INTERNATIONAL SUMMER SCHOOL: LARGE FLUCTUATIONS AND EXTREME EVENTS

Tails of Natural Hazards

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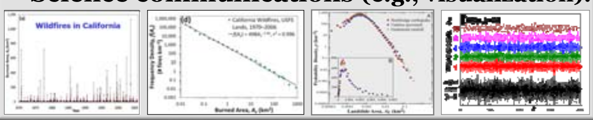
Outline

I. Overview: Main Research Interests

- Natural and environmental hazards
  - Geological
    - o Landslides, Earthquakes
  - Hydro-Meteorological
    - o Wildfires, Floods, Tornadoes
  - Multi-Hazard Interactions & Cascades
  - Impact of hazards on infrastructure.
  - Heavy-metal contamination (water/foodcrops)

I. Overview: Research Subthemes

- Observational data
  - Gathering, Analysis, Exploration, Visualisation
- Synthetic data
  - Construction in 1-D and 2-D
- Time series analysis & mathematical models
  - Probability distributions
    - o How many of a given size (in a given spatial region and temporal period)?
    - o Implications? Risk, bioecological, erosion, etc.
  - Persistence (clustering, spectral analyses)
- Science communications (e.g., visualization).



I. Overview: Take Home Messages

- This talk. Two main take home messages:
  - LARGE vs. SMALL EVENTS. Natural hazard events are not 'just' the large ones we see in the media—there are also medium and small ones.
  - SINGLE EVENTS vs. GROUPS OF EVENTS. Natural hazard events can be studied as groups (in given region and time period), not always just as single events.
- This talk. *Illustrate vs. educate.*

Outline

IIa. Landslides: Introduction

- **Landslide** (mass movement): down slope movement of bedrock and/or *regolith* near Earth's surface. Main force gravity.
- **Regolith:** unconsolidated rock debris, (including base soil horizons overlying bedrock).


Evidence of Soil Creep (Trees)


Rock Fall Fraser Canyon, Canada
http://www.cgenarchive.org

Deep Seated Soil Slump, 1997, San Mateo (California, USA)
walrus.wr.usgs.gov/elnino/landslides-sfbay/photos.html


Debris Fall, 12/2004, Sultan River, Oregon, USA
Video by Andrew Oberhardt

I. Overview | II. Landslides | III. Wildfires | IV. Multi Hazards | V. Other Hazards | VI. Closing
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IIa. Landslides: Introduction


Wang Shan, Gansu, China Landslide 13 September 2012
(Video B.D. Malamud, http://vimeo.com/50837463)

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IIa. Landslides: Introduction

- **Many ways to study landslides (indeed, all natural hazards):**
  - Spatial, Temporal, Process, Policy, etc.
- Here, we will examine:

Triggered Landslide Events
and their
Frequency-Size Statistics

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IIb. Landslides: Triggered Landslide Events

- **Triggers:**
  - Earthquakes
  - Heavy rainfall
  - Rapid snowmelt
- **Landslides in a Triggered Event:**
  - Time: Minutes to weeks.
  - Number: Individual to many 1000s.
  - Areas: From metres squared to kilometres squared.

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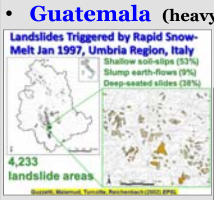
IIb. Landslides: Triggered Landslide Events

Three triggered events

- Umbria, Italy (snowmelt triggered landslides)
- Northridge, Calif., USA (earthquake triggered landslides)
- Guatemala (heavy rainfall, triggered landslides)



Research with Donald L Turcotte, Fausto Guzzetti and Paola Reichenbach

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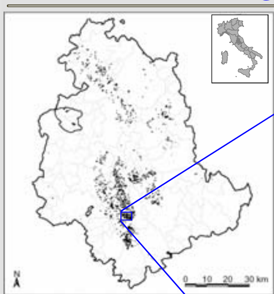
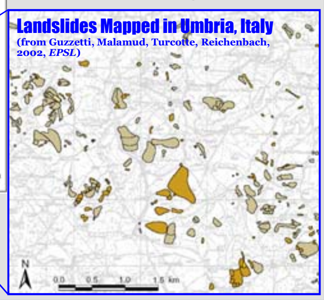
IIb. Landslides: Triggered Landslide Events

