Landscape System Response Under a Changing Climate

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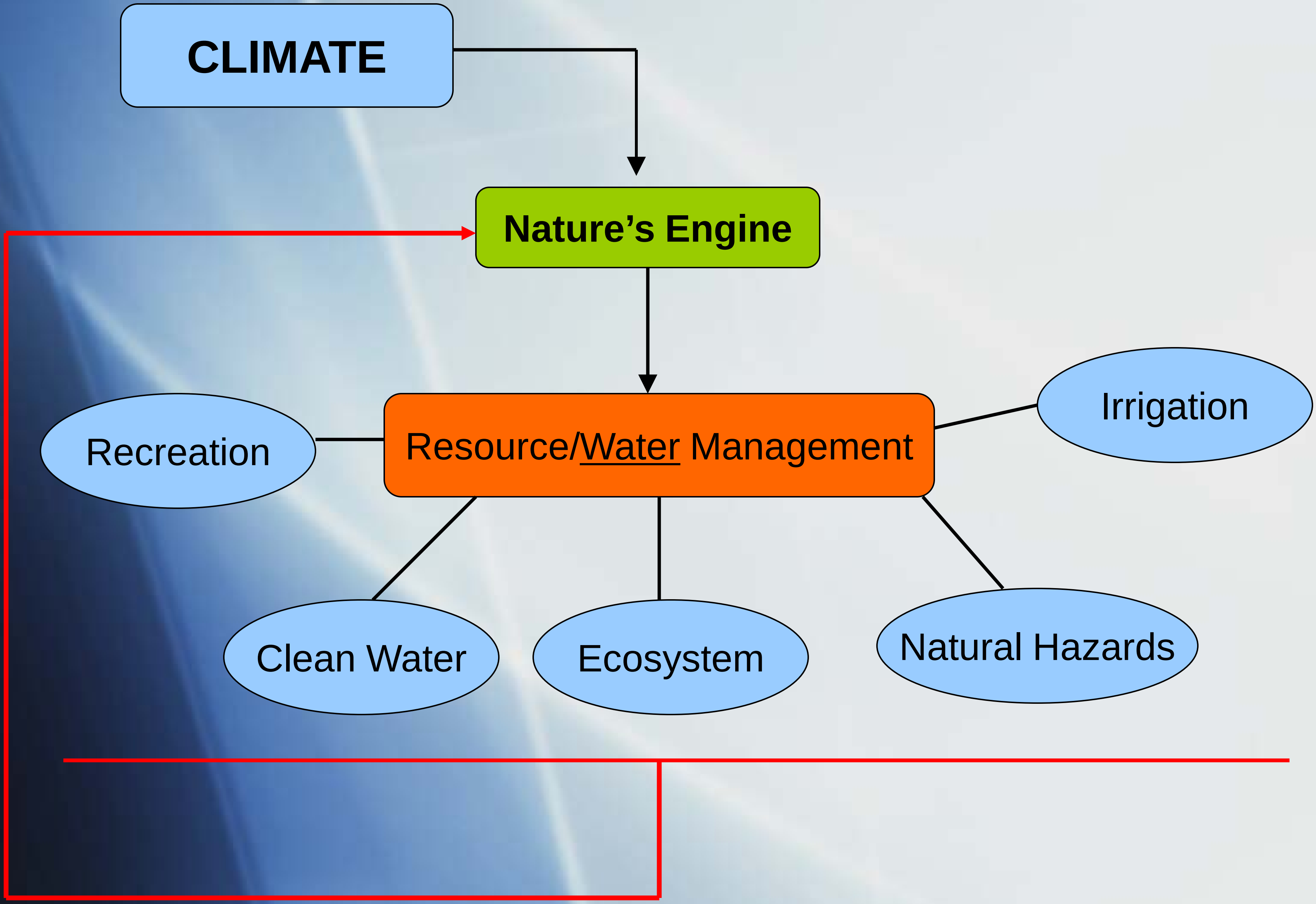


CLIMATE

Nature’s Engine

Resource/Water Management

Recreation

Irrigation

Clean Water

Ecosystem

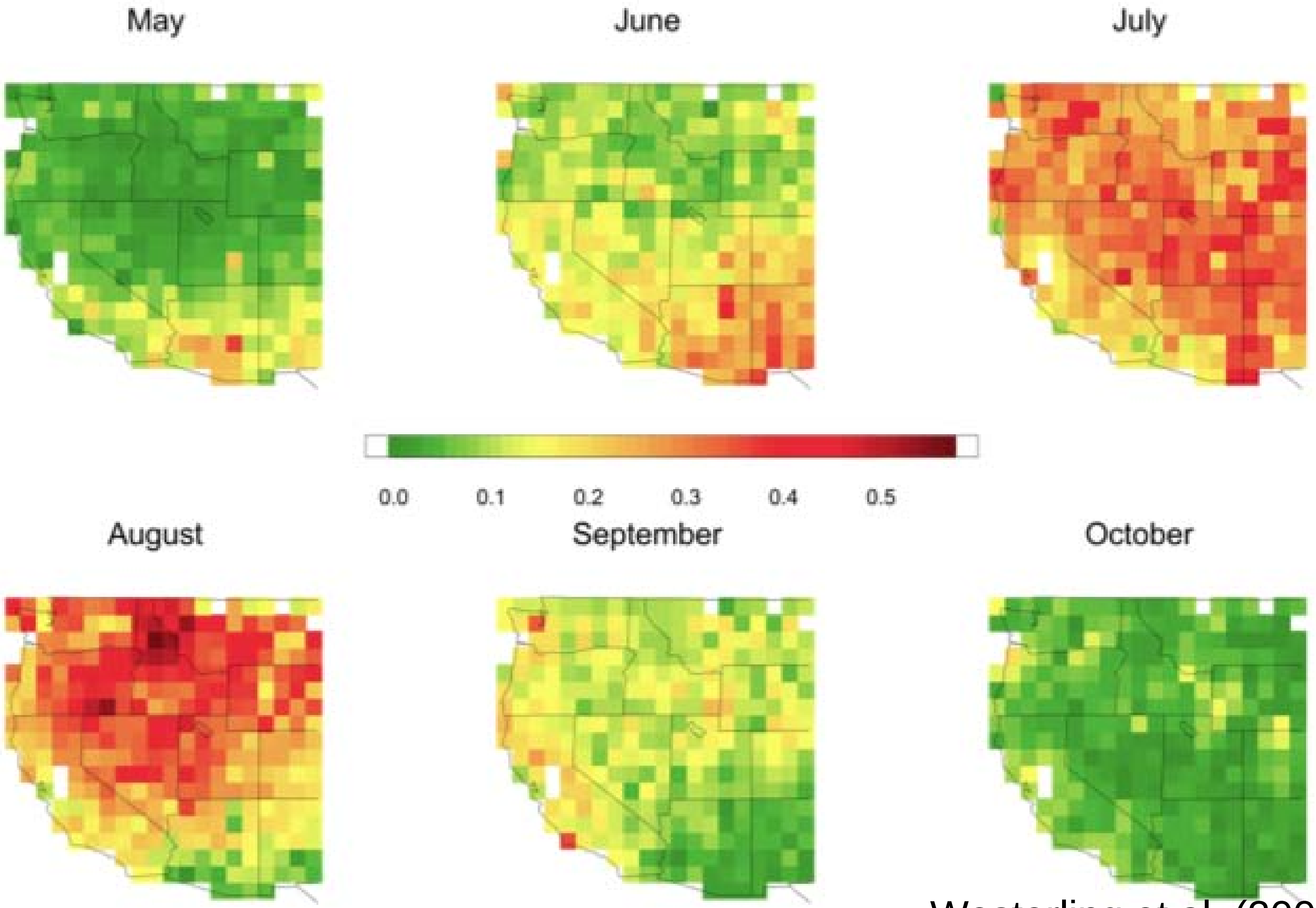
Natural Hazards

Wildfire causes:

- Accumulation of biomass
- Dry plant residue
- Dry soil conditions
- High temperatures
- Ignition by lightening

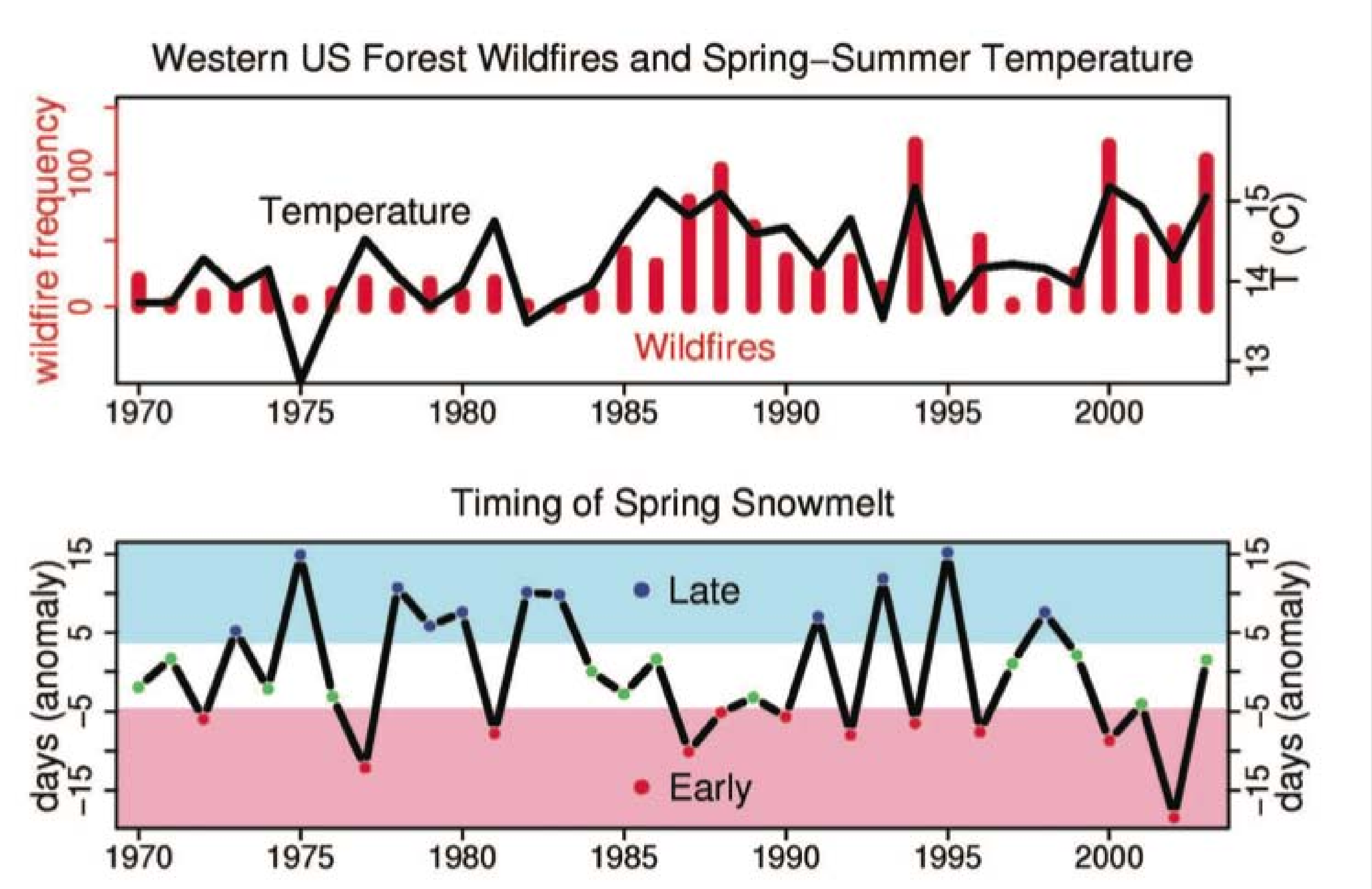
National Interagency Fire Center, Boise, Idaho

Seasonality and fire ignition percentages (1980-1999)



Westerling et al. (2003)

Climate and wildfire frequency in the western U.S.: role of temperature and snowmelt



Westerling et al. (2003)

How will the forests respond to climate change?

