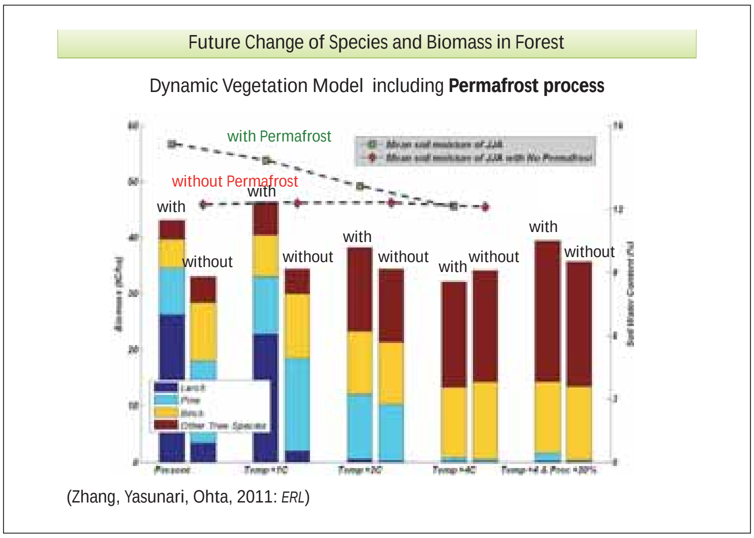
Decadal Trend of AMTD

AMTD : Annual Maximum Thawing Depth

- Deepening of AMTD
- Abrupt deepening after 1980's
- More than 30 cm deepening around permafrost boundaries

⇒ Due to increase in winter snowfall and soil moisture

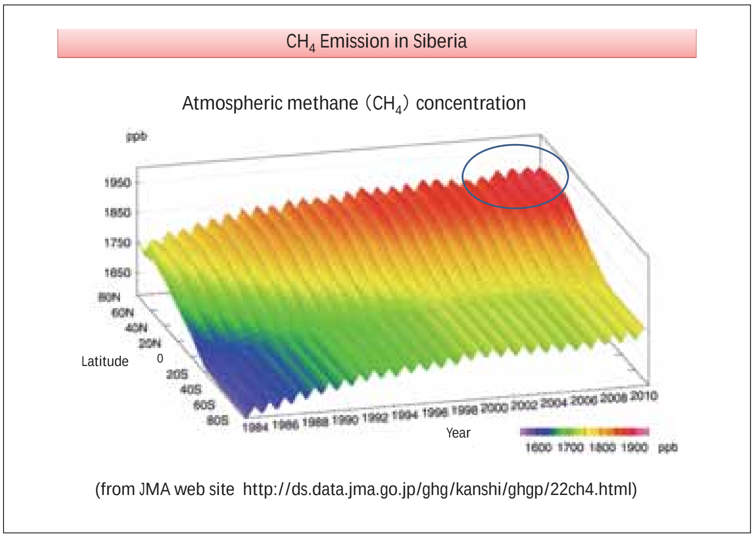
(Park)



Future Change of Species and Biomass in Forest

Dynamic Vegetation Model including **Permafrost process**

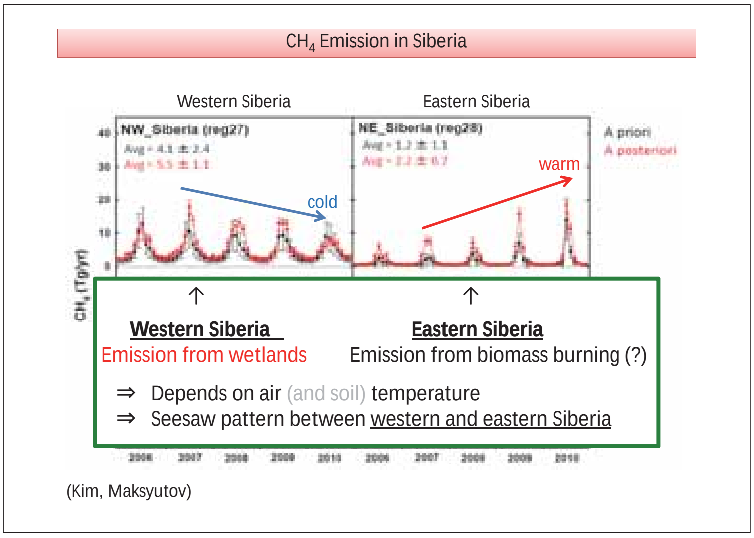
(Zhang, Yasunari, Ohta, 2011: *ERL*)



CH_4 Emission in Siberia

Atmospheric methane（CH_4）concentration

(from JMA web site http://ds.data.jma.go.jp/ghg/kanshi/ghgp/22ch4.html)



CH_4 Emission in Siberia

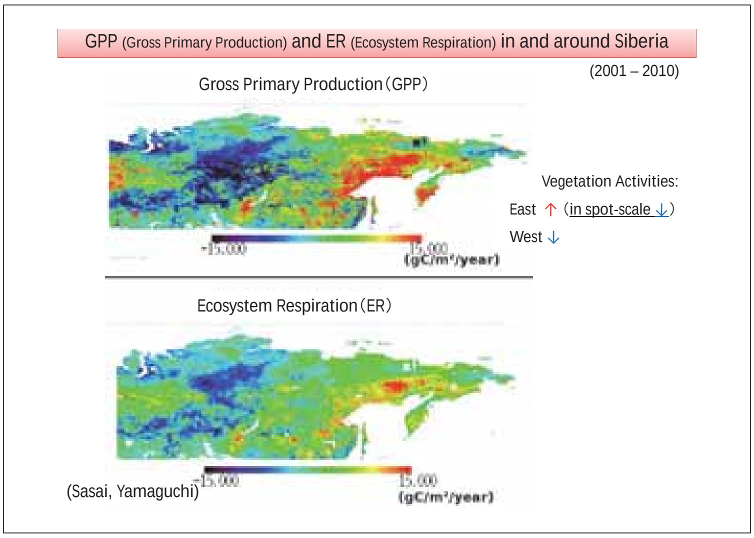
↑ **Western Siberia**
Emission from wetlands

↑ **Eastern Siberia**
Emission from biomass burning (?)

⇒ Depends on air (and soil) temperature

⇒ Seesaw pattern between western and eastern Siberia

(Kim, Maksyutov)



GPP (Gross Primary Production) and ER (Ecosystem Respiration) in and around Siberia

(2001 – 2010)

Gross Primary Production（GPP）

Vegetation Activities:
East ↑（in spot-scale ↓）
West ↓

Ecosystem Respiration（ER）

(Sasai, Yamaguchi)

Impact of River Floods to the Social Adaptation

Cattle-Horse Pastoralism（river sandbanks） ⇒ Submerge of grass & hay
Houses & Villages（along the river） ⇒ Inundation of houses

【Subjects in FR5】

- How does the Global Warming affect river floods ?
- How does the Local Society adapt on river floods ?

【Social Adaptation】

- Subsistence Activities ⇒ Aggregation of local knowledge (Smit and Wandel, 2006)
- Global Warming ⇒ Limits in adaptation (Adger *et al.*, 2007)

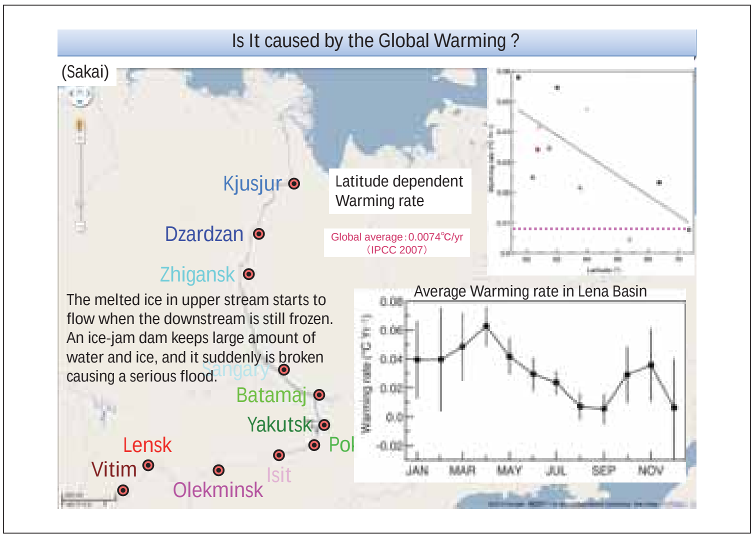
（River Ice Jams）（Inundated Houses in Spring）（Harvesting Grasses）

Is the Risk of River Flood getting more Serious by Global Warming ?