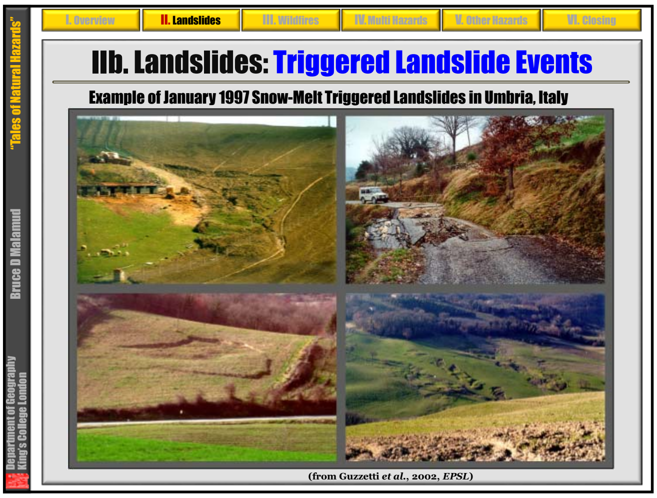


Landslides Triggered by Rapid Snow-Melt January 1997, Umbria Region, Italy



Landslides Mapped in Umbria, Italy
(from Guzzetti, Malamud, Turcotte, Reichenbach, 2002, *EPSL*)

4,233 landslide areas
- Shallow soil-slips (53%)
- Slump earth-flows (9%)
- Deep-seated slides (38%)


I. Overview
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V. Other Hazards
VI. Closing
IIb. Landslides: Triggered Landslide Events
Example of January 1997 Snow-Melt Triggered Landslides in Umbria, Italy
(from Guzzetti et al., 2002, EPSL)
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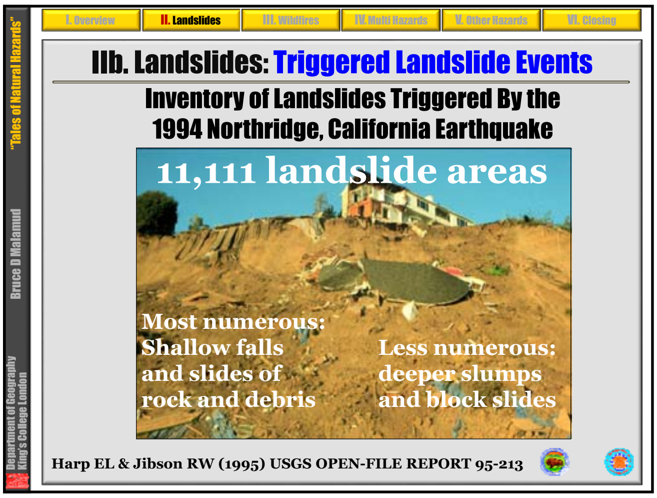
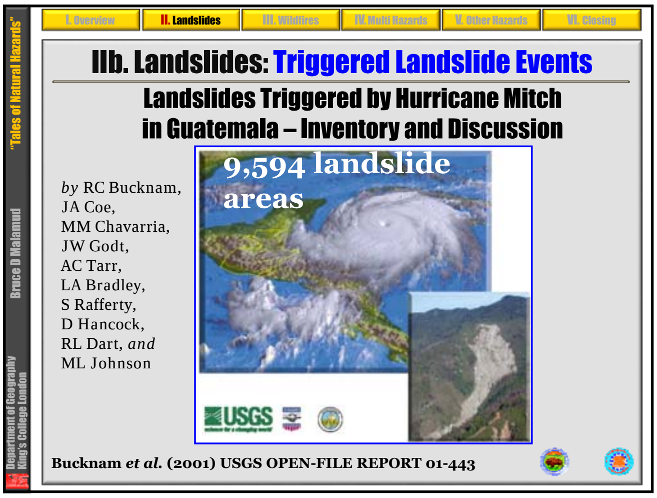
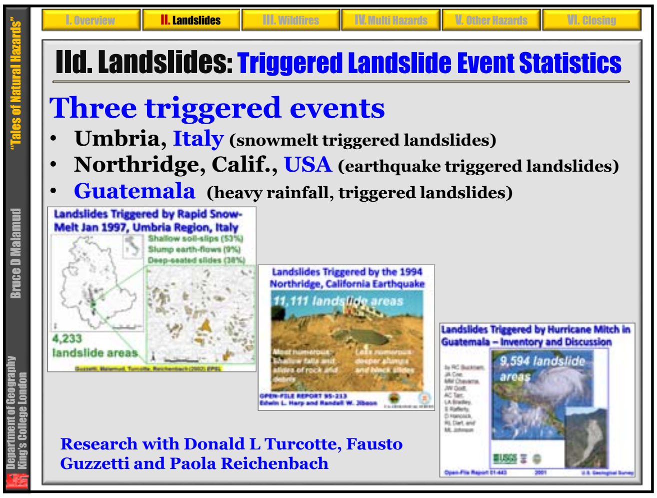