Modeled Temperatures show up to 3 degrees C increase

Winter **Spring** **Summer** **Fall**

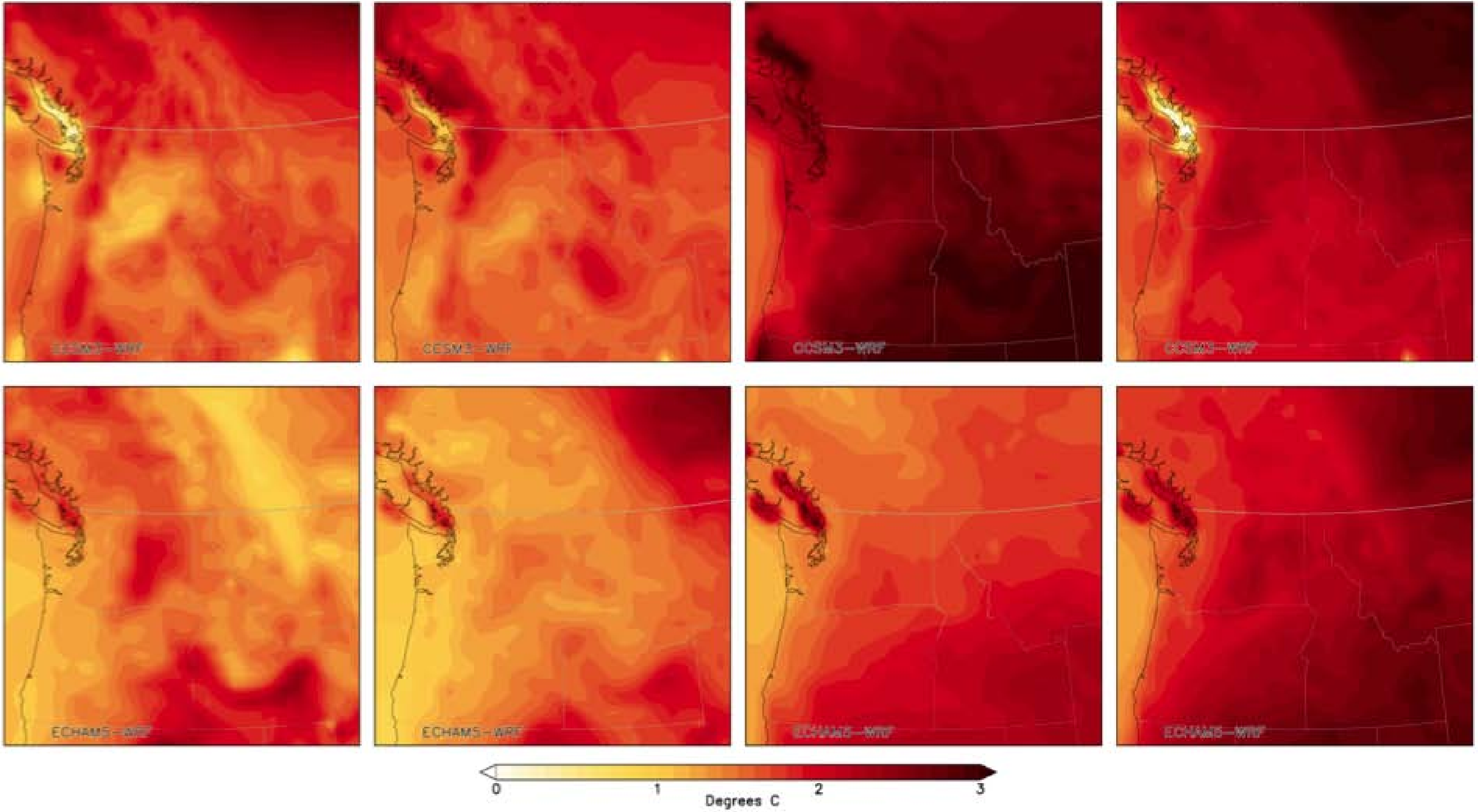
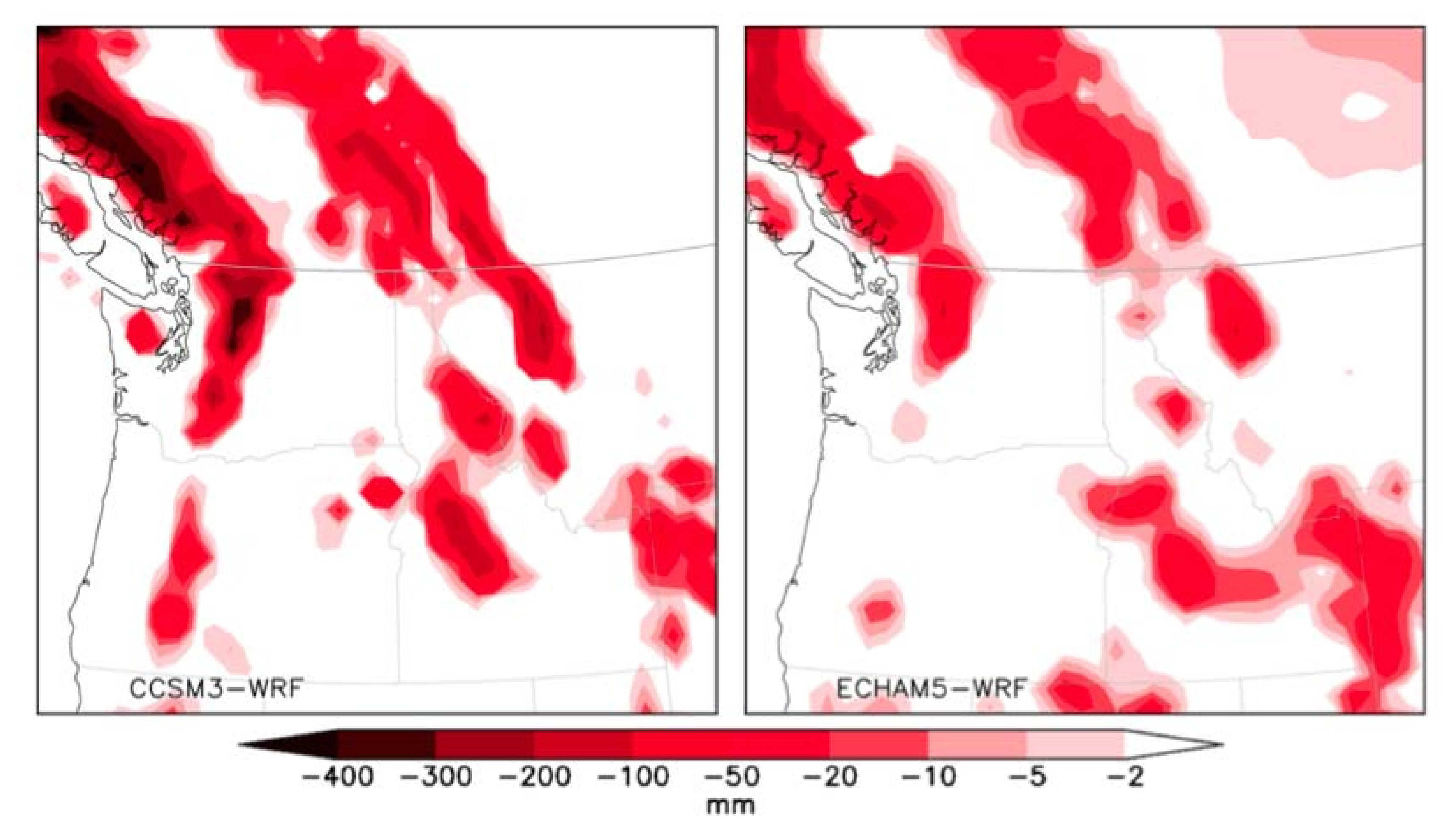


Figure 7. Change in temperature (°C) from 1970-1999 to 2030-2059 for CCSM3-WRF (top row) and ECHAM5-WRF (bottom row) for the four seasons.

Salathe et al., (2009)

Predicted changes in Snow Water Equivalence

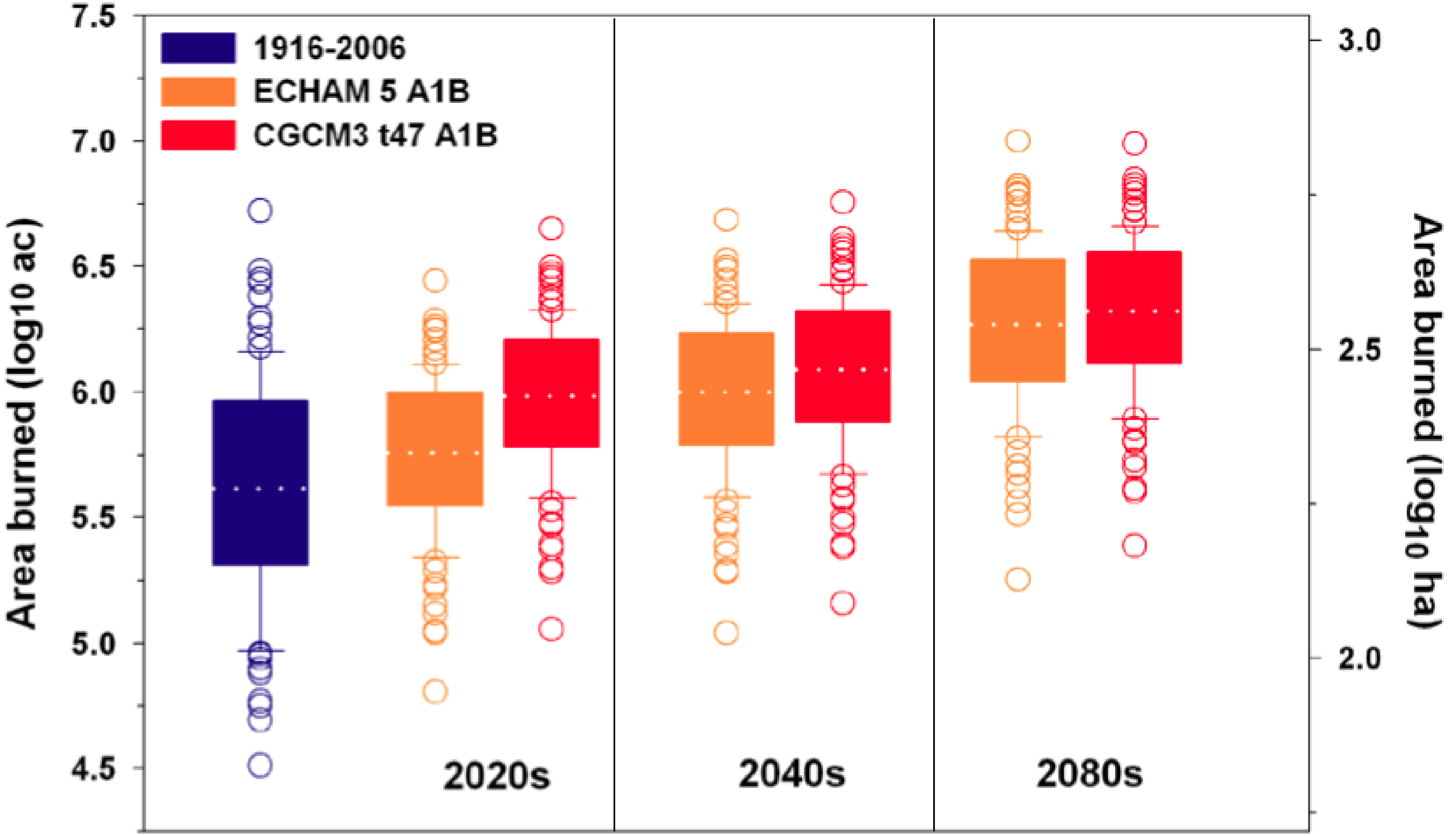


Change in April 1 snow water equivalent (mm) from CCSM3-WRF (left) and ECHAM5- WRF (right).

Salathe et al., (2009)

Models Predict increase in Fire Areas with Climate Change…

Changes in the distribution of annual area burned for the 2020s, 2040s, and 2080s for two medium scenario GCMs



Little et al. (2009)

Wildfire impacts on surface processes:

- Hydrology
- Water flow on hillslopes and channels
- Geomorphic processes

Canopy Interception

E&T

QuickTime™ and a decompressor are needed to see this picture.

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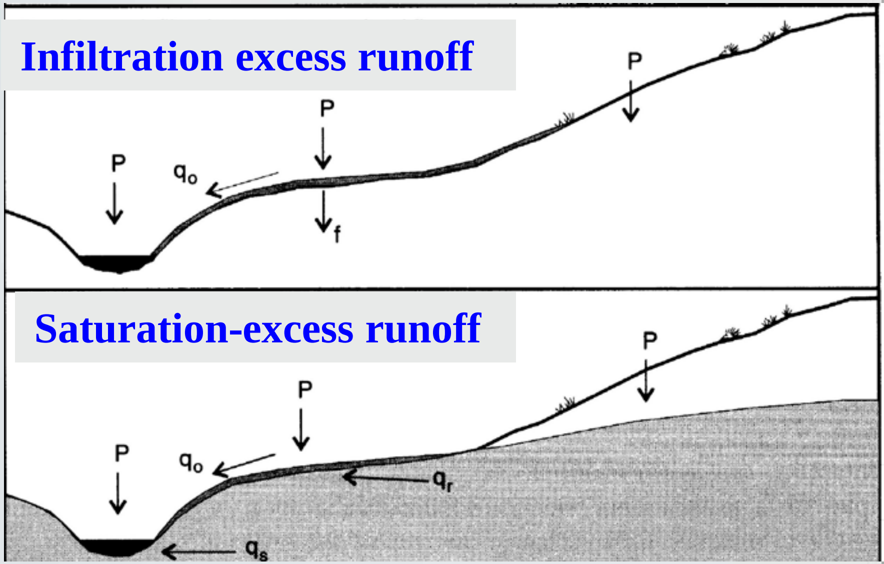