Ice-Jam Flood

The spring thaw brings ice-jams from the upper stream when the downstream is still frozen.
Ice-jam dam keeps large amount of water and ice, and it suddenly broken.
This derives a serious flood.

(Sakai)



Is It caused by the Global Warming ?

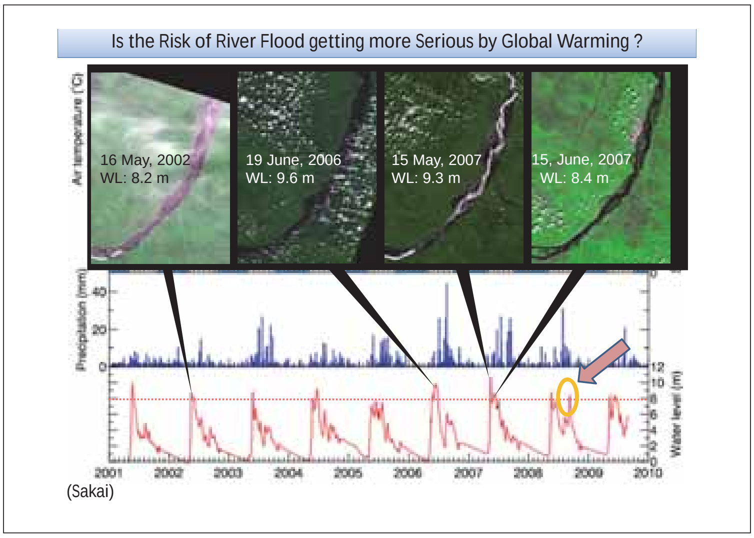
(Sakai)

Latitude dependent Warming rate

Global average：0.0074℃/yr（IPCC 2007）

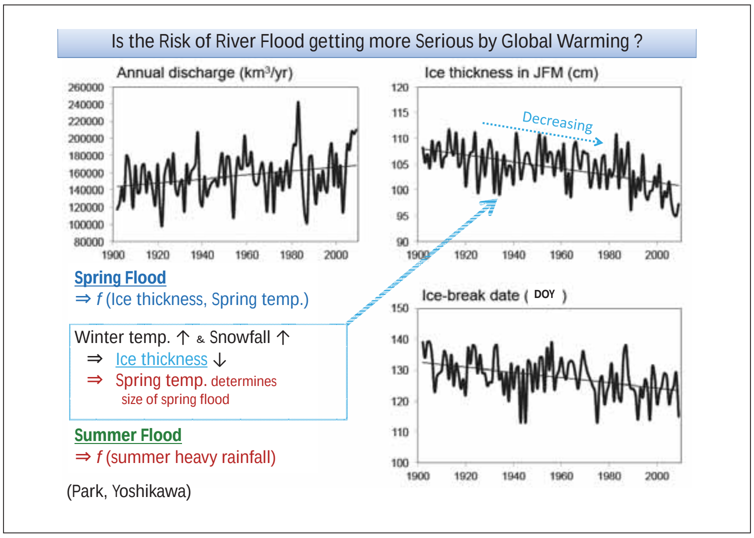
The melted ice in upper stream starts to flow when the downstream is still frozen. An ice-jam dam keeps large amount of water and ice, and it suddenly is broken causing a serious flood.

Average Warming rate in Lena Basin



Is the Risk of River Flood getting more Serious by Global Warming ?

(Sakai)



Is the Risk of River Flood getting more Serious by Global Warming ?

Annual discharge (km³/yr)

Ice thickness in JFM (cm)

Decreasing

Spring Flood
⇒ *f* (Ice thickness, Spring temp.)

Winter temp. ↑ & Snowfall ↑
⇒ Ice thickness ↓
⇒ Spring temp. determines size of spring flood

Ice-break date (DOY)

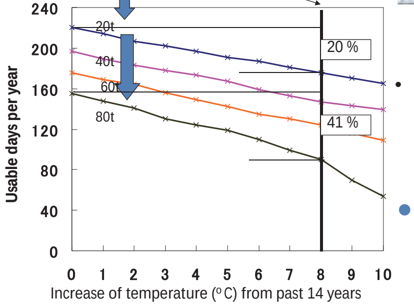
Summer Flood
⇒ *f* (summer heavy rainfall)

(Park, Yoshikawa)

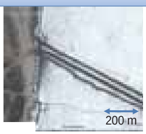
Future Impact to Winter River Road for Transportation

Squeeze of winter road period

If 8 °C increase of temperature after100 years



(Okumura)



Frozen period is almost half of a year

About 2/3 of road in Sakha is road usable only in winter.

- Squeeze rate is larger for heavier vehicles
  - 20 t -------- 20 % decrease
  - 80 t -------- 41 % decrease
- Non-linear decrease of usable days

Impact of River Floods to the Social Adaptation

Houses & Villages (along the river) ⇒ Inundation of houses
Cattle-Horse Pastoralism (river sandbanks) ⇒ Submerge of grass & hay

【Hazards or Benefits ?】

- Spring Floods: Increase since 1998, Possible to adapt by local knowledge
- Summer Floods: No local knowledge, Impossible to adapt so far

【Adaptation Strategies】

- Spring Floods: Seasonal Migration ⇐ strong community
- Summer Floods: Improvement of information transmission and feed-hay distribution networks

(River Ice Jams)

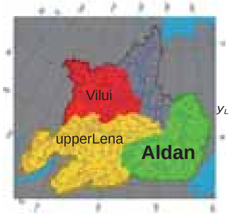
(Inundated Houses in Spring)

(Harvesting Grasses)

Another aspects on river discharge

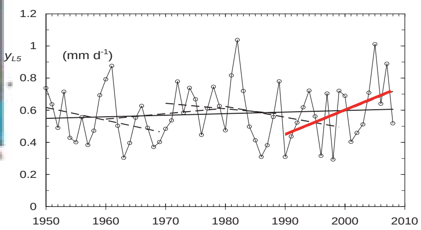
(base flow or low flow)

Long-Term Base Flow Measurements ⇒ Annual Maximum Thawing Depth (AMTD)



The Lena River Basin

Interannual variations of summer base flow



$$\left.\begin{aligned} y &= y_0 \exp(-t/K) \\ S &= Ky \end{aligned}\right\} \quad \left.\eta_0 = S/n_e\right\} \quad \frac{d\eta_0}{dt} = -\frac{\eta_{or}}{K_r}\frac{dK}{dt}$$

(Brutsaert and Hiyama, 2012: *JGR-Atmosphere*)

Long-Term Base Flow Measurements ⇒ AMTD Trend

Equations

Eq. (1) $$\frac{d\eta_0}{dt} = \frac{\eta_{0r}}{2y_r}\frac{dy}{dt}$$

Eq. (2) $$\frac{d\eta_0}{dt} = \frac{K}{2n_e}\frac{dy}{dt}$$

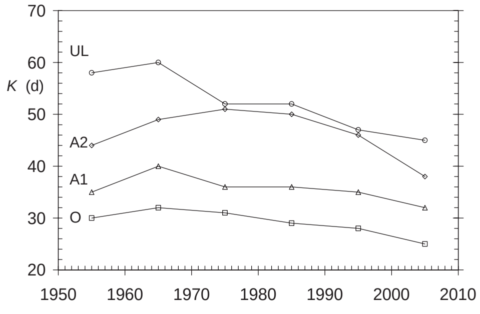
} Use of base flow change

Eq. (3) $$\frac{d\eta_0}{dt} = -\frac{\eta_{or}}{K_r}\frac{dK}{dt}$$

→ Use of change in storage coefficient

Long-Term Base Flow Measurements ⇒ AMTD Trend

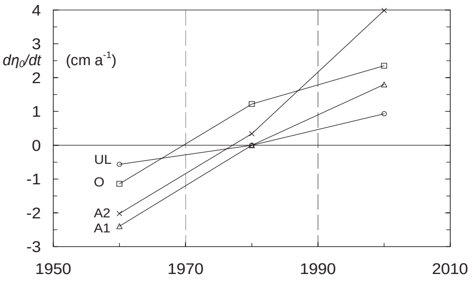
Decadal variation of storage coefficient (*K*) in the Lena River Basin



(Brutsaert and Hiyama, 2012: *JGR-Atmosphere*)

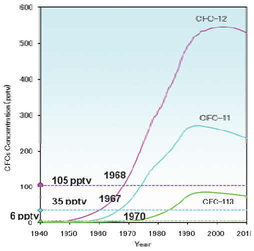
Long-Term Base Flow Measurements ⇒ AMTD Trend

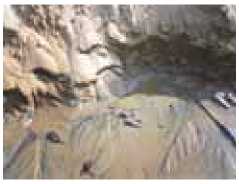
Decadal trend of active layer depth ($d\eta_0/dt$) in the Lena River Basin

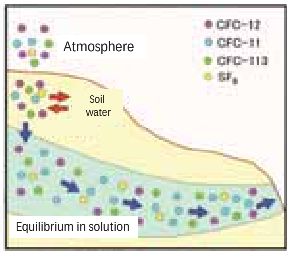


(Brutsaert and Hiyama, 2012: *JGR-Atmosphere*)

Is the Ground-Ice is melting as the Result of Global Warming ?