IIb. Landslides: Triggered Landslide Events
Inventory of Landslides Triggered By the 1994 Northridge, California Earthquake
11,111 landslide areas
Most numerous: Shallow falls and slides of rock and debris
Less numerous: deeper slumps and block slides
Harp EL & Jibson RW (1995) USGS OPEN-FILE REPORT 95-213


IIb. Landslides: Triggered Landslide Events
Landslides Triggered by Hurricane Mitch in Guatemala – Inventory and Discussion
by RC Bucknam, JA Coe, MM Chavarria, JW Godt, AC Tarr, LA Bradley, S Rafferty, D Hancock, RL Dart, and ML Johnson
9,594 landslide areas
USGS
Bucknam et al. (2001) USGS OPEN-FILE REPORT 01-443


IId. Landslides: Triggered Landslide Event Statistics
Three triggered events
• Umbria, Italy (snowmelt triggered landslides)
• Northridge, Calif., USA (earthquake triggered landslides)
• Guatemala (heavy rainfall, triggered landslides)
Landslides Triggered by Rapid Snow-Melt Jan 1997, Umbria Region, Italy
4,233 landslide areas
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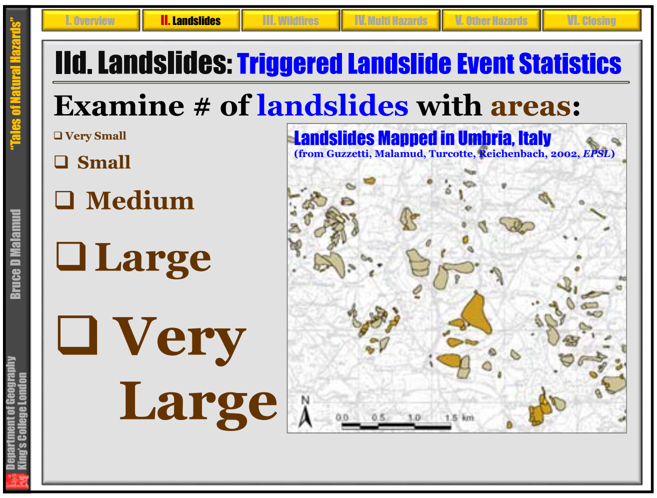
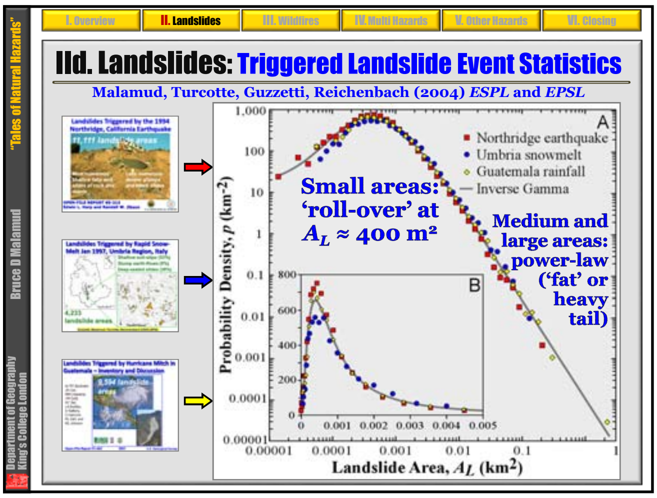
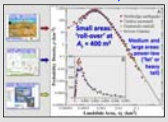

IId. Landslides: Triggered Landslide Event Statistics
Examine # of landslides with areas:
❑ Very Small
❑ Small
❑ Medium
❑ Large
❑ Very Large
Landslides Mapped in Umbria, Italy
(from Guzzetti, Malamud, Turcotte, Reichenbach, 2002, EPSL)
0.0 0.5 1.0 1.5 km


IId. Landslides: Triggered Landslide Event Statistics
Malamud, Turcotte, Guzzetti, Reichenbach (2004) ESPL and EPSL
A
Northridge earthquake
Umbria snowmelt
Guatemala rainfall
Inverse Gamma
Small areas: 'roll-over' at $A_L \approx 400$ m²
Medium and large areas: power-law ('fat' or heavy tail)
B
Probability Density, p (km⁻²)
Landslide Area, A_L (km²)