Infiltration excess runoff

Saturation-excess runoff

Water repellent soil

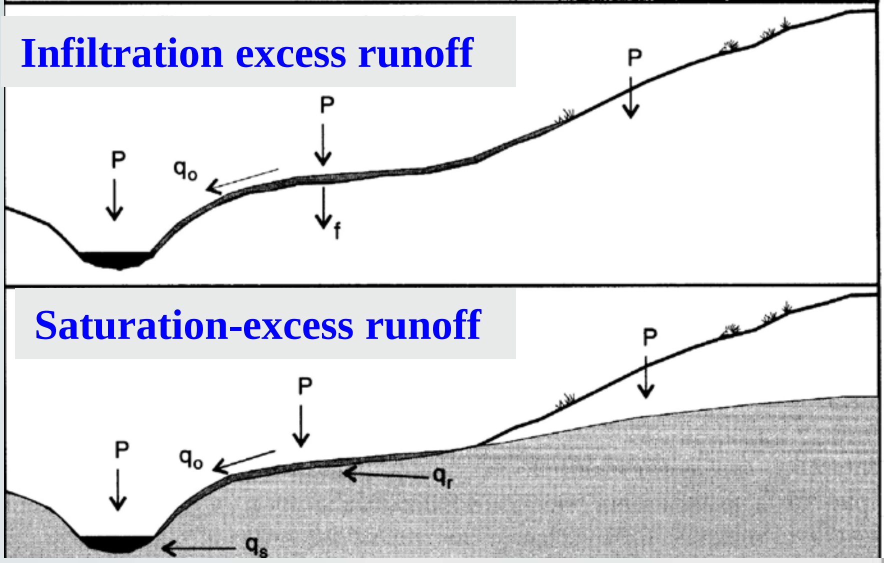
DHSVM sketch: http://hydrology.pnl.gov/

Increase in Runoff generation

$$R=P-I$$

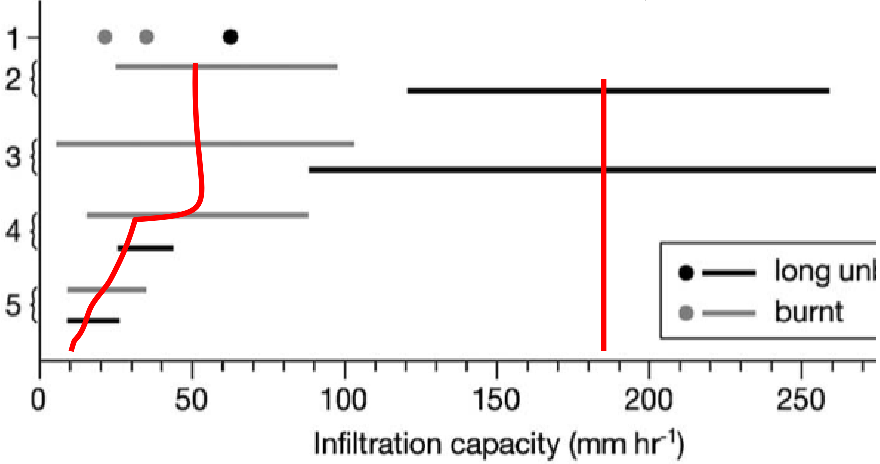
burned

unburned



Infiltration excess runoff

Saturation-excess runoff



1. Ponderosa pine, Arizona (Campbell et al., 1977)
2. Ponderosa pine and mixed conifer, Washington (Martin and Moody, 2001a)
3. Pine and eucalypt, Portugal (Shakesby et al., 1993)
4. Pine and oak scrub, Israel (Kutiel et al., 1995)
5. Oak scrub, Spain (Imeson et al., 1992)

Shakesby and Doerr (2006)

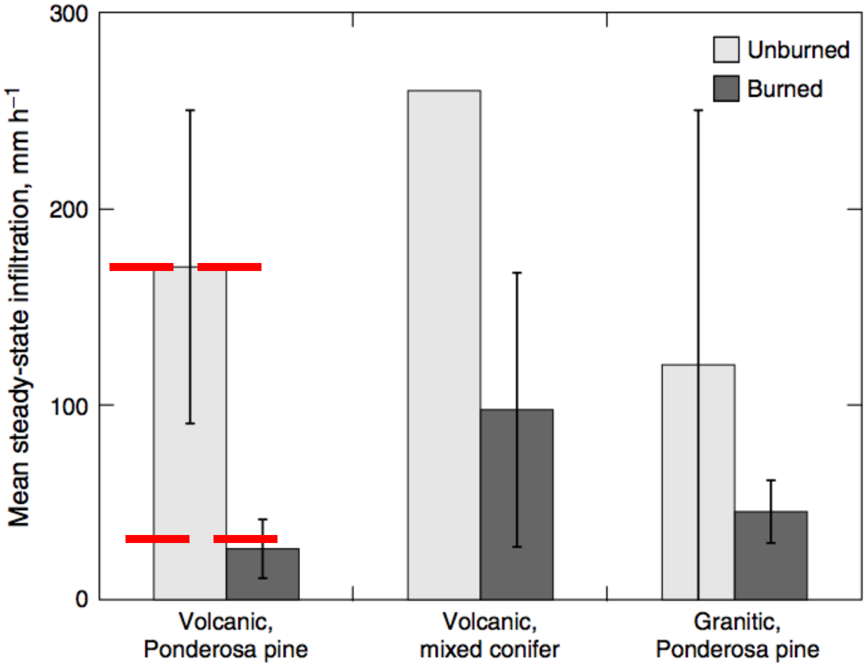


Figure 3. Steady-state infiltration rate in unburned and burned sites

Martin & Moody, 2001

Wildfire impacts on surface processes:

- **Rainsplash erosion:**

QuickTime™ and a
decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

Rain detaches particles and makes them available for runoff transport

- **Runoff erosion: Rill and gully incisions**

Gully incision NF of the Boise River, ID

QuickTime™ and a
decompressor
are needed to see this picture.

Buffalo Creek Fire, NM. Photo by John A. Moody

Wildfire impacts on surface processes:

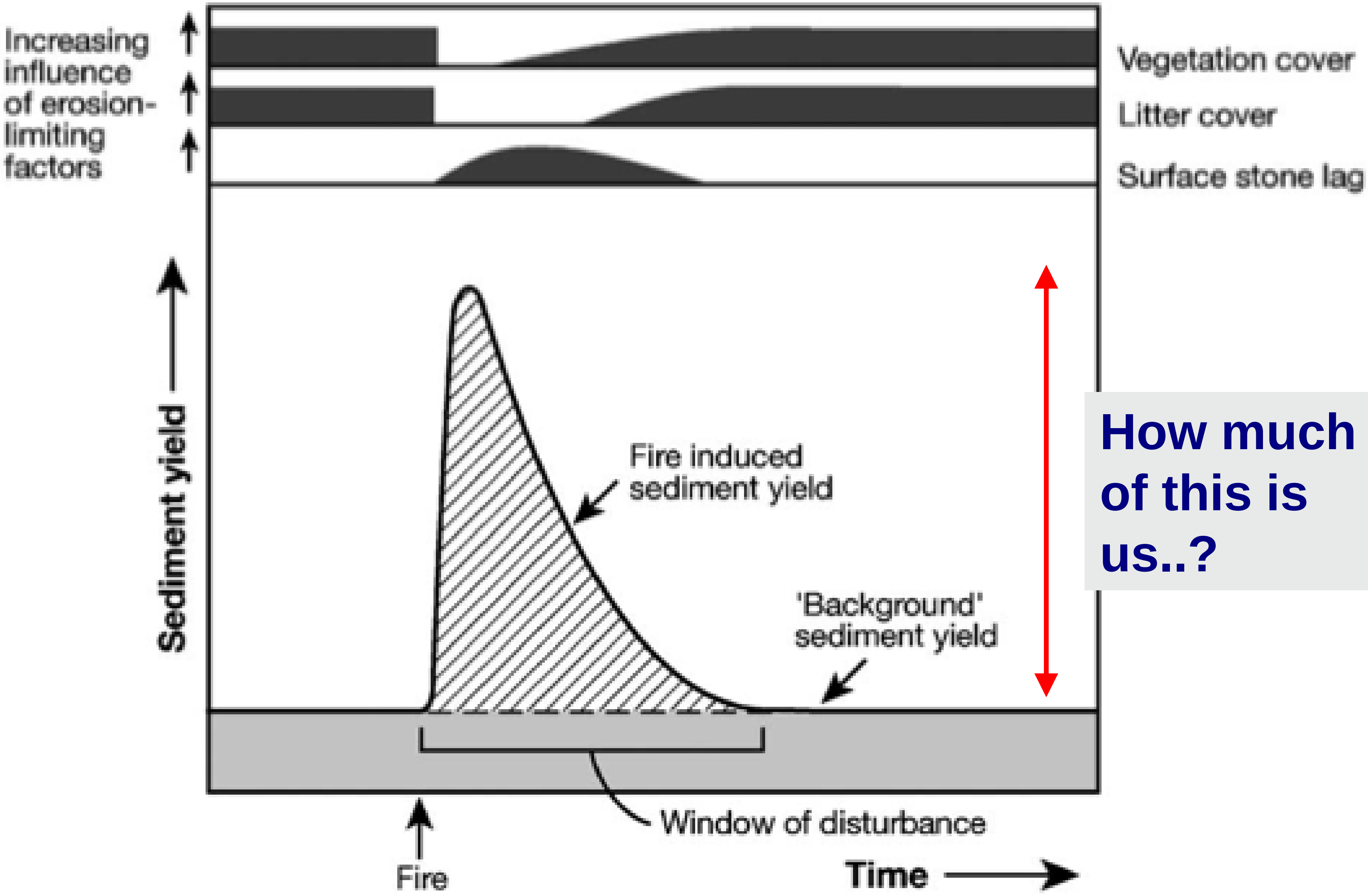
- **Landsliding**

QuickTime™ and a
decompressor
are needed to see this picture.

Landslides & Debris flows in Italy, Switzerland, China

Timing of different erosion forms after fire

R.A. Shakesby, S.H. Doerr / Earth-Science Reviews 74 (2006) 269–307



How much of this is us..?

)

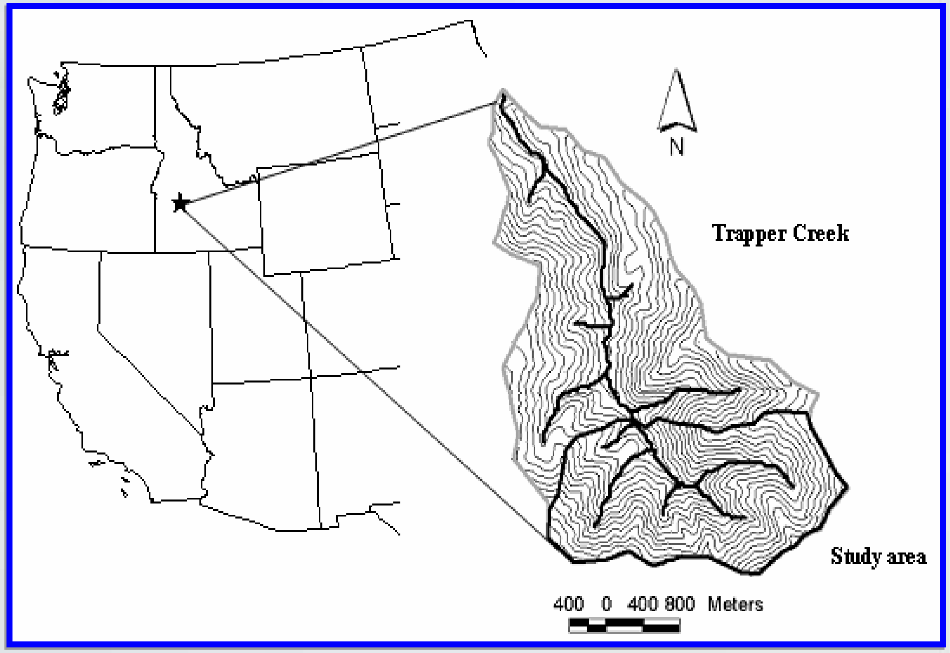
Though Questions for Future Management Directions

- What will happen under climate change with increased fire frequency and earlier snowmelt?
- What is the role of humans (forest roads, timber harvest etc.) in modulating the response?
- What are the objective criteria to evaluate human impact?

FIELD AREA

Headwaters of Trapper Creek, Idaho Batholith

- Granite Bedrock
- Mountainous forested basin
- V-shaped valleys
- Episodic stand-replacing wildfires
- High intensity-short duration summer storms (e.g., ~80 mm/h rain has a RI of 1 in 4 years)
- March – May snowmelt rain on snow
- Hollow evacuation (surface erosion, landsliding)