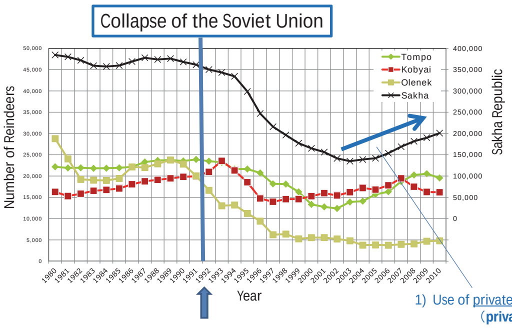




Tentative ages observed are in the range of 1950-1970. Several tens of years older than fresh water.

(Hiyama et al, 2013: *ERL*)

Population of Domestic Reindeers



1) Use of private network
（**privatization**）

2) Governmental conservation
（**governance**）
（**subsidizing**）

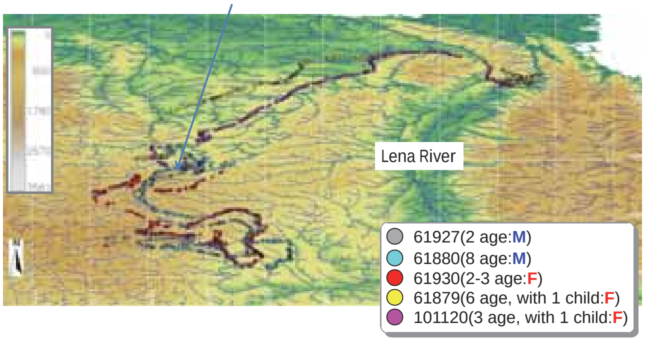
Social change : Important for the local peoples

---> **Combined Risk** from “Environmental and Social Changes”

(Nakada)

Tracking the Wild Reindeers (2010 summer - 2011 spring)

Capture site of wild reindeers



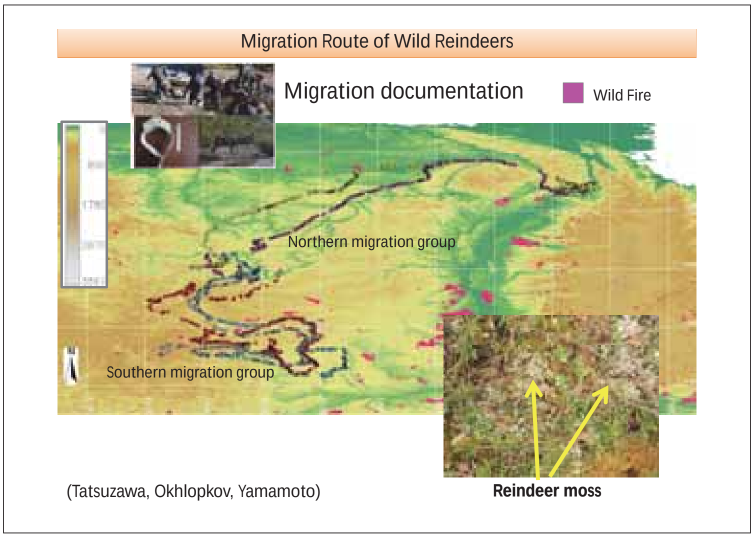
(Tatsuzawa, Okhlopkov, Yamamoto)

Installation of Transmitters to Wild Reindeers

(Tatsuzawa, Okhlopkov)

Capture Wild Reindeers and Install Transmitters (2010 summer)

(Tatsuzawa, Okhlopkov)

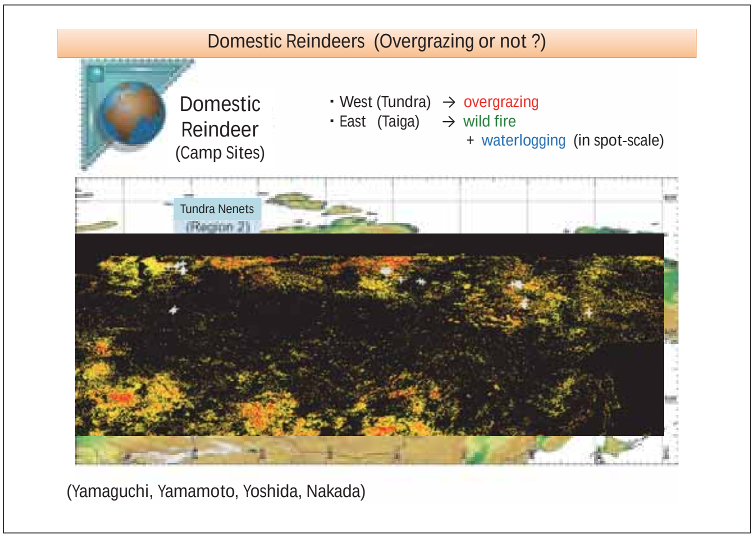


Migration Route of Wild Reindeers

Migration documentation

(Tatsuzawa, Okhlopkov, Yamamoto)

Reindeer moss

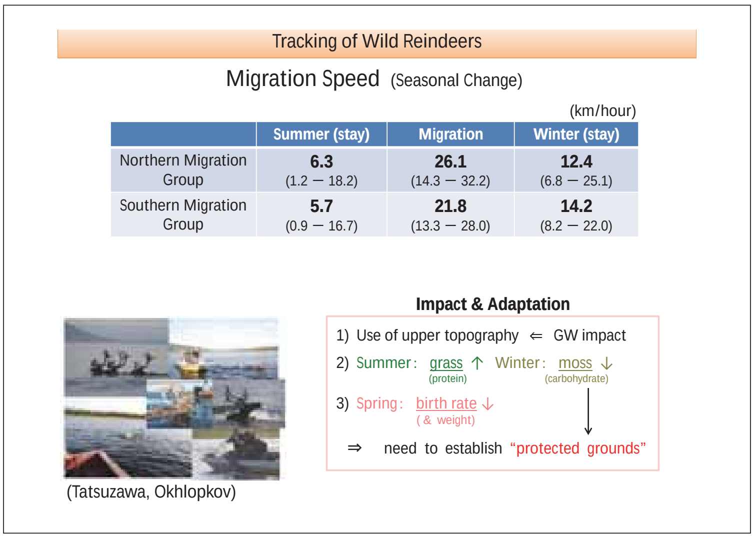


Domestic Reindeers (Overgrazing or not ?)

Domestic Reindeer
(Camp Sites)

- West (Tundra) → overgrazing
- East (Taiga) → wild fire
  + waterlogging (in spot-scale)

(Yamaguchi, Yamamoto, Yoshida, Nakada)



Tracking of Wild Reindeers

Migration Speed (Seasonal Change)

(km/hour)

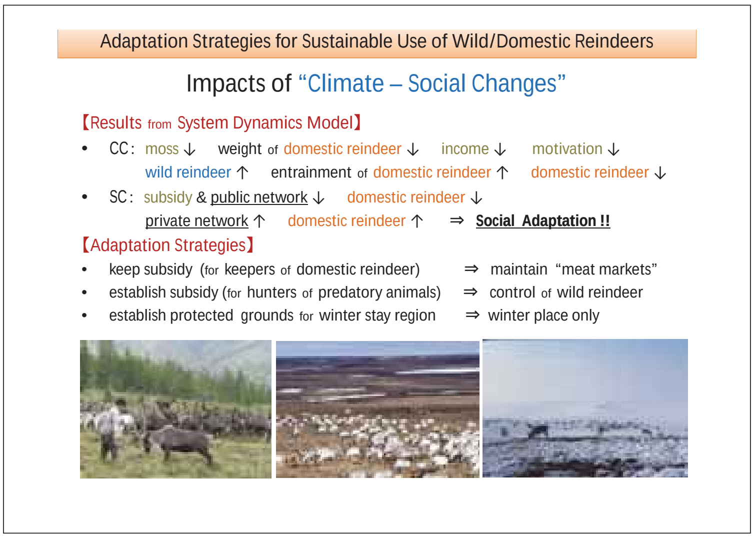
	Summer (stay)	Migration	Winter (stay)
Northern Migration Group	**6.3** (1.2 — 18.2)	**26.1** (14.3 — 32.2)	**12.4** (6.8 — 25.1)
Southern Migration Group	**5.7** (0.9 — 16.7)	**21.8** (13.3 — 28.0)	**14.2** (8.2 — 22.0)