IIe. Landslides: Implications of the Statistics

Malamud, Turcotte, Guzzetti, Reichenbach (2004) *ESPL* and *EPSL*

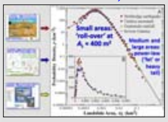


These three landslide inventories:

- Are substantially complete.
- Are all medium-high relief topography (Guatemala, Italy, California).
- Have different triggers (heavy rainfall, earthquake, sudden snow melt).
- Are low-mobility landslides.
- Have the same 'general' three-parameter probability distribution.

IId. Landslides: Triggered Landslide Event Statistics

Malamud, Turcotte, Guzzetti, Reichenbach (2004) *ESPL* and *EPSL*



These three landslide inventories follow a three parameter inverse-gamma probability distribution:

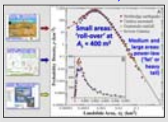
$$p(A_L) = \frac{1}{a\Gamma(\rho)}\left[\frac{a}{A_L - s}\right]^{\rho+1} \exp\left[-\frac{a}{(A_L - s)}\right]$$

Power-law tail for medium & large landslides

Exponential rollover for small landslides

IId. Landslides: Triggered Landslide Event Statistics

Malamud, Turcotte, Guzzetti, Reichenbach (2004) *ESPL* and *EPSL*



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$$p(A_L) = \frac{1}{a\Gamma(\rho)}\left[\frac{a}{A_L - s}\right]^{\rho+1} \exp\left[-\frac{a}{(A_L - s)}\right]$$

Best-fit to three data sets ($r^2 = 0.97$)

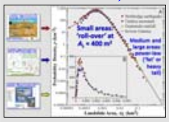
$\rho = 1.40$ *(primarily controls: power-law decay)*

$a = 1.28 \times 10^{-3}$ km^2 *(primarily controls: max probability location)*

$s = -1.32 \times 10^{-4}$ km^2 *(primarily controls: exponential decay)*

IIe. Landslides: Implications of the Statistics

Malamud, Turcotte, Guzzetti, Reichenbach (2004) *ESPL* and *EPSL*



What can we do with this 'general' landslide probability distribution?

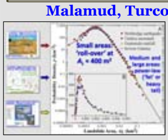
- Calculate total area of all landslides in a triggered event from just total number of landslides.

$$\overline{A_L} = 0.00307 \text{ km}^2$$
$$\approx 3{,}000 \text{ m}^2$$

$\overline{A_L}$ = Average landslide area in triggered event.

IIe. Landslides: Implications of the Statistics

Malamud, Turcotte, Guzzetti, Reichenbach (2004) *ESPL* and *EPSL*



What can we do with this 'general' landslide probability distribution?

- Calculate total area of all landslides in a triggered event from just total number of landslides.
- Using landslide area to volume conversion, calculation erosion due to triggered event.

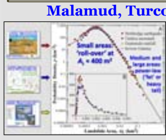
$$V_{LT} = 7.30 \times 10^{-6} N_{LT}^{1.1222}$$

V_{LT} = Total volume of landslides in a 'triggered' event (in km^3).

N_{LT} = Total number of landslides triggered.

IIe. Landslides: Implications of the Statistics

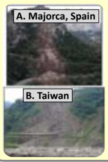
Malamud, Turcotte, Guzzetti, Reichenbach (2004) *ESPL* and *EPSL*



What can we do with this 'general' landslide probability distribution?

- Calculate total area of all landslides in a triggered event from just total number of landslides.
- Using landslide area to volume conversion, calculation erosion due to triggered event.
- Quick 'assessment' of triggered landslide numbers using just the largest landslide areas.
- Theoretical implications.

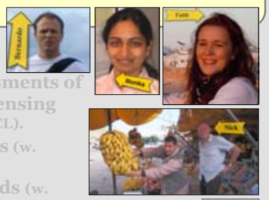
IIe. Landslides: Implications of the Statistics



EC Framework 7 Research Grant (3/2013 to 2/2015): *Landslide Modelling and Tools for Vulnerability Assessment Preparedness & Recovery Management*

Nine partners. *Fausto Guzzetti (CNR, Italy)* coordinating.

€2M with €300k to KCL (two 20 month postdocs: Drs. Bernardo Mota & Monika Mihir; associated scientist: NERC funded PhD student Faith Taylor).