Following a wildfire in 1995

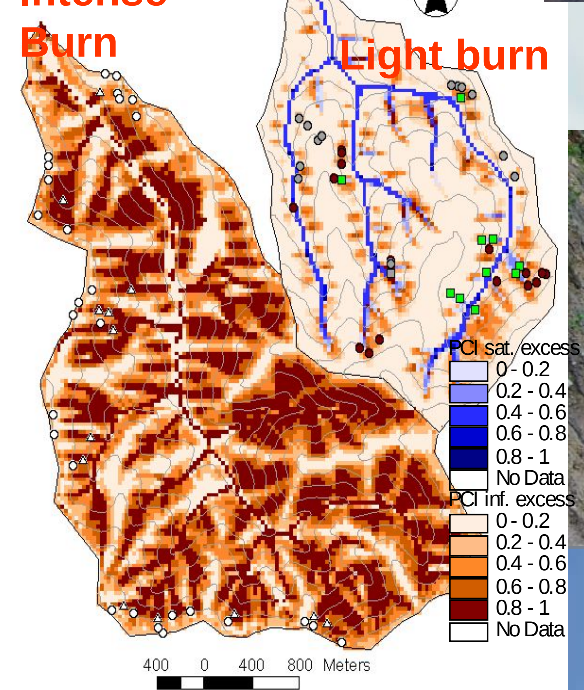
EPISODIC EROSION IN THE IDAHO-Batholith

Fluvial Erosion

Water repellent soils due to wildfires + surface vegetation loss

Summer storms

Landscape scale response

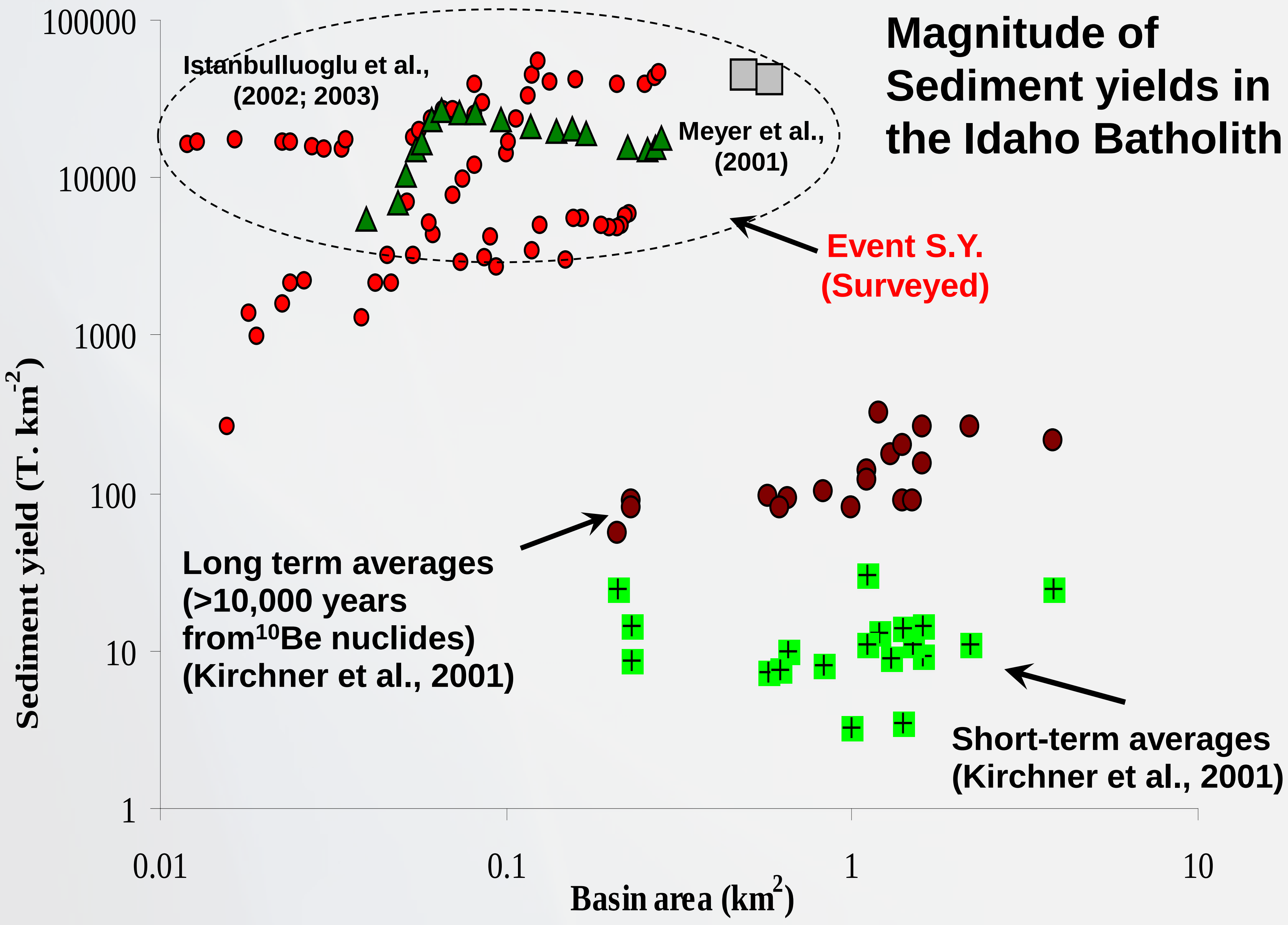


Landsliding & Debris flows

Loss of tree root cohesion

Winter rain-on-snow

Magnitude of Sediment yields in the Idaho Batholith



Istanbulluoglu et al., (2002; 2003)

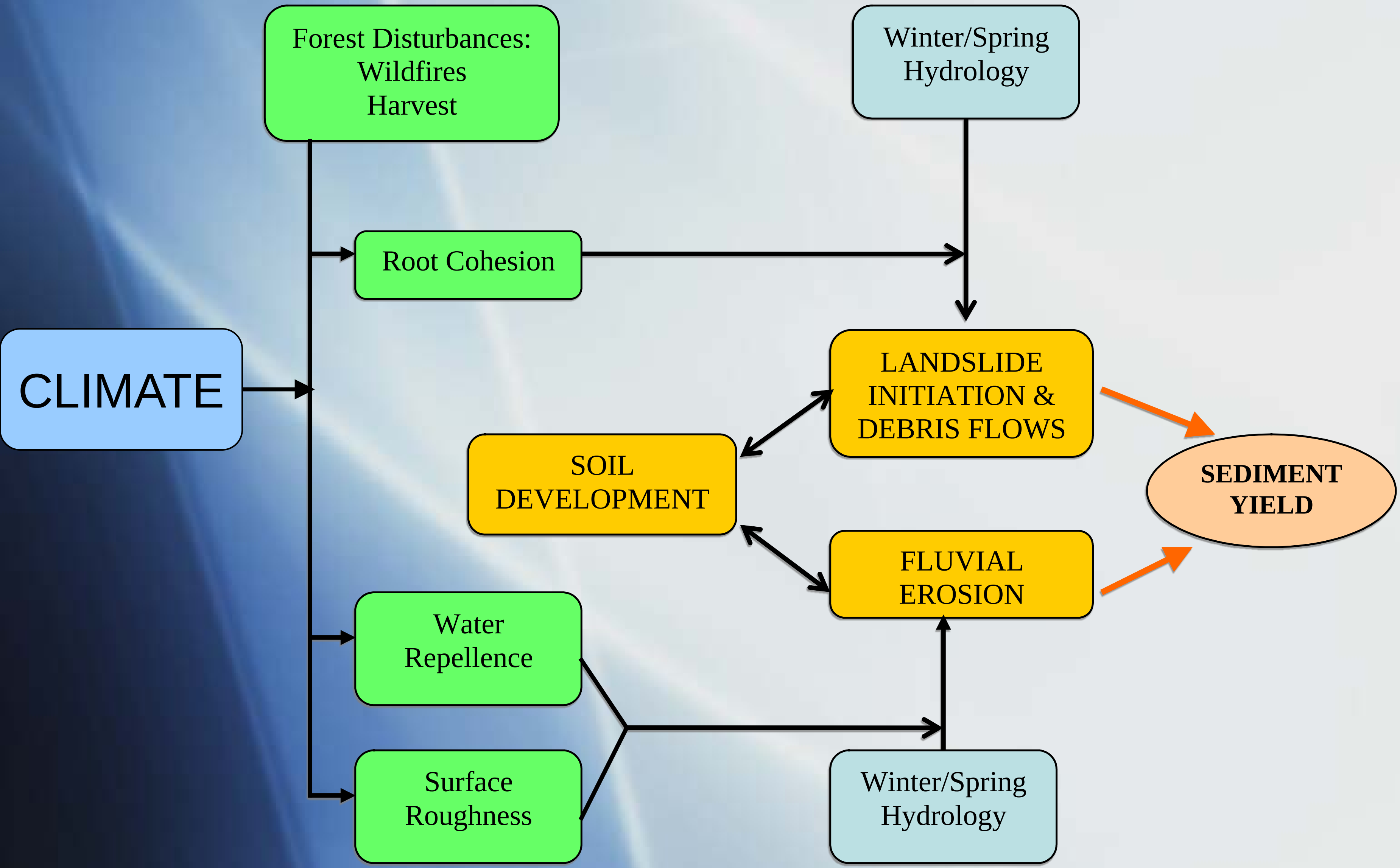
Meyer et al., (2001)

Event S.Y. (Surveyed)

Long term averages (>10,000 years from ^{10}Be nuclides) (Kirchner et al., 2001)

Short-term averages (Kirchner et al., 2001)

NUMERICAL MODEL



Forest Disturbances:
Wildfires
Harvest

Winter/Spring Hydrology

Root Cohesion

CLIMATE

LANDSLIDE INITIATION & DEBRIS FLOWS

SOIL DEVELOPMENT

SEDIMENT YIELD

FLUVIAL EROSION

Water Repellence

Surface Roughness

Winter/Spring Hydrology

CHANGE IN SOIL STORAGE:

$$\left.\frac{\partial h_s}{\partial t}\right| = -\frac{\rho_r}{\rho_s}\frac{\partial z_{b-s}}{\partial t} + \nabla(K\nabla z) - \nabla q_{fluvial} - \infty$$

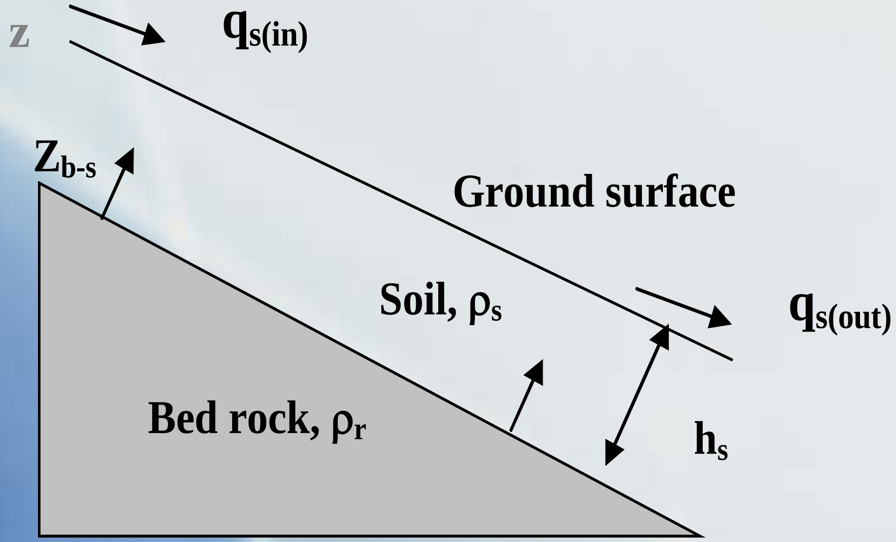
weathering

Soil creep

Fluvial processes

Sliding

s



CLIMATE FORCING

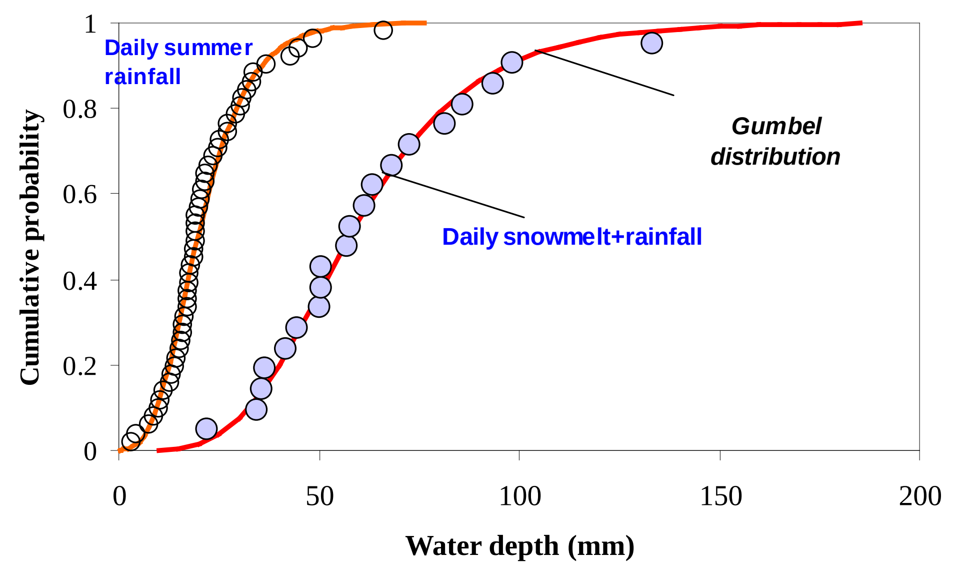
Daily maximum winter-spring water input and summer precipitation obtained from meteorological data

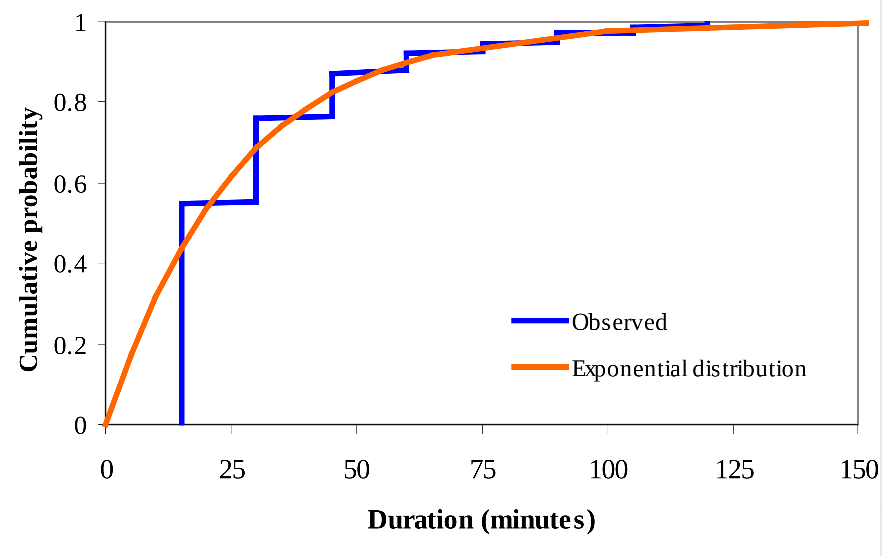
Summer storm durations from 15-minute rainfall data

$$\begin{array}{ll} wi = (SD_{i-1} - SD_i)RSW + P_i & SD_i < SD_{i-1} \\ wi = 0 & SD_i \ge SD_{i-1} \end{array}$$