(Tatsuzawa, Okhlopkov)

Impact & Adaptation

1) Use of upper topography ⇐ GW impact
2) Summer: grass ↑ (protein) Winter: moss ↓ (carbohydrate)
3) Spring: birth rate ↓ (& weight)

⇒ need to establish "protected grounds"



Adaptation Strategies for Sustainable Use of Wild/Domestic Reindeers

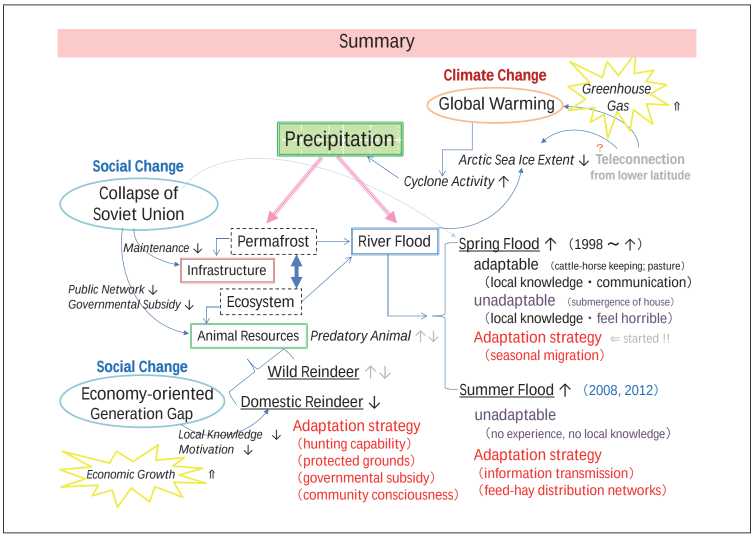
Impacts of "Climate – Social Changes"

【Results from System Dynamics Model】

- CC: moss ↓ weight of domestic reindeer ↓ income ↓ motivation ↓
  wild reindeer ↑ entrainment of domestic reindeer ↑ domestic reindeer ↓
- SC: subsidy & public network ↓ domestic reindeer ↓
  private network ↑ domestic reindeer ↑ ⇒ **Social Adaptation !!**

【Adaptation Strategies】

- keep subsidy (for keepers of domestic reindeer) ⇒ maintain "meat markets"
- establish subsidy (for hunters of predatory animals) ⇒ control of wild reindeer
- establish protected grounds for winter stay region ⇒ winter place only



Summary

Climate Change
Global Warming
Greenhouse Gas ⇑
Arctic Sea Ice Extent ↓
Teleconnection from lower latitude ?
Cyclone Activity ↑
Precipitation

Social Change
Collapse of Soviet Union
Maintenance ↓
Public Network ↓
Governmental Subsidy ↓

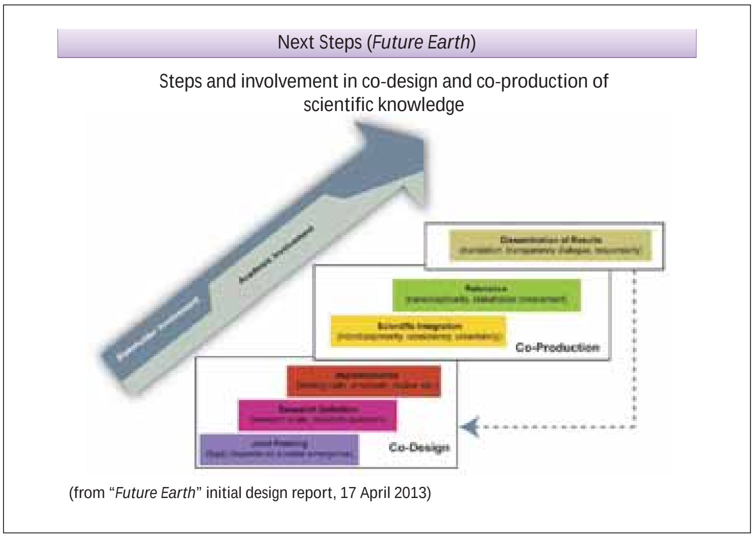
Permafrost
Infrastructure
Ecosystem
River Flood
Animal Resources
Predatory Animal ↑↓
Wild Reindeer ↑↓
Domestic Reindeer ↓

Social Change
Economy-oriented Generation Gap
Local Knowledge ↓
Motivation ↓
Economic Growth ⇑

Adaptation strategy
(hunting capability)
(protected grounds)
(governmental subsidy)
(community consciousness)

Spring Flood ↑ (1998 ~ ↑)
adaptable (cattle-horse keeping; pasture)
(local knowledge・communication)
unadaptable (submergence of house)
(local knowledge・feel horrible)
Adaptation strategy ⇐ started !!
(seasonal migration)

Summer Flood ↑ (2008, 2012)
unadaptable
(no experience, no local knowledge)
Adaptation strategy
(information transmission)
(feed-hay distribution networks)



Next Steps (*Future Earth*)

Steps and involvement in co-design and co-production of scientific knowledge

(from "*Future Earth*" initial design report, 17 April 2013)

L10: Global/local hydrometeorology and forest (2)

Hatsuki Fujinami (*Hydrospheric Atmospheric Research Center, Nagoya University*)

Abstract

The Asian monsoon brings abundant precipitation to the land during summer. The bountiful forests, cropland, and paddy fields in Asia are maintained by the monsoonal precipitation. The Asian monsoon is the world's most vigorous monsoon system, and is induced by the seasonal differential heating between the Eurasian continent, extending to the low latitudes, and the surrounding oceans. The heat contrast between the land and oceans (i.e., warm land and cold oceans) generates differences in pressure fields. A low pressure area develops over the heated land, while relatively high pressure is observed over the ocean. The pressure gradient and the effect of the Earth's rotation (i.e., the Coriolis force) induces strong monsoon westerlies/southwesterlies around South/Southeast Asia, resulting in substantial water vapor transport from the ocean to the land. The water vapor condenses over and around the land leading to an abundance of rainfall and the release of latent heating. The moist process with the phase transition of water enhances the entire monsoon circulation effectively. In addition to the moist process, the presence of the Tibetan Plateau can strengthen the monsoon circulation because it increases the meridional heat contrast and creates a stronger pressure gradient between the land and the ocean. A vegetated land surface can also moisten the atmospheric boundary layer over the land and increase the convergence due to surface roughness, resulting in an increase of rainfall over the land. Thus, land-atmosphere interaction, including the influence of vegetation, is an important factor in maintaining both the vigorous Asian monsoon system and the bountiful surface vegetation.

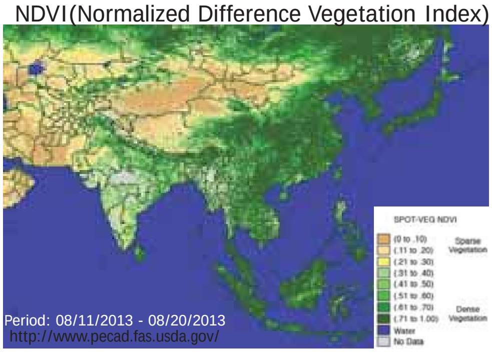
IHP Training Course 2014
Lecture 10

Global/local hydrometeorology and forest (2)

Hatsuki Fujinami
Hydrospheric Atmospheric Research Center, Nagoya University

Vegetation greenness in Asia

NDVI(Normalized Difference Vegetation Index)

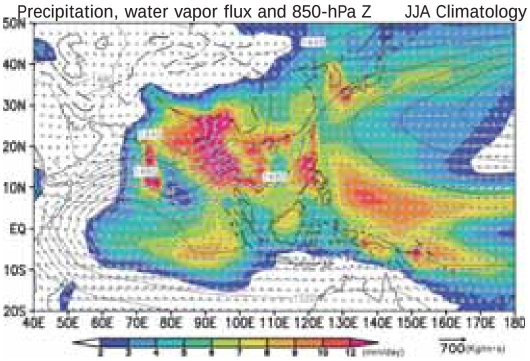


Period: 08/11/2013 - 08/20/2013
http://www.pecad.fas.usda.gov/

What maintains the greenness in Asia?