KCL PART:

(1) Rapid course-resolution assessments of landslide areas using remote sensing (with Bernardo Mota & Nick Drake, KCL).

(2) Landslide Susceptibility Models (w. Monika Mihir, KCL).

(3) Landslide general Other Hazards (w. Monika Mihir & Faith Taylor, KCL).

(4) Landslide-Road Impact Model (with Faith Taylor, KCL).

I. Overview | II. Landslides | III. Wildfires | IV. Multi Hazards | V. Other Hazards | VI. Closing

IIf. Landslides: Triggering Events and Road Networks

Research led by Faith Taylor, NERC funded PhD student.

Route 14, Utah, USA after a landslide destroyed 400 m of road.
(Image: MSNBC Photoblog, 2011)

Attabad Landslide (Jan 2010), Karakoram Highway.
(Image: Parmir Times, 2010)

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IIf. Landslides: Triggering Events and Road Networks

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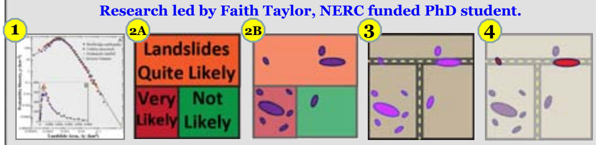

Landslide-Road Impact Computer Model.

1. User chooses number of landslides, and then the model randomly selects synthetic landslide areas from our 'general' landslide probability distribution.
2. Randomly drop landslides over study region, conditioned by landslide susceptibility map.
3. Overlay synthetic triggered landslides with road network.
4. Examine potential road impacts.

[Model repeated hundreds of times in Monte Carlo simulation].

Figures 2 to 4 courtesy of F. Taylor.

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IIf. Landslides: Triggering Events and Road Networks

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Example *Landslide Road Impact Model* output for Collazzone region (Umbria, Central Italy)

- Simulated triggered landslides (413) in blue.
- Road blocks (52) with red warning signs.
- This is one iteration of one hundred.

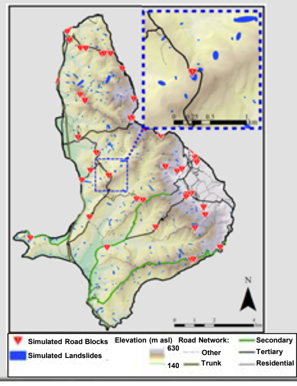

Figure courtesy of F. Taylor.

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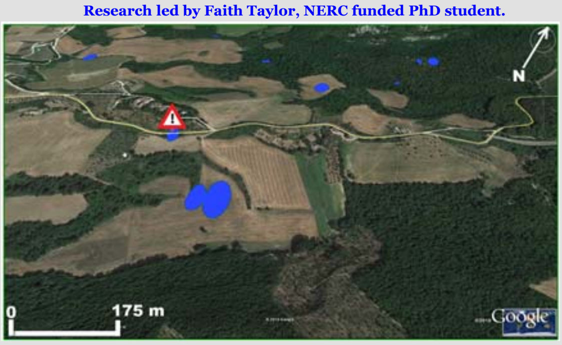

Zoomed in example *Landslide Road Impact Model* synthetic output for Collazzone region (Umbria, Central Italy)

Figure courtesy of F. Taylor.

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IIg. Landslides: Summary

- Three well-documented triggered landslide inventories result in same 'general' probability (frequency-area) distribution.
- Probability distribution can be used to infer:
  - total # of landslides, area & volume in landslide event
  - erosion rate estimates
- For incomplete inventories, largest landslides can be used to infer the COMPLETE distribution.
- Theoretical implications (e.g., what processes cause the 'maximum' probability—a rollover?).
- Distribution can be used to simulate synthetic landslide distributions for modelling landslide-road impact scenarios.

IIg. Landslides: Summary

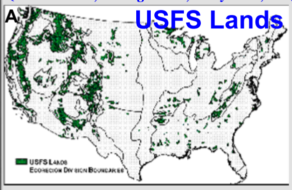
- Recall two take home messages:
  - LARGE vs. SMALL EVENTS. Natural hazard events are not 'just' the large ones we see in the media—there are also medium and small ones.
  - SINGLE EVENTS vs. GROUPS OF EVENTS. Natural hazard events can be studied as groups (in given region and time period), not always just as single events.