Exponential distribution fitted to the data

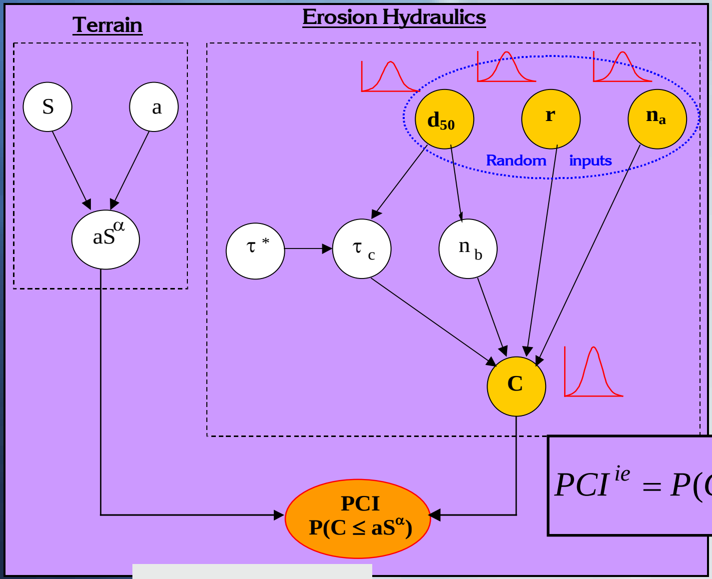
Gumbel distribution fitted to the data





EPISODIC GULLY EROSION

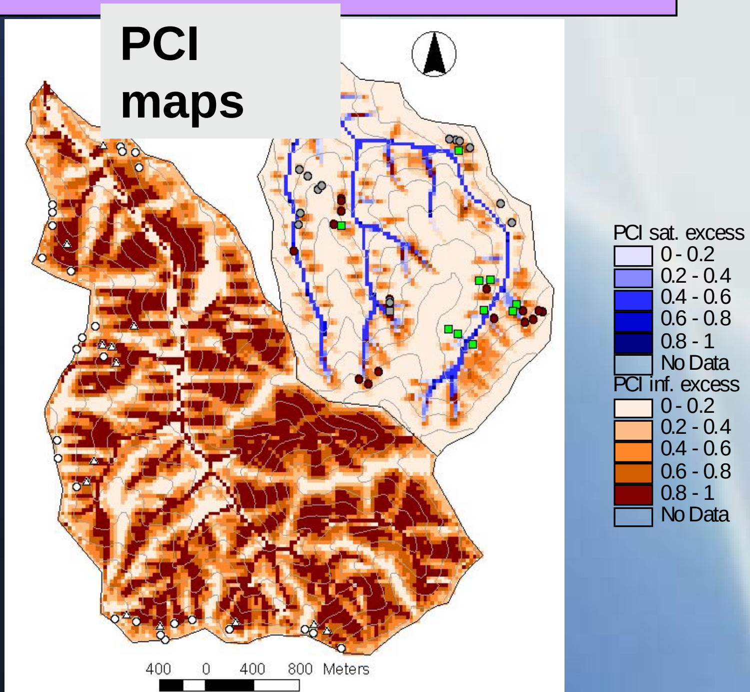
The PCI model;

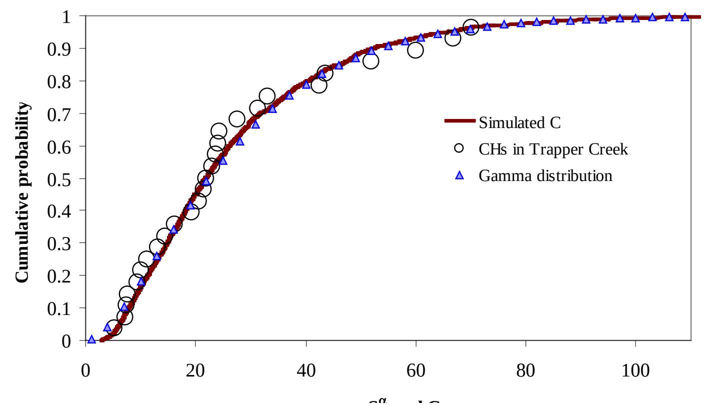


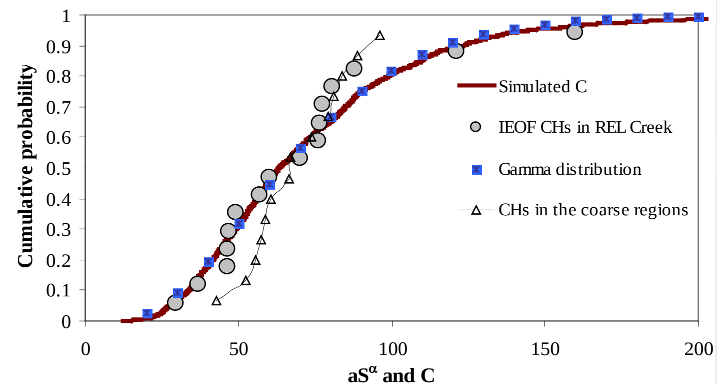
$$PCI^{ie} = P(C \le aS^{\alpha}) = \int_{0}^{aS^{\alpha}} f_C(C)dC$$

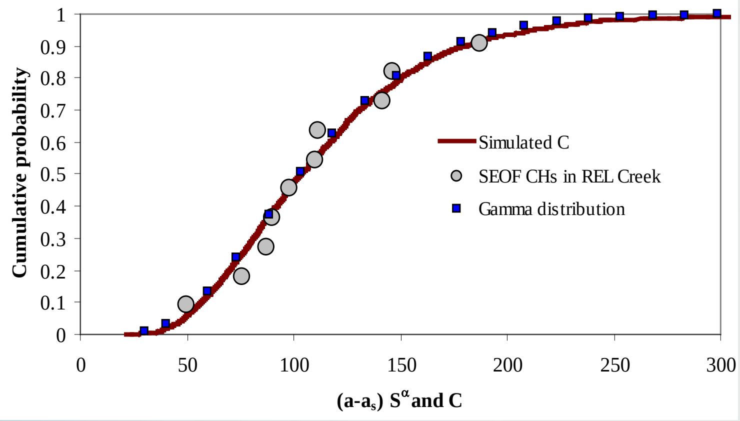
Model was tested in study basins in the Idaho Batholith

PCI maps









Sediment Transport Function

Dimensionless Sediment Transport Equation

$$q_{s*} = \kappa(\tau'_*)^p$$

$$\tau'_* = \tau_*(1-\tau_{*c}/\tau_*)$$

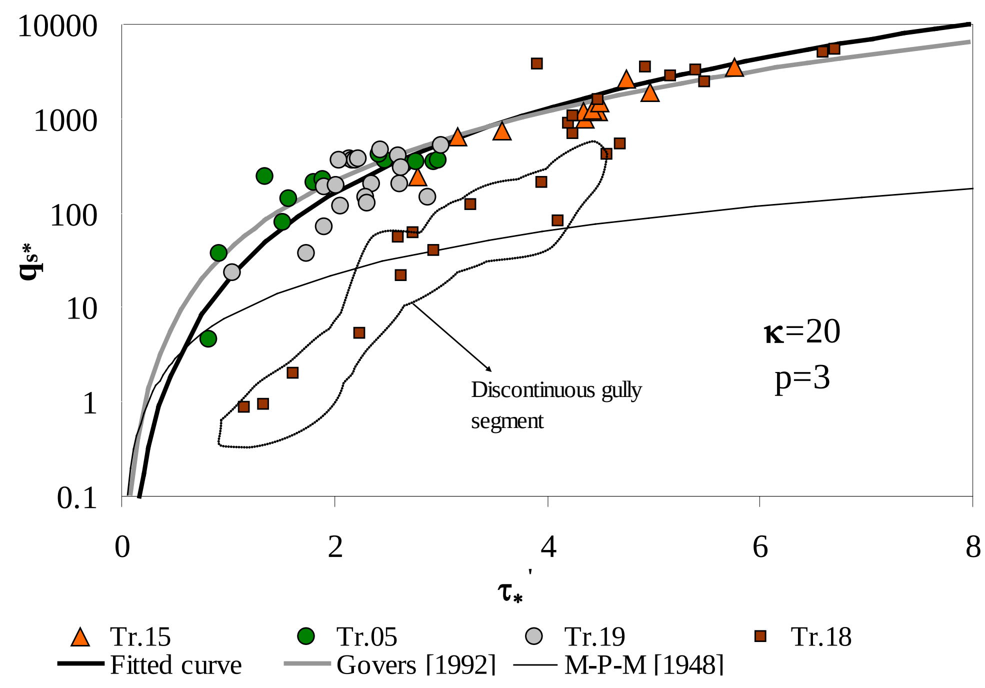
$$q_{s*} = \frac{q_s}{\sqrt{g(s-1)d^3}} \qquad \tau_* = \frac{\tau/(\rho_w g)}{(s-1)d}$$

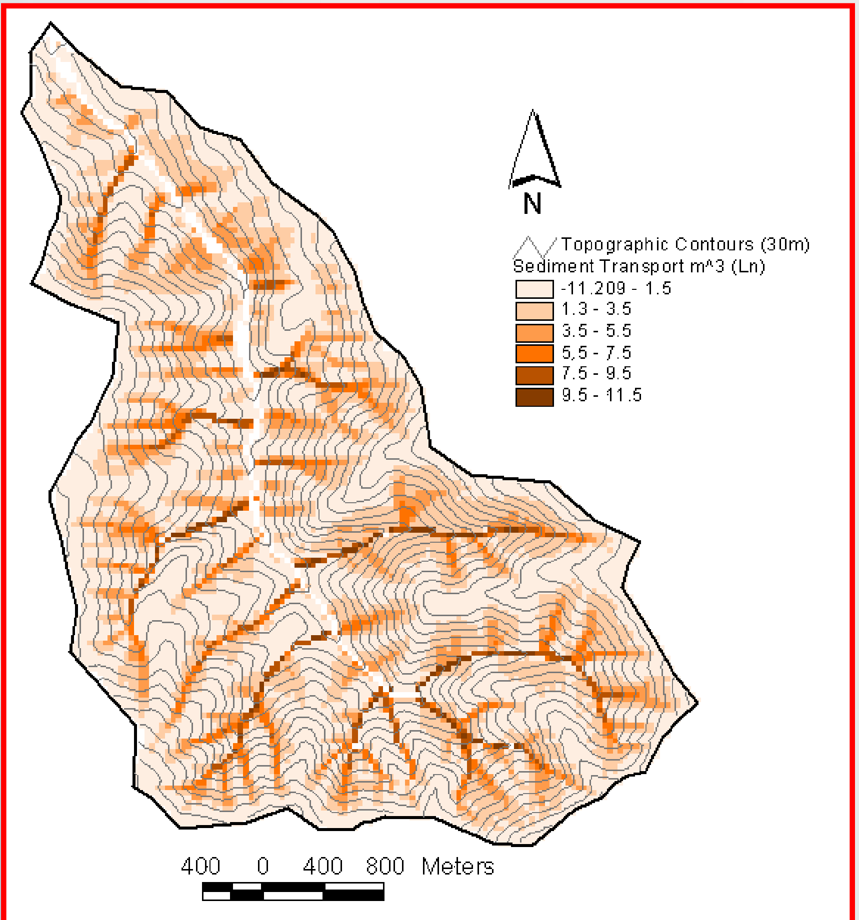
Expected Sediment Transport

$$\overline{Q}_s = \chi_{Q_s} A^M S^N PCI$$

M=2.1 and N=2.25

Calibration using geomorphic data





LANDSLIDES & DEBRIS FLOWS

Infinite plane slope stability model for shallow landslide initiation:

$$FS = \frac{C_r + C_s}{h_s \rho_b g \sin\theta} + \frac{\cos\theta \tan\phi [1 - Rw\, \rho_w / \rho_b]}{\sin\theta}$$

Relative wetness

$$Rw = \min\left(\frac{wi.a}{K_s h_s \sin\theta}, 1 \right)$$

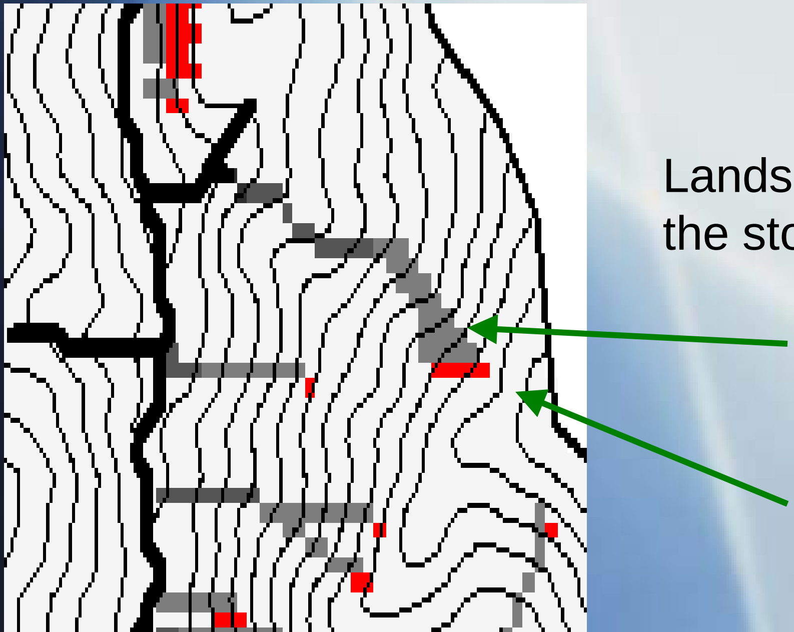
Root cohesion

$$C_r(t) = C_{pre} D_r(t) + C_m R_r(t)$$

Exponential decay

Logistic growth function

DEM topography



Landslides initiate debris flows that scour the stored colluvium in hollows

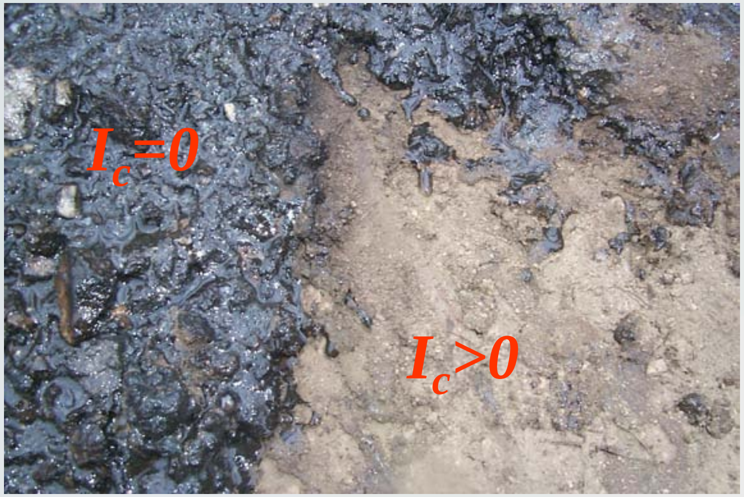
Debris flow scour

Landslide initiation zone

Runoff generation

Storm runoff and discharge

$$r = \begin{cases} (p-I_c)(1-\eta)+p\eta & p>I_c \\ p\eta & p\le I_c \end{cases}$$