Asian monsoon: a huge water cycle

Precipitation, water vapor flux and 850-hPa Z JJA Climatology



- Abundant rainfall by Asian summer monsoon

What is a “monsoon”?

- The origin:
  the Arabic word *mausim* which means **season**
- The **seasonal reversals of prevailing wind**
- Two distinct phases: the “**Wet**” and ”**Dry**”

Cumulonimbi over the Tibetan Plateau in summer (wet phase)

Contents:

1. Seasonal difference in wind fields and precipitation
2. Driving mechanism of Asian monsoon
   2.1. Fundamental mechanisms
   2.2. Mechanisms for enhancing Asian monsoon
3. Surface condition and its impact on precipitation system over East Asia
4. Atmospheric water budget and its interpretation
5. Regionality of Asian monsoon
6. Interannual variation of Asian monsoon

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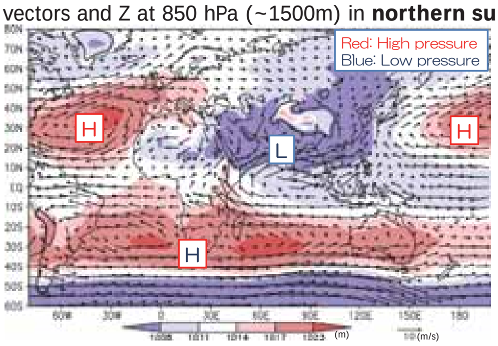
1. Seasonal difference in wind fields and precipitation

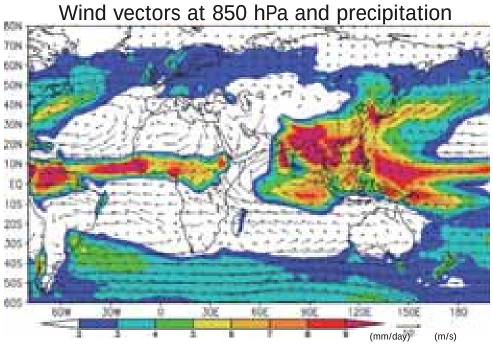
Wind vectors and Z at 850 hPa (~1500m) in **northern summer**



- Low pressure area over the Eurasian continent
- Westerlies/southwesterlies around S/SE/E Asia

Northern summer

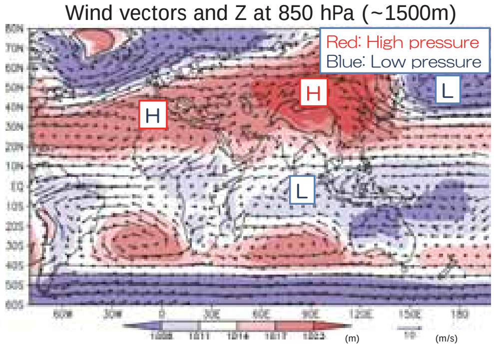
Wind vectors at 850 hPa and precipitation



- ●Abundant rainfall extending form South to East Asia

Northern winter

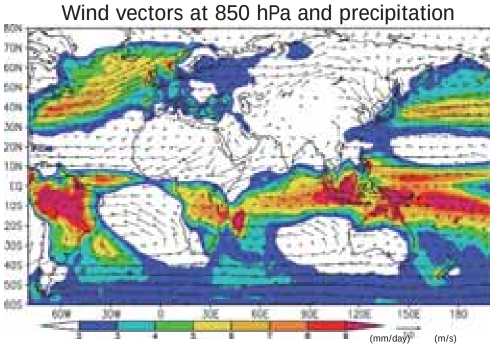
Wind vectors and Z at 850 hPa (~1500m)



- ● High pressure area over the Eurasian continent (Siberian high)
- ● Northwesterlies over East Asia, easterlies over S/SE Asia

Northern winter

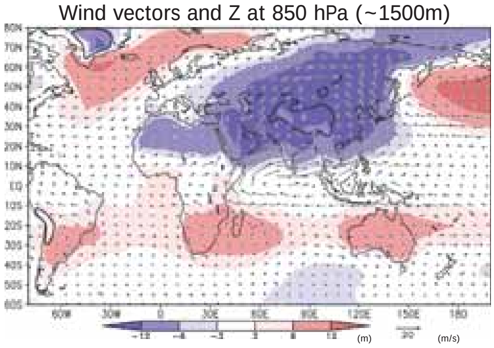
Wind vectors at 850 hPa and precipitation



- ●Low precipitation over Asia
- ●High precipitation over the maritime continent/N Australia

Difference between summer and winter

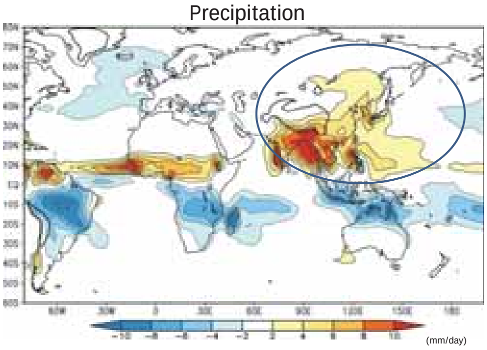
Wind vectors and Z at 850 hPa (~1500m)



- ● Low pressure anomaly over the Eurasian continent
- ● Wind anomalies in a counterclockwise direction around Asia

Difference between summer and winter

Precipitation



Asian monsoon region:
most vigorous monsoon system on the earth

2. Driving mechanisms

2.1. Fundamental mechanisms:

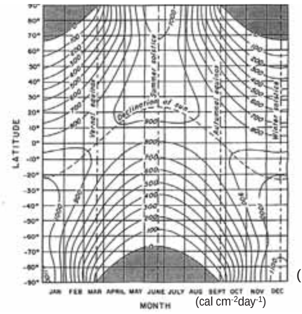
- ➢ Annual cycle of incoming solar radiation
- ➢ Differential heating between the land and sea
- ➢ Effect of the earth's rotation (the Coriolis force)

2.2. Mechanisms for enhancing Asian monsoon:

- ➢ Moist process (latent heating due to condensation)
- ➢ Topography (Tibetan Plateau and other mountains)
- ➢ Land surface (vegetation, cropland, paddy fields, soil...)

2.1. Fundamental mechanisms:
Annual cycle of incoming solar radiation

Insolation at the top of atmosphere



(Salby, 1996)

- Solar radiation incident in boreal summer: Northern hemisphere > Southern hemisphere

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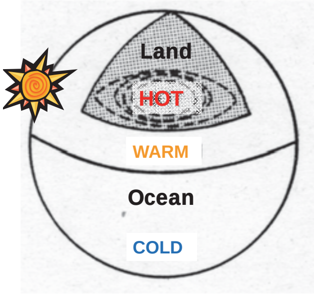
Surface heating in boreal summer



1. Solar Radiation: NH > SH

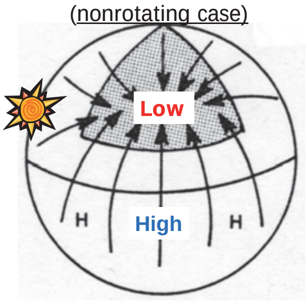
2. Specific heat and heat capacity: water(ocean)>dry soil(land)

3. Land-ocean heating contrast: Hot land surface and cold ocean surface

- Land : soon hot, soon cold

(Figure: Monsoons 1987)

Response of the heating distribution at low-level troposphere



4. Low pressure over the land and high pressure over the ocean

5. Pressure gradient between the land and the ocean

6. The wind directly from the ocean into the land

(Figure: Monsoons 1987)

Effect of the earth's rotation (the Coriolis force)
- The earth rotates from west to east -

The Coriolis force: the **deflection force** when the object is moving with respect to the rotating earth

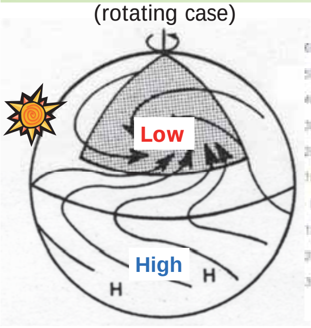
$$\boxed{f_{\text{(Coriolis force)}} = 2\,\Omega \sin\varphi}$$

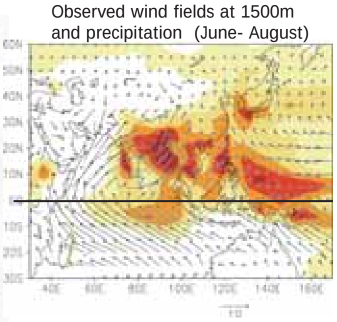
(Ω: the angular speed of rotation of the earth , φ : latitude)

$$\boxed{\frac{du}{dt} = f\,v}$$

(u: zonal wind , v : meridional wind, f > 0 in NH)

A particle moving northward (v>0) in NH is deflected eastward (u>0).