Outline

I. Brief Overview of Research Interests
II. Landslides
III. Wildfires
IV. Multi Hazard Interactions
V. Other Hazards
VI. Closing Remarks

IIIa. Wildfires: USA

Characterizing USA wildfire regimes
(Malamud BD, Millington DA, Perry GLW, 2005, *PNAS*)



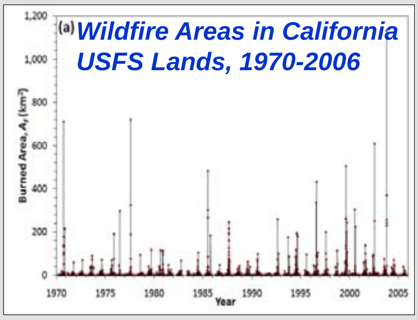
(A) Wildfire Inventory.
- 657,949 wildfires on USA federal wildlands.
- From this we use:
  - USDA Forestry Service (USFS)
  - $A_F \geq 0.004$ km²
  - 1970 – 2000
  - 88,916 wildfires

(B) Bailey ecoregion divisions.
- Common characteristics of: Climate, Vegetation, Soil
- In each ecoregion: what are the frequency-area statistics?

IIIb. Wildfires: USA (Frequency-Area)

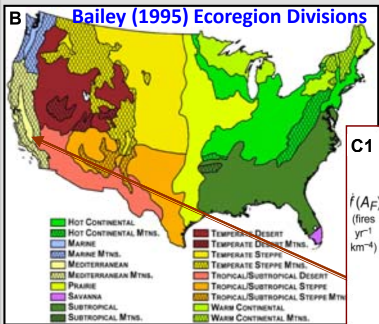
Examine # of wildfires with areas:

- Very Small
- Small
- Medium
- Large
- Very Large

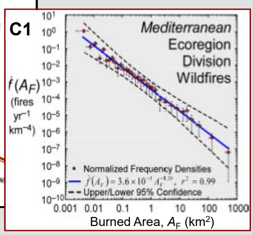


IIIb. Wildfires: USA (Frequency-Area)

Characterizing USA wildfire regimes
(Malamud BD, Millington DA, Perry GLW, 2005, *PNAS*)

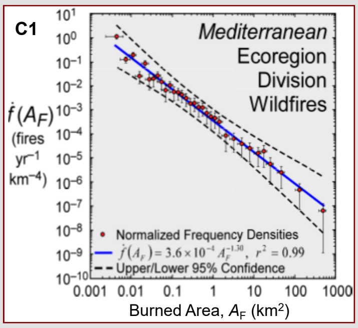


$$\dot{f}(A_F) = \alpha A_F^{-\beta}$$
$$\beta = 1.30$$



IIIb. Wildfires: USA (Frequency-Area)

Characterizing USA wildfire regimes
(Malamud BD, Millington DA, Perry GLW, 2005, *PNAS*)



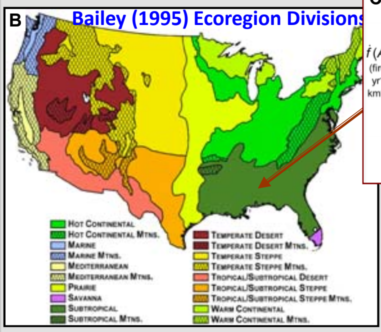
$$\dot{f}(A_F) = \alpha A_F^{-\beta}$$
$$\beta = 1.30$$

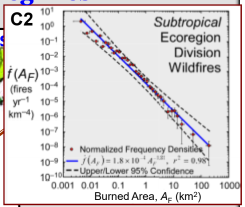
This frequency-area distribution is a power-law

IIIb. Wildfires: USA (Frequency-Area)

Characterizing USA wildfire regimes

(Malamud BD, Millington DA, Perry GLW, 2005, *PNAS*)





$$\dot{f}(A_F) = \alpha A_F^{-\beta}$$

$$\beta = 1.81$$

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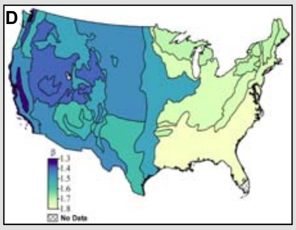
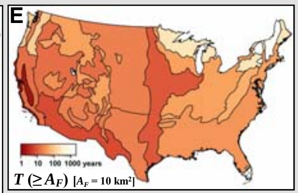
IIIc. Wildfires: Frequency Area Implications

Characterizing USA wildfire regimes

(Malamud BD, Millington DA, Perry GLW, 2005, *PNAS*)



(D) Wildfire Statistics, β, ratio of # of big vs. small fires. (Best-fit power-law exponents *β* for all conterminous USA ecoregions.)