Average storm runoff rate assuming exponential distribution for rainfall intensity during storms;

$$\bar{r} = \int_0^{I_c\eta} r f_{R1}(r)\,dr + \int_{I_c\eta}^{\infty} r f_{R2}(r)\,dr = \bar{p}\left[\eta + e^{-I_c/\bar{p}}(1-\eta)\right]$$

Average storm rate

Water repellent fraction

Channel flow

$$\bar{Q} = \bar{r}A$$

Surface Vegetation Recovery;

Fractional ground cover as a function of biomass

$$F_{gc} = 1 - e^{-B_m B_c}$$

Biomass growth rate depends on available space

$$\frac{dB_m}{dt} = k_B k_V (1 - F_{gc})$$

Post-fire water repellence proportional to fractional ground cover

$$\eta(t) = 1 - [P_f^{post} + \frac{F_{gc}(t)}{F_{gc}^{\max}}(1 - P_f^{post})]$$

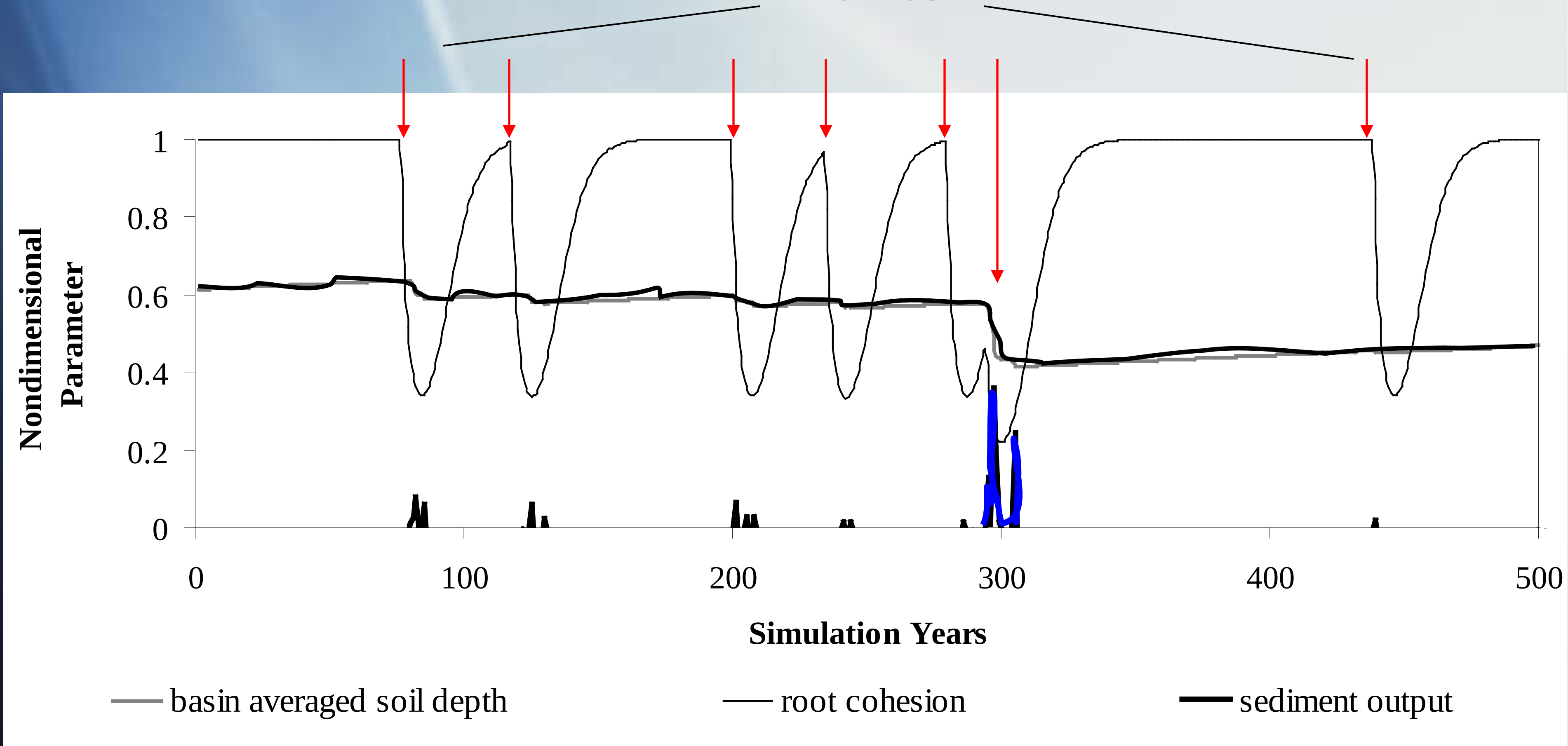
$$P_f^{post} = P_f^{pre}(1 - R_f)$$

Post-fire vegetation roughness proportional to fractional ground cover

$$n_v(t) = n_v^R \frac{F_{gc}(t)}{F_{gc}^R}$$

BASIN RESPONSE TO FIRES

Wildfires



How does vegetation influence the Frequency and Magnitude of erosion?

SIMULATION SCENARIOS

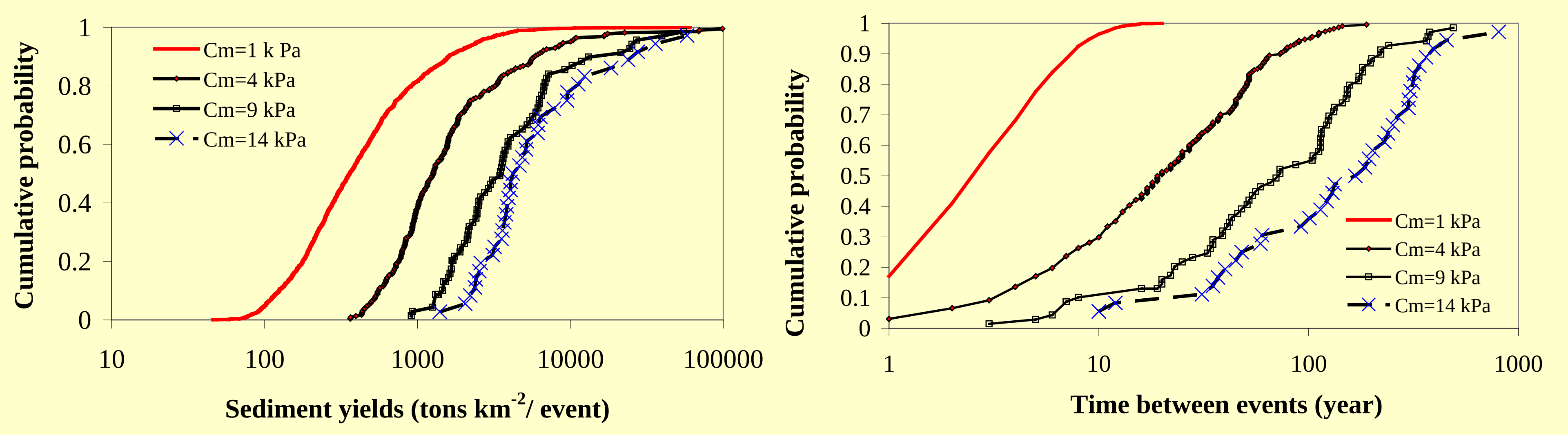
- **Constant Root Cohesion (C_r= 1 kPa, 4 kPa, 9kPa, 12 kPa)**
- **Forest Fires (P_F= 200 yr, C_m= 4 kPa, 9kPa, 12 kPa)**
- **Timber Harvest / Forest fire comparison**

Initial Condition:

(1) Soil evolution for 3000 years by diffusion and bedrock weathering.

(2) Spin up period of 3000 years in each run to limit the sensitivity to the initial conditions.

CONSTANT ROOT COHESION (No Vegetation Disturbance)



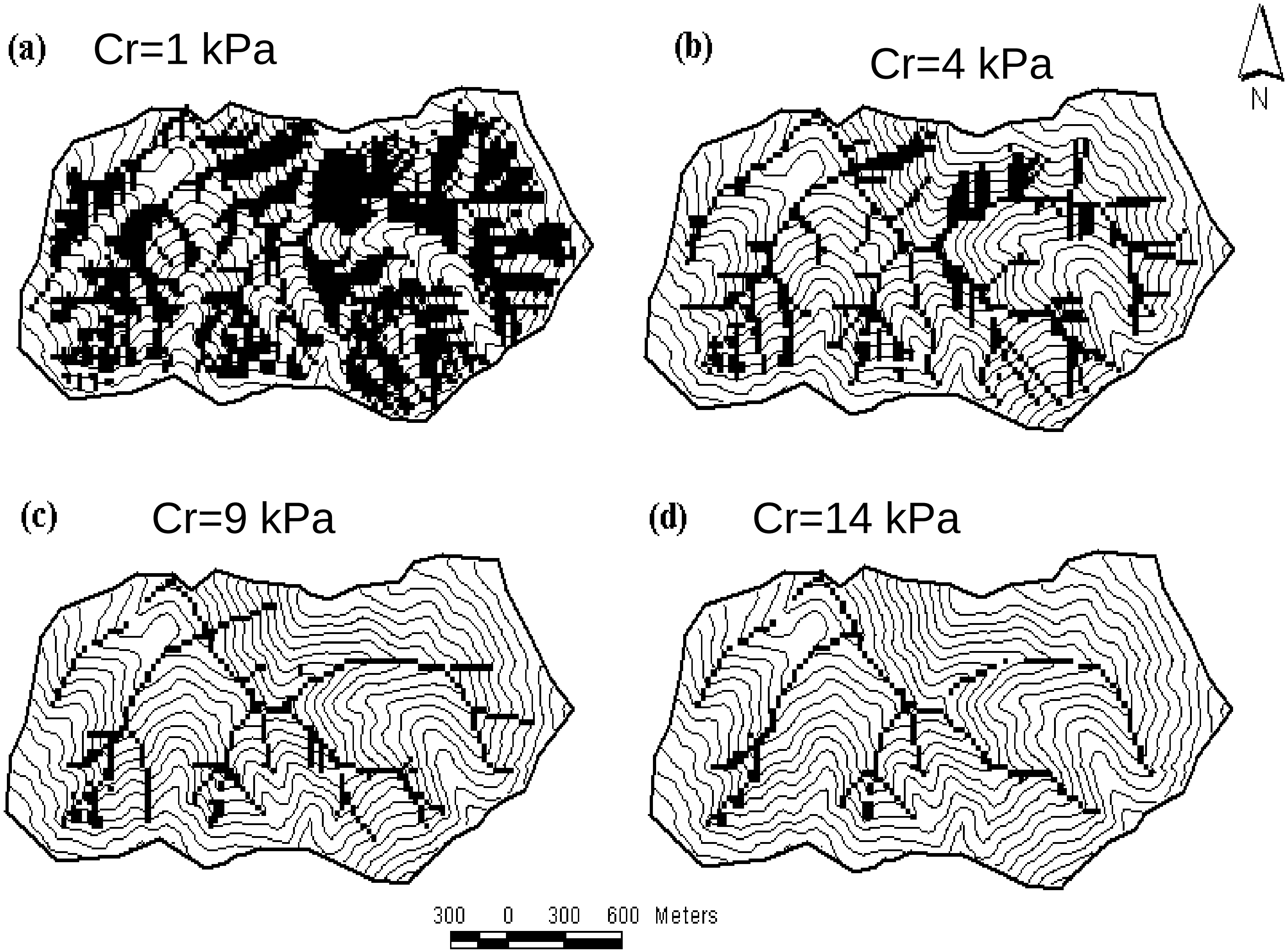
Summary of the simulations

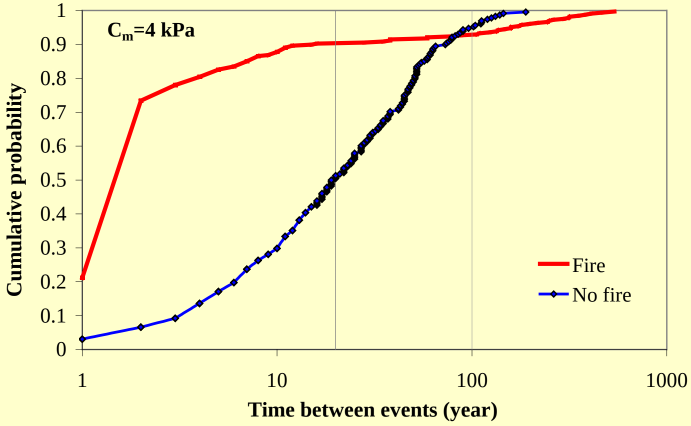
Simulation	Time between events (years)			Sediment yield (T. km^{-2}/ event)		
	Mean	q[¶]=0.05	q=0.95	Mean	q=0.05	q=0.95
C_r=1 kPa	3.86	1(0.17)[§]	9	728	101	2,400
C_r=4 kPa	30.6	1.8	102	3,313	483	10,000
C_r=9 kPa	100	6	371	8,162	1,258	27,100
C_r=14 kPa	191	10	524	8,841	2,050	40,300