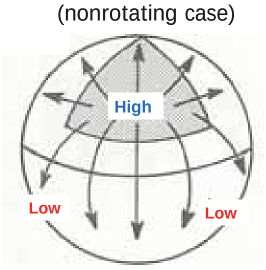


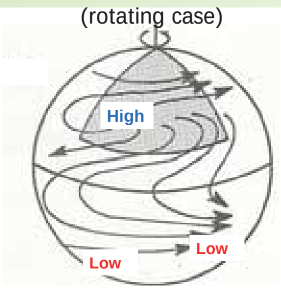
7. Southwesterlies in NH and southeasterlies in SH

8. Abundant moisture transport toward the land

(Figure: Monsoons 1987)

Upper-level troposphere





- Upper-level high over the land and low over the ocean
- Direct flow out from the land to the ocean
- The swirling due to the Coriolis force
- Typical features in observed upper-level troposphere

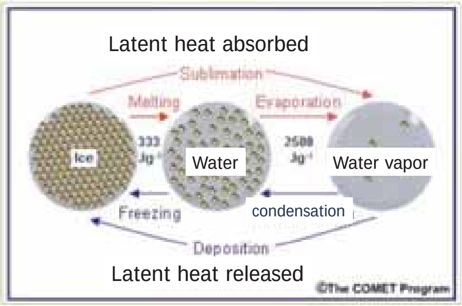
2.2. Mechanisms for enhancing Asian monsoon
- The role of moist process -

Latent heating due to condensation

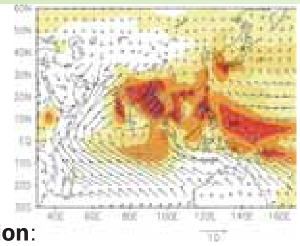
(photo by T. Ebisawa)

Condensation:
phase transition from water vapor to liquid water

Latent heating due to the phase transition



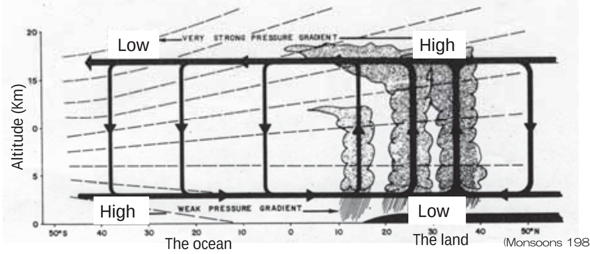
The moist process of the monsoon system



- **Evaporation**:
  Water vapor from the ocean due to solar incident
- Water vapor transport (with trapped or absorbed energy) by monsoon southwesterlies
- **Condensation**:
  heat release in precipitation systems near/over the land

The enhancement of monsoon circulation by condensation heating

Meridional-vertical circulation between the land and ocean



(Monsoons 1987)

- **Stronger buoyancy** induced by the **latent heat release**
- **Stronger upward motion** over the land
- The **enhancement of the whole circulation** due to the mass conservation

---

Role of topography and vegetated surface

©NASA World wind

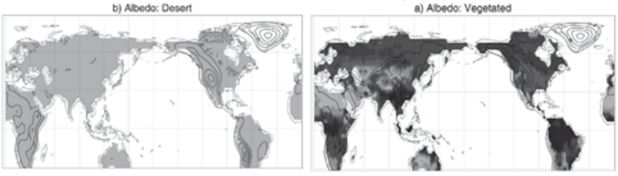
Roles of the Tibetan Plateau on the Asian monsoon: aspects from modelling studies

Atmospheric numerical models:
Fundamental conservation lows which govern atmospheric motions and numerical methods to obtain the solution

We can modify the topography and land surface condition in the numerical model to examine their effect on circulation

- No mountain in Asia
- All desert condition

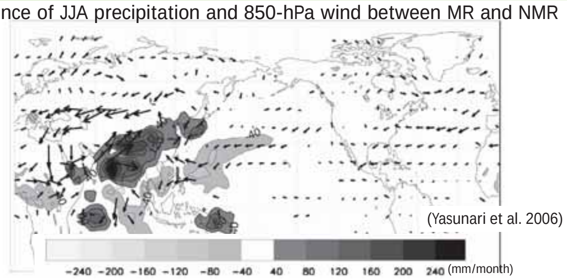
- With mountain in Asia
- Vegetated surface



(Yasunari et al. 2006)

A relative role of the Tibetan Plateau

Difference of JJA precipitation and 850-hPa wind between MR and NMR



(Yasunari et al. 2006)

(mm/month)

(MR: case with the TP and no vegetation, NMR: case without the TP nor vegetation)

Possible effects of the TP: an elevated heat source and a barrier

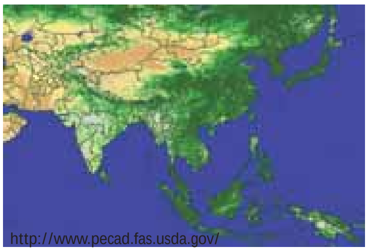
- The TP enhances precipitation in East and South Asia due to the enhancement of the meridional heat contrast

---

Roles of the vegetation

Possible effects:

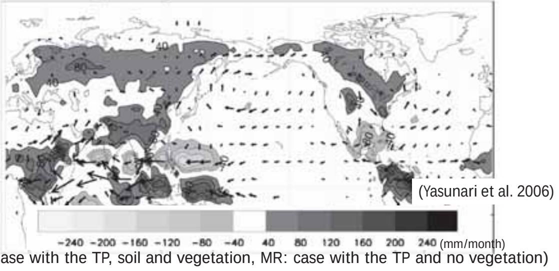
- Surface albedo: net radiation available at the surface
- Roughness: large-scale wind divergence
- Evapotranspiration: moisten the atmospheric boundary layer



http://www.pecad.fas.usda.gov/

A relative role of vegetation

Difference of JJA precipitation and 850-hPa wind between MVS and MR



(Yasunari et al. 2006)

(mm/month)

(MVS: case with the TP, soil and vegetation, MR: case with the TP and no vegetation)

- The increase in precipitation due to the increase of available radiation, roughness and evaporation
- Contribution to the increase in Asia: the land surface (soil-vegetation) effect ≅ the TP effects

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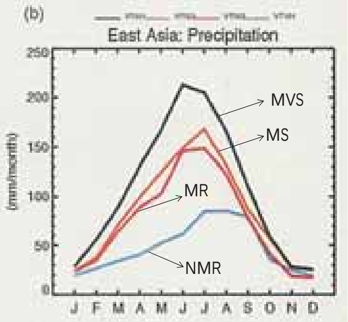
Seasonal change in precipitation over East Asia



- TP effects are important for the seasonal variation
- Vegetation effects induce the large increase in precipitation

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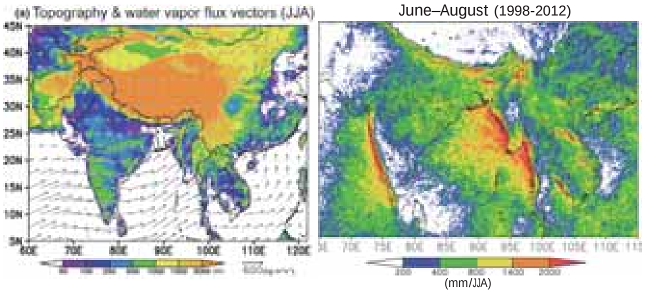
Effects of regional-scale mountains on seasonal mean rainfall distribution

Precipitation climatology from TRMM-PRv7
June–August (1998-2012)



(mm/JJA)

- The formation of local rainfall maxima in the windward slopes of regional-scale mountains

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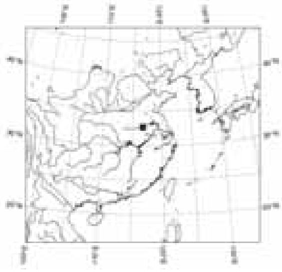
3. Surface condition and its effect on precipitation system over East Asia



The observation site(■)

Shouxian meteorological bureau, China

- The surface condition changes dramatically related to the double-cropping system (from wheat to paddy fields)

The change of surface condition related to the double-cropping system

(a) Mature wheat on 27 May 2004

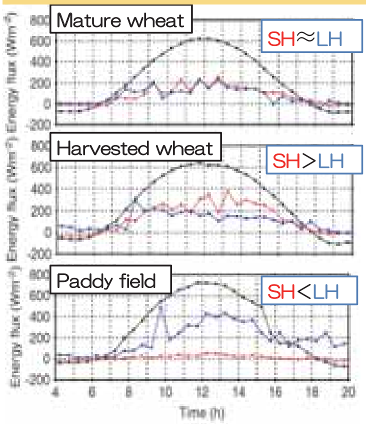
How do the surface changes affect **surface heat fluxes** and the **structure of atmospheric boundary layer**?