(E) Wildfire Probabilistic Hazard (Recurrence Intervals: Average time between events with burned area ≥10 km², occurring in 1,000 km² region within ecoregion division; assumes 'independence' of events.)

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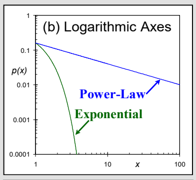
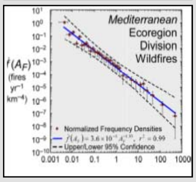
IIIc. Wildfires: Frequency Area Implications

Implications for Government Reporting

- **Power-laws are fat-tailed** (heavy tailed).
- **Exponential** (tail of Gaussian distribution) are thin-tailed.
- Fat tails **much more conservative** than 'thin' tails when calculating probabilistic risk.





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I. Overview | II. Landslides | III. Wildfires | IV. Multi Hazards | V. Other Hazards | VI. Closing

IIIc. Wildfires: Frequency Area Implications

Implications for Government Reporting

REPORT: Number of fires & burnt area 1980-2009 (Portugal, Spain, France, Italy, Greece)

- With fat-tailed distributions, one must be careful when reporting **total burned area** or **#** of fires!
- As **smallest fire area** reported in a country increases, total # and area of fires increase.
- For example, if frequency-area distribution **power-law exponent is 1.5**, decreasing area reported by **factor of ten**, increases number of wildfires by **factor of three**.

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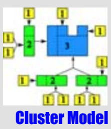
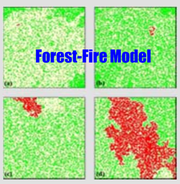
IIId. Wildfires: Summary

- Robust **frequency-area power-law scaling over 5–6 orders of area** for 17 ecoregions in the conterminous USA.
- Reduces characterization to **fat-tailed distribution with just two parameters**.
- Potential use for **examining risk** and **driving forces of wildfire regimes**.
- **Theoretical implications**.





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IIId. Wildfires: Summary

Some Questions to ask Ourselves Regarding Wildfire Frequency-Area Statistics

- If scaling, over **how many orders**?
- What is **smallest scale** useable for method?
- How do the **statistical distributions vary** due to different factors (e.g., human activities, bio-physical factors)?
- What **theoretical questions** (e.g., ecological) are raised by heavy-tails?
- What are implications for **Government Reporting & Risk**?

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Bruce D Malamud
Department of Geography
King's College London

IIId. Wildfires: Summary

- Recall two take home messages:
  - **LARGE vs. SMALL EVENTS.** Natural hazard events are not 'just' the large ones we see in the media—there are also medium and small ones.
  - **SINGLE EVENTS vs. GROUPS OF EVENTS.** Natural hazard events can be studied as groups (in given region and time period), not always just as single events.

Outline

IVa. Multi-Hazard Interactions

Multi-Hazard Risk Assessments (NERC/ESRC funded PhD student, Joel Gill). Recent Paper: **Gill & Malamud (2014) Reviewing and Visualizing the Interactions of Natural Hazards. *Reviews of Geophysics.***


AGU PUBLICATIONS
Reviews of Geophysics
REVIEW ARTICLE
Reviewing and visualizing the interactions of natural hazards
Joel C. Gill and Bruce D. Malamud
Abstract This paper presents a broad overview, characterization, and visualization of the interaction relationships between 21 natural hazards, drawn from six hazard groups (geophysical, hydrological, shallow Earth, atmospheric, biophysical, and space hazards). A synthesis is presented of the identified interaction relationships between these hazards, using an accessible visual format particularly suited to end users.

www.tinyurl.com/GillMalamudInteractions

IVa. Multi-Hazard Interactions

[Research led by Joel Gill]

- **Single hazard assessments:** Considers one hazard at a time.
- **Multi-hazard assessment:** Considers interactions between hazards.