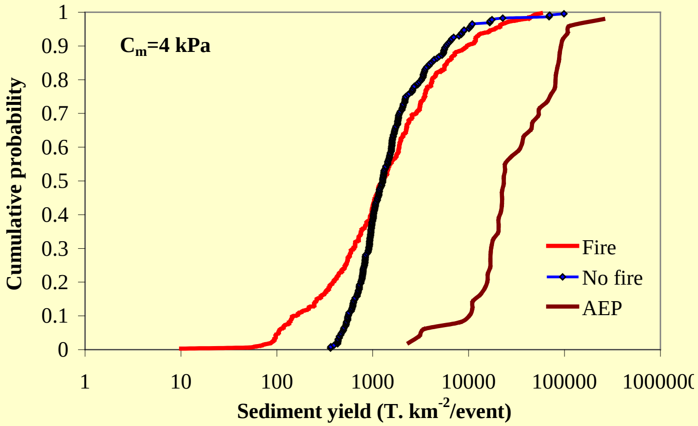
[¶] q represents quantile

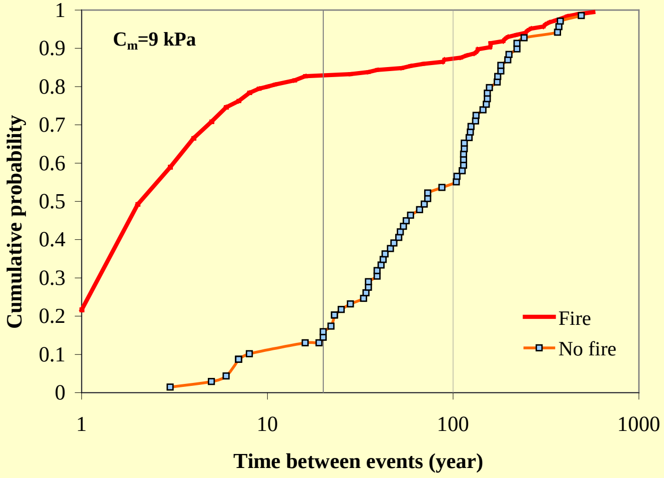
[§] Number in paranthesis is the minimum cumulative probability

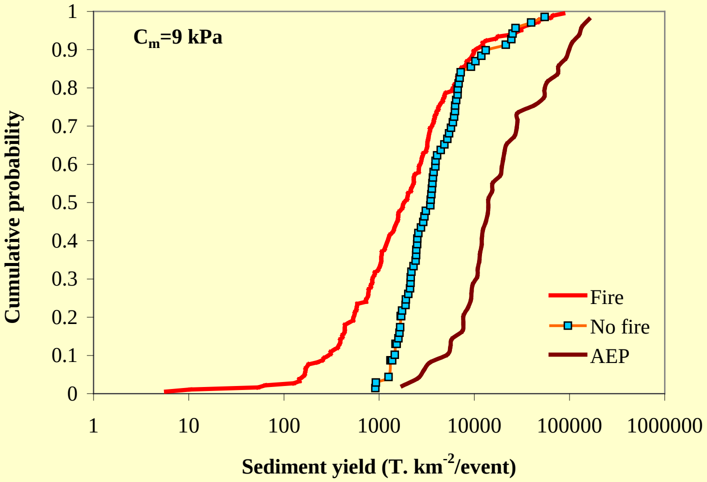
MAP of Net Erosion on the landscape

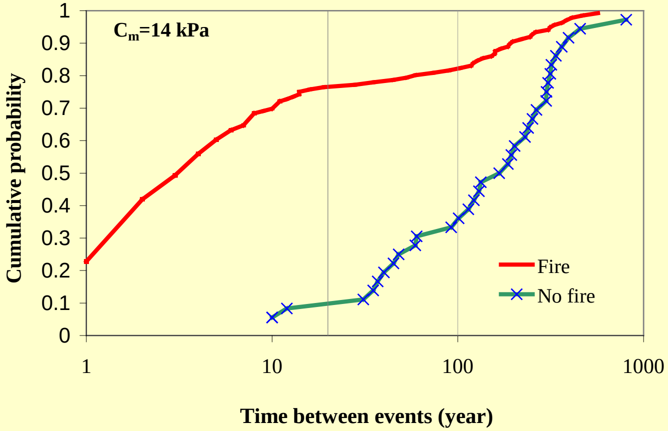


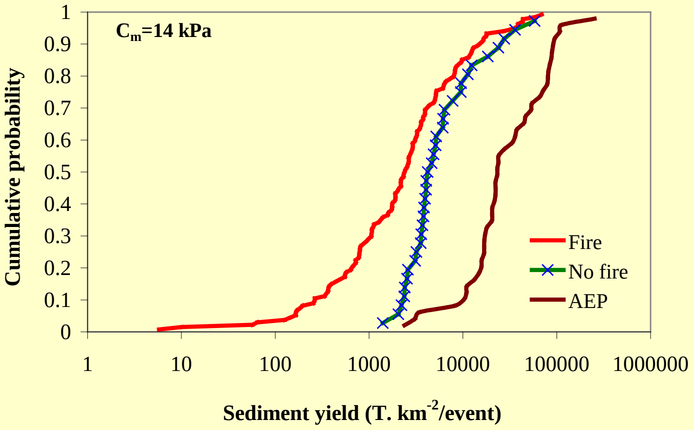

C$_m$=4 kPa
Cumulative probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
10
100
1000
Time between events (year)
Fire
No fire


C$_m$=4 kPa
Cumulative probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
10
100
1000
10000
100000
1000000
Sediment yield (T. km^{-2}/event)
Fire
No fire
AEP

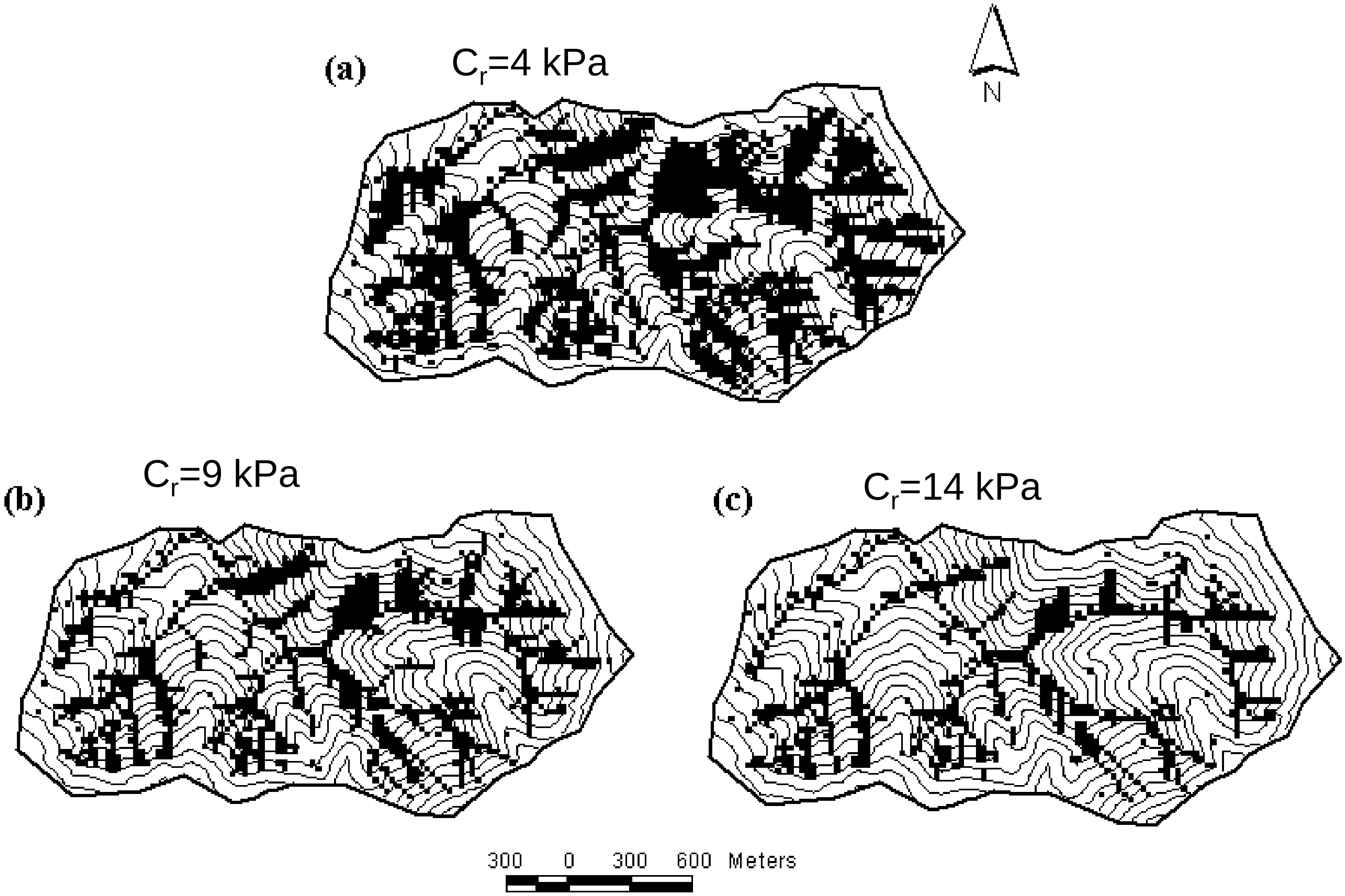

C$_m$=9 kPa
Cumulative probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
10
100
1000
Time between events (year)
Fire
No fire

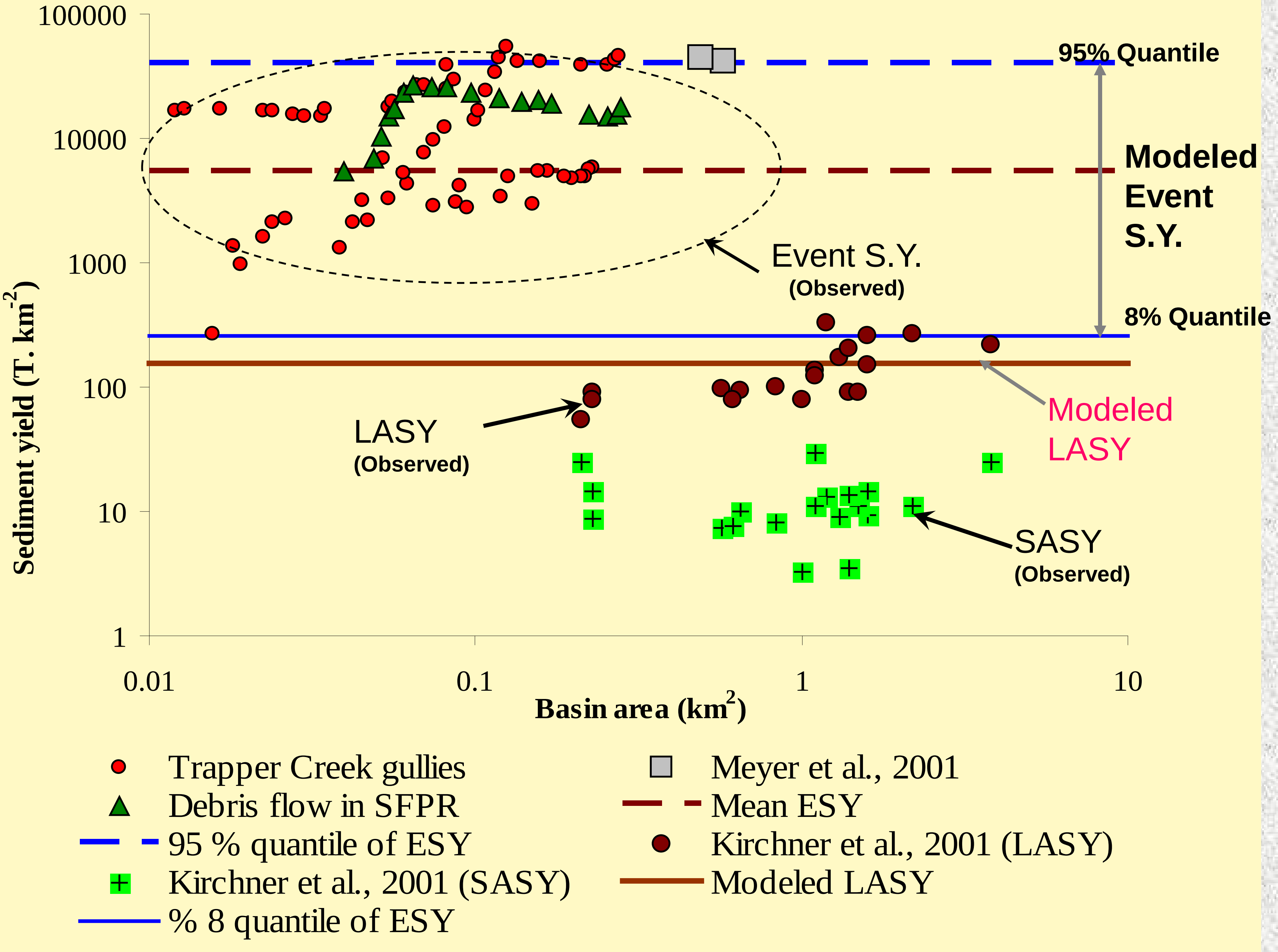

C$_m$=9 kPa
Cumulative probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
10
100
1000
10000
100000
1000000
Sediment yield (T. km^{-2}/event)
Fire
No fire
AEP