(b) Harvested wheat on 1 June 2004

(c) Planted rice on 16 June 2004

(Tanaka et al. 2007)

Diurnal variation in surface energy fluxes over the different surface conditions



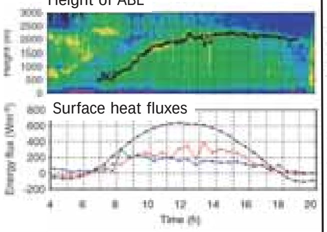
Black: net radiation
Red: sensible heat flux(SH)
Blue: latent heat flux (LH)

- The increase in SH from a dry soil
- The increase in LH due to large amount of evapotranspiration

(Tanaka et al. 2007)

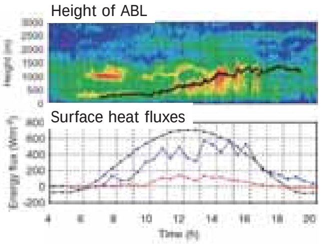
Structure of atmospheric boundary layer over dry and wet surfaces

Harvested wheat: dry soil



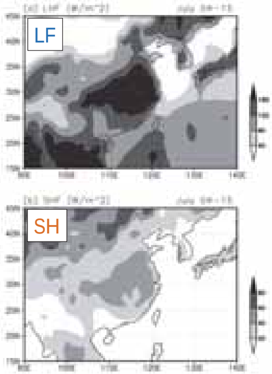
- High atmospheric boundary (mixed) layer due to large sensible heat flux
- Rapid development

Paddy field: flooded fields

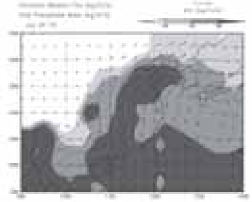


- Shallower boundary layer due to small sensible heat flux
- Gradual development

Impact of widely distributed paddy fields

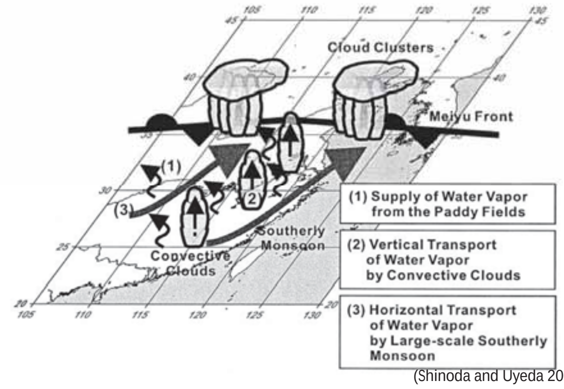


(Shinoda and Uyeda 2005)



- Evapotranspiration from the paddy fields: an effective factor to moisten the ABL and the change moist static stability over eastern China
- Large southerly moisture transport

A possible impact of paddy fields on the development of Meiyu front



(Shinoda and Uyeda 2002)

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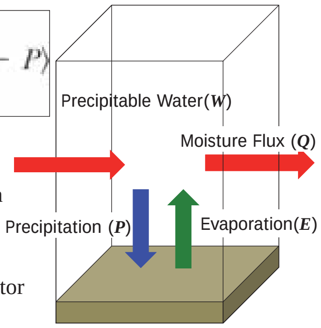
4. Atmospheric water budget

Evaluation of the contribution of evapotranspiration and large-scale convergence to precipitation:

$$\left\langle \frac{\partial W}{\partial t} \right\rangle + \langle \nabla \cdot \mathbf{Q} \rangle = \langle E - P \rangle$$

⟨ ⟩ : area average
P: Precipitation
E: Evaporation/Evapotranspiration
W: Total column water vapor
$\frac{\partial W}{\partial t}$: Time tendency of W
Q: Total column moisture flux vector



If W tendency is negligible ($i.e.,\ \frac{\partial W}{\partial t} \approx 0$)

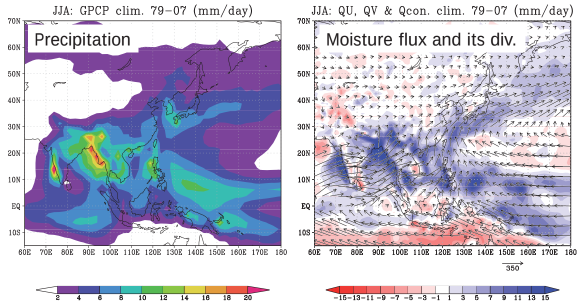
$$\boxed{\langle P \rangle = -\langle \nabla \cdot Q \rangle + \langle E \rangle}$$

$-\langle \nabla \cdot Q \rangle$:Convergence of moisture flux transported by atmospheric circulation

$\langle E \rangle$: *In-situ* evapotranspiration from the surface

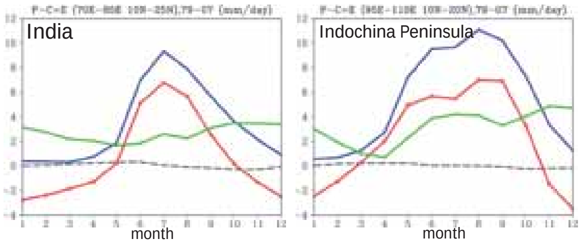
If $\langle E \rangle \gg -\langle \nabla \cdot Q \rangle$:
in-situ evapotranspiration process
(recycling process of precipitation) is important
as a source of precipitation

Precipitation and vertically integrated moisture flux and its divergence in JJA (climatology)



- Areas of high precipitation corresponds well with those of large moisture convergence (blue shadings)

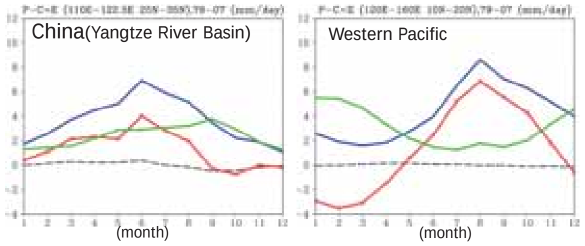
Annual cycle of the atmospheric water budget
India and Indochina Peninsula



Red: Moisture convergence
Blue: Precipitation (GPCP)
Green: Evaporation (P-C)
Black: W tendency

- India: $-\langle \nabla \cdot Q \rangle > \langle E \rangle$
- Indochina peninsula: $-\langle \nabla \cdot Q \rangle \cong \langle E \rangle$

Annual cycle of the atmospheric water budget
China and Western Pacific



Red: Moisture convergence
Blue: Precipitation (GPCP)
Green: Evaporation (P-C)
Black: W tendency

- China: $-\langle \nabla \cdot Q \rangle > \langle E \rangle$
- Western Pacific: $-\langle \nabla \cdot Q \rangle \gg \langle E \rangle$ in summer

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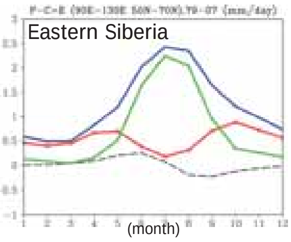
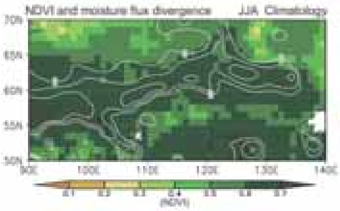
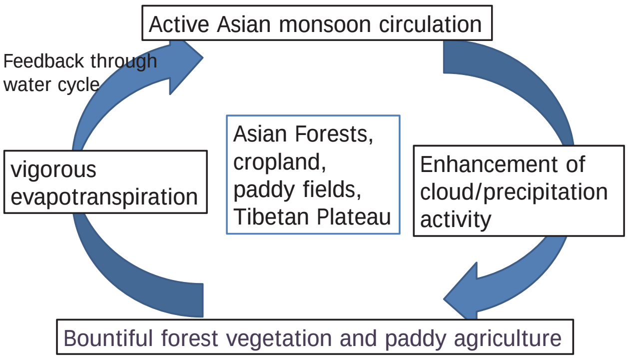
Annual cycle of the atmospheric water budget
Eastern Siberia





- Eastern Siberia: $-\langle \nabla \cdot Q \rangle \ll \langle E \rangle$ in summer
- Evapotranspiration is a dominant source of precipitation
- Taiga forest: a fundamental source of water vapor

A feedback through water cycle



Active Asian monsoon circulation

Feedback through water cycle

vigorous evapotranspiration

Asian Forests, cropland, paddy fields, Tibetan Plateau

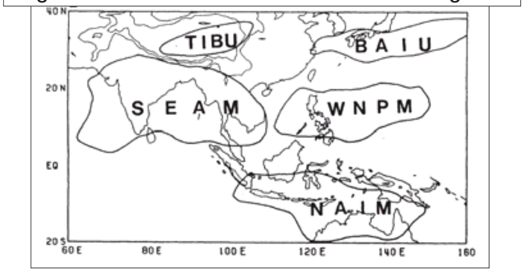
Enhancement of cloud/precipitation activity

Bountiful forest vegetation and paddy agriculture

(Yasunari 2006)

5. Regionality of Asian monsoon

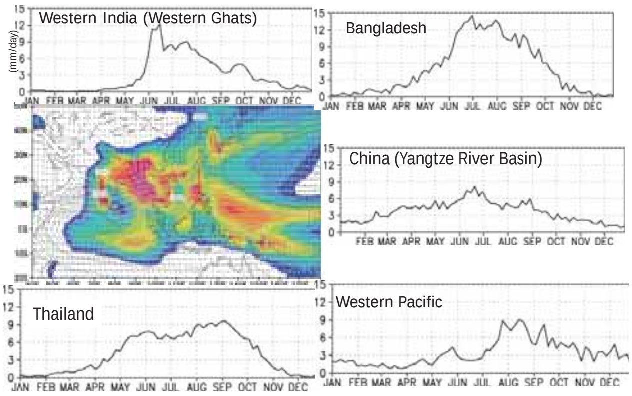
Regional classification of Asian monsoon regions



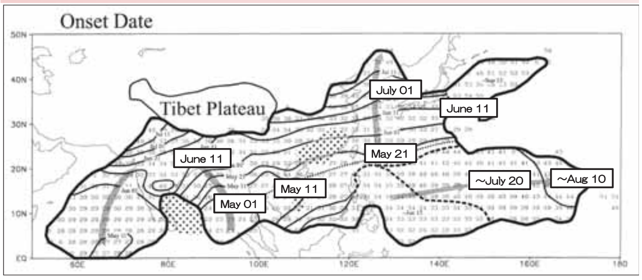
(Murakami and Matsumoto 1994)

SEAM: Southeast Asian monsoon
TIBU: Wet climate regime over the Tibetan Plateau
BAIU: Wet climate regime over East Asian rainy season
WNPM: western North Pacific summer monsoon

Regional differences in the seasonal march



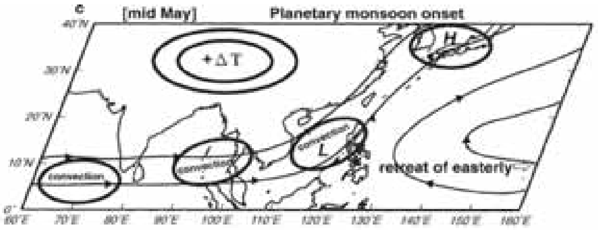
Progression of the onset date of rainy season



(Wang and LinHo 2002)

- Northward migration of the onset date over S/SE/E Asia
- Eastward progression over western Pacific

Broad-scale monsoon onset on mid-May



(Ueda 2005)

- Broad-scale monsoon onset occurs over the Arabian Sea, the Bay of Bengal and the South China Sea in mid-May.

The spatial distribution in temperature

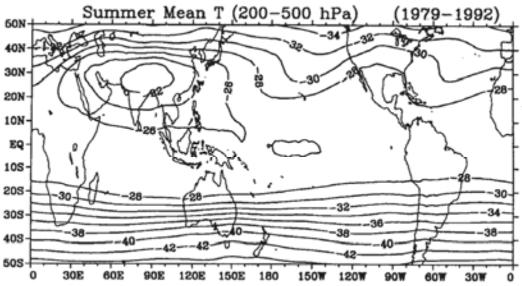


FIG. 3. The mean upper-tropospheric (200–500 hPa) temperature (°C) for summer, averaged over 14 years (1979–1992).

(Li and Yanai 1996)

- Distinct temperature contrast around Asia: warmer temperature over the land than over the ocean

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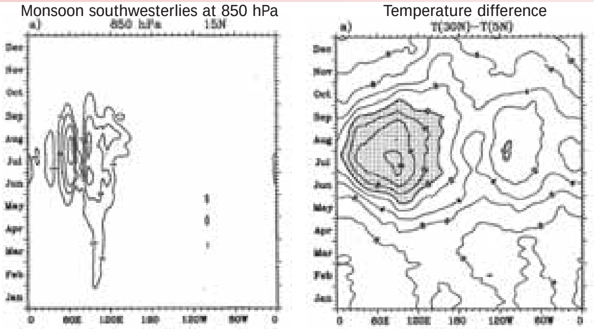
The timing of onset in southwesterlies



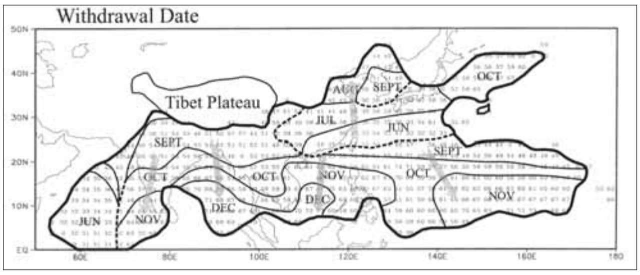
Monsoon southwesterlies at 850 hPa

Temperature difference

(Li and Yanai 1996)

- The timing of the onset depends on that of the meridional temperature reversal.

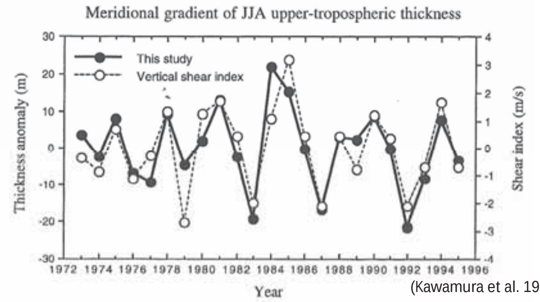
Progression of the withdrawal date



(Wang and Linho 2002)

- ●Southward migration of the monsoon withdrawal date
- ●Northward migration over East Asia

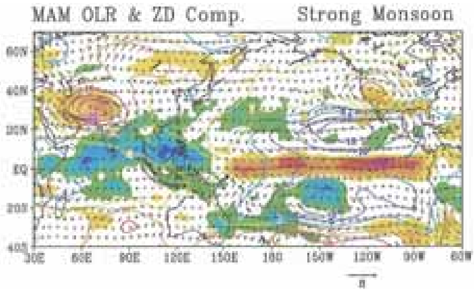
6. Interannual variation of broad scale Asian monsoon



(Kawamura et al. 1998)

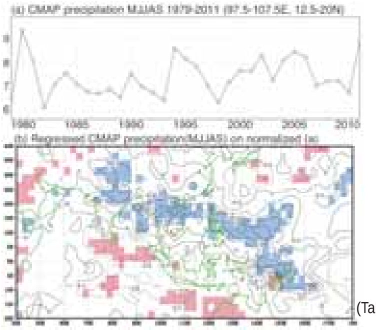
- ● The meridional temperature gradient (MTG) : Driving force of Asian monsoon
- ● The MTG value: broad scale monsoon index

Atmospheric circulation and convections occurring before strong summer monsoon



- ● **La Nina** phase: higher SST from western North Pacific to North Indian Ocean accompanied by strong convection
- ● Suppressed convection to the west of the TP
- ● Strong meridional thermal gradient in pre-monsoon period

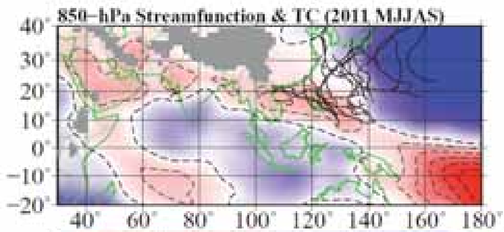
Interannual variation of summer monsoon rainfall over Indochina Peninsula



(Takahashi et al. 2014)

- ●Zonally-elongated high precipitation anomalies from western North Pacific to India

Westward-propagating tropical cyclones including Typhoon



(Takahashi et al. 2014)

- ● The interannual variation of summer (MJJAS) rainfall over Thailand depends on the frequency of westward propagating tropical cyclones (TCs) including Typhoon.

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