C$_m$=14 kPa
Cumulative probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
10
100
1000
Time between events (year)
Fire
No fire


C$_m$=14 kPa
Cumulative probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
10
100
1000
10000
100000
1000000
Sediment yield (T. km^{-2}/event)
Fire
No fire
AEP

SPATIAL EXTENT OF EROSION UNDER FOREST FIRE DISTURBANCES



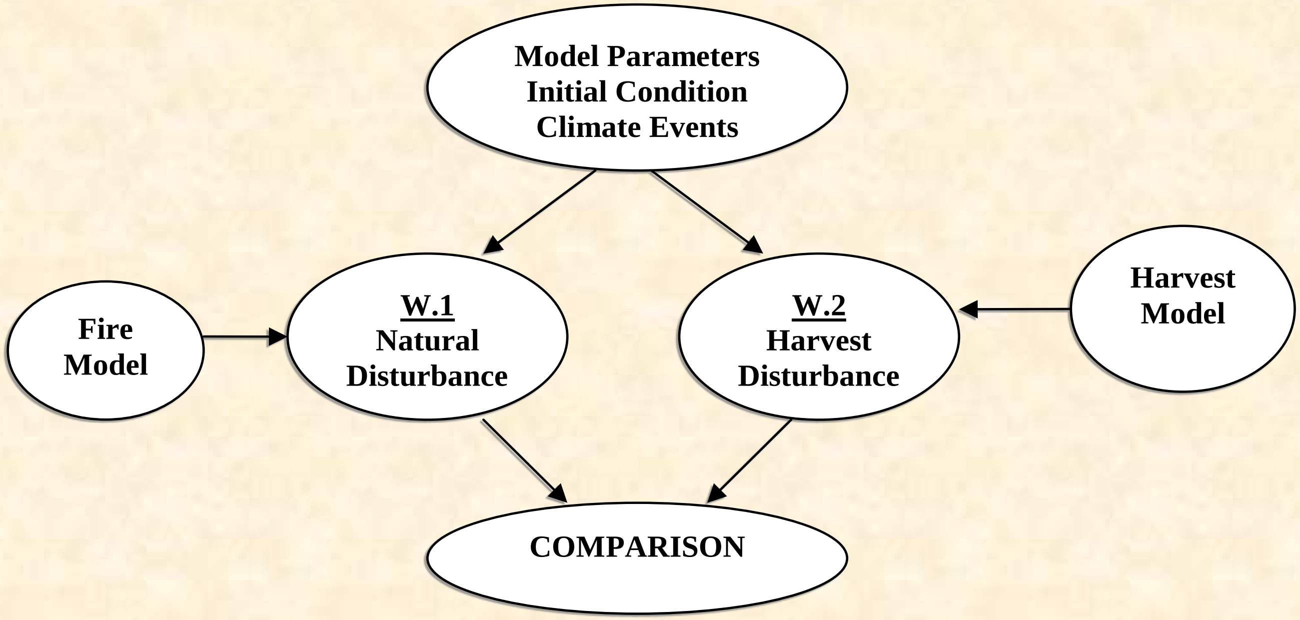

100000
10000
1000
100
10
1
Sediment yield (T. km^{-2})
0.01
0.1
1
10
Basin area (km^2)
95% Quantile
Modeled Event S.Y.
Event S.Y. (Observed)
8% Quantile
Modeled LASY
LASY (Observed)
SASY (Observed)
Trapper Creek gullies
Debris flow in SFPR
95 % quantile of ESY
Kirchner et al., 2001 (SASY)
% 8 quantile of ESY
Meyer et al., 2001
Mean ESY
Kirchner et al., 2001 (LASY)
Modeled LASY

Model results and field observations show that;

Approximately 92 % of the S.Y. is due to the Low Frequency and High Magnitude Episodic Erosion Events in the Idaho Batholith under the natural (wildfire) disturbance regime.

How might forest management alter this inherently episodic erosion rates?

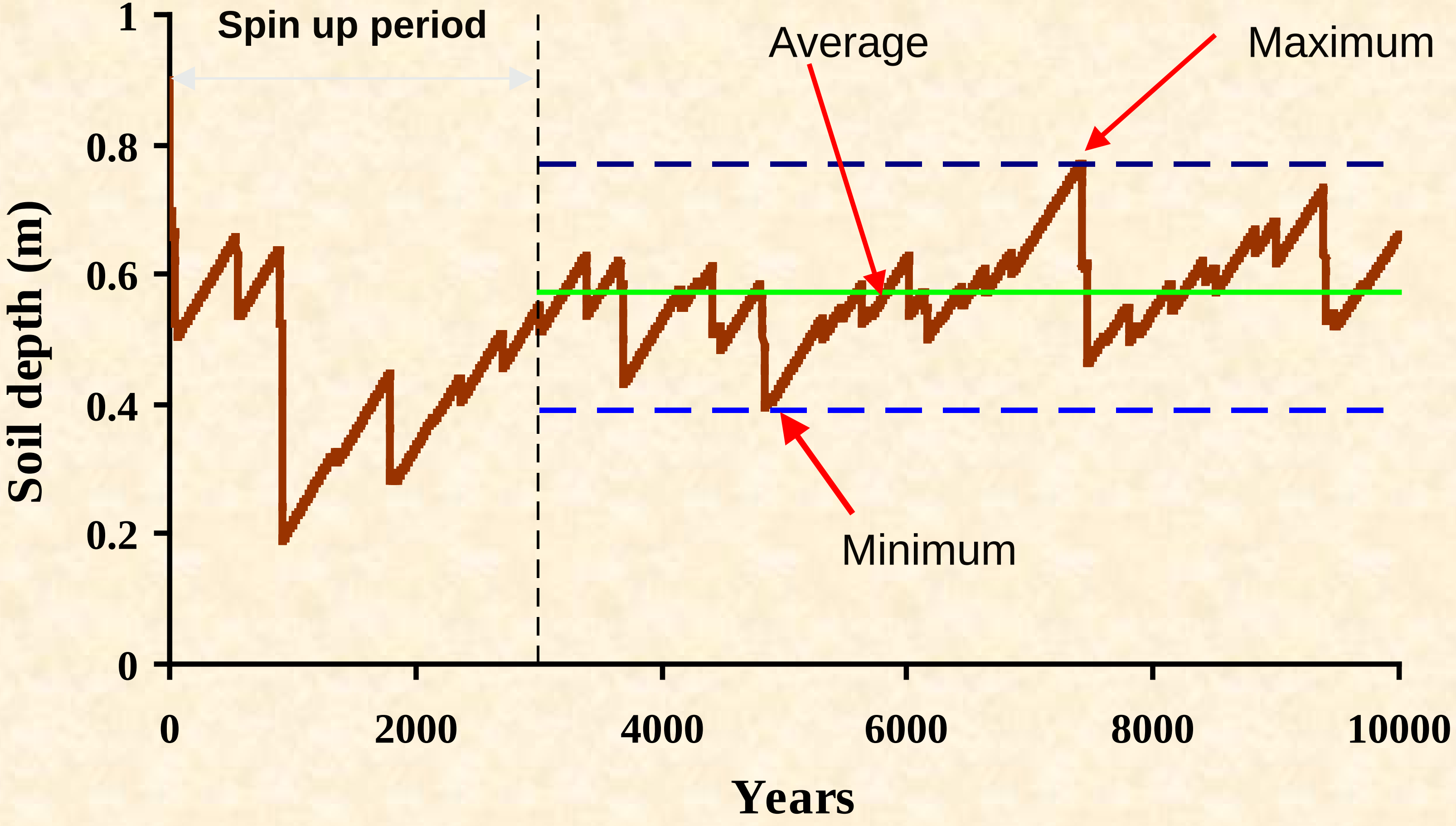
NUMERICAL PAIRED WATERSHED EXPERIMENT



Method: Timber harvest rotation length is taken 100 years. 3 rotations are simulated. The experiment is repeated 21 times.

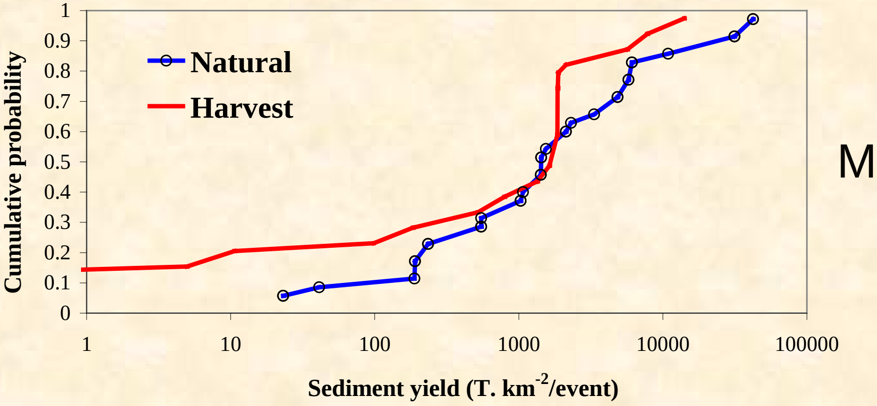
Initial Condition for Soil Depths are selected to represent range of conditions

Mean soil depth variation under wildfire disturbance regime

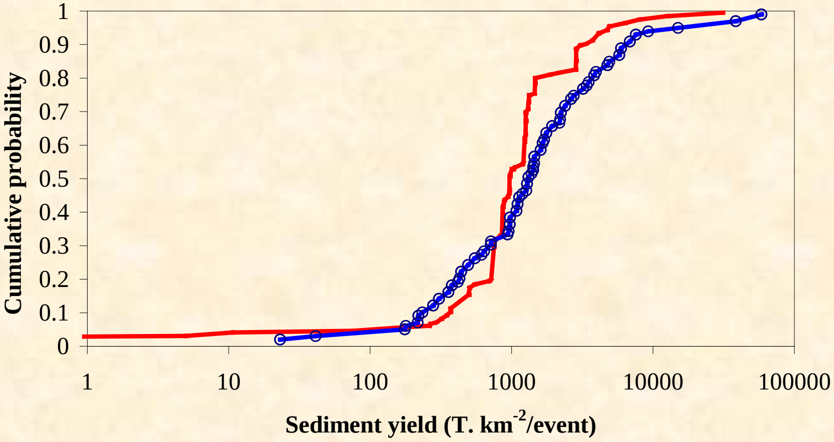


Statistical comparison of the experiment with the long term rates

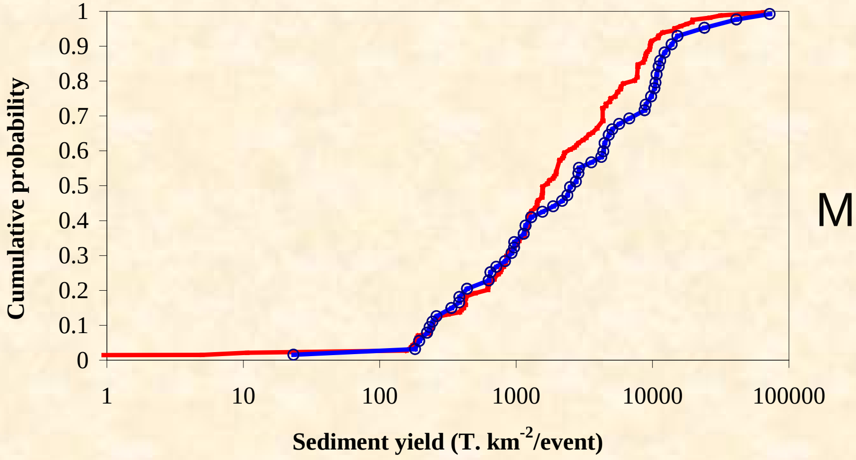
Statistical parameter	Sediment yield (T km^2/event)		
	Harvest	Natural	Long term
Mean	1,814	3,964	5,363
q=0.05	110	175	164
q=0.95	4,900	15,048	30,960



Minimum



Average



Maximum

CONCLUSIONS

- Model results showed good correspondence with field observations of event sediment yields.

- Forest vegetation acts as an erosion threshold.

- Undisturbed dense forests promote less frequent high magnitude erosion events.

- Forest fires lead to more frequent erosion with smaller magnitudes.

- Under the simulated forest fire regime erosion is concentrated to the periods with low erosion thresholds “Accelerated Erosion Period” (AEP). During the AEPs the amount of erosion modeled was larger than event sediment yields under undisturbed forest cover conditions.

- Initial soil/colluvium depths matter ..!!

- In a numerical paired watershed experiment forest cleacutting was shown to cause a 2-fold increase in the number of erosion events in the Idaho batholith. In contrast to that geomorphic response appeared to be more severe under wildfire disturbances.