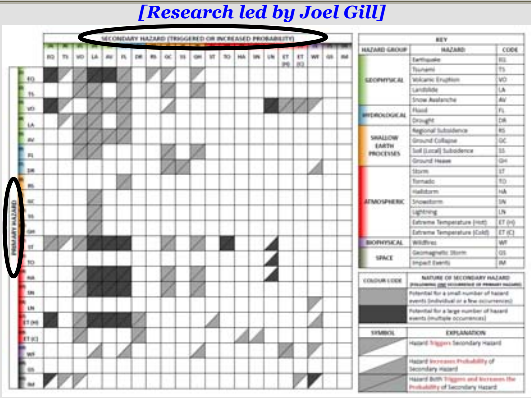
Increases probability

Triggers

Figure design: J. Gill. Credits: [1] Earthquake, Italy. (R. Civico, INGF), [2] Landslide, El Salvador (Ed Harpp, USGS); [3] Forest Fire, Ecuador (S. Makowski, Philipps Universität Marburg).

IVa. Multi-Hazard Interactions

[Research led by Joel Gill]



IVa. Multi-Hazard Interactions

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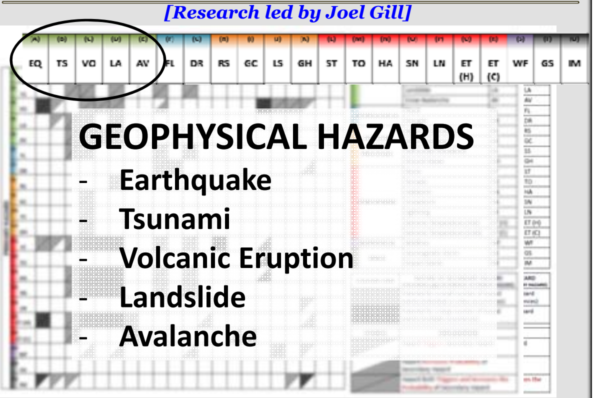

IVa. Multi-Hazard Interactions

[Research led by Joel Gill]

SYMBOL	EXPLANATION
	Hazard Triggers Secondary Hazard
	Hazard Increases Probability of Secondary Hazard
	Hazard Both Triggers and Increases the Probability of Secondary Hazard

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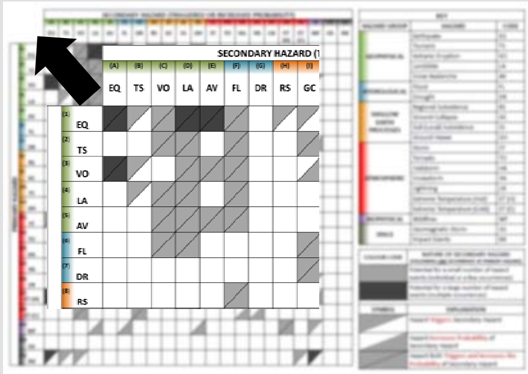
IVa. Multi-Hazard Interactions

[Research led by Joel Gill]



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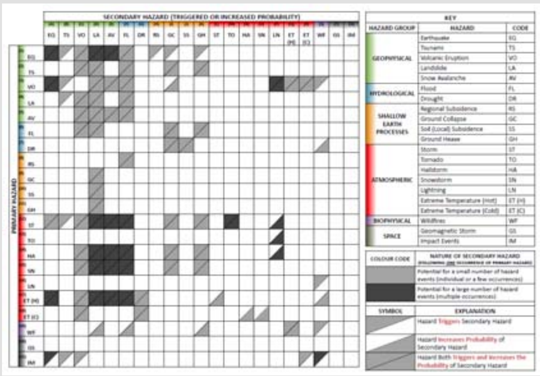
IVa. Multi-Hazard Interactions

[Research led by Joel Gill]



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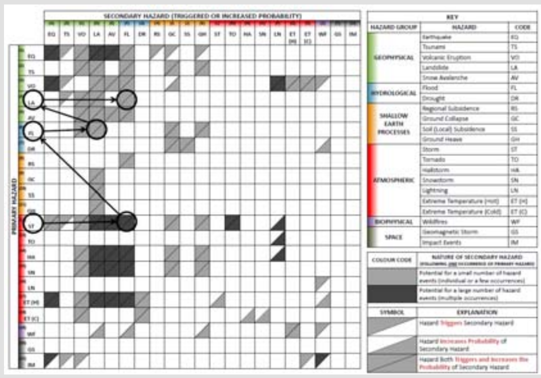
IVa. Multi-Hazard Interactions

[Research led by Joel Gill]



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IVa. Multi-Hazard Interactions

[Research led by Joel Gill]

Joel Gill and Bruce in Guatemala, February to March 2014

I. Overview | II. Landslides | III. Wildfires | IV. Multi Hazards | V. Other Hazards | VI. Closing

Outline

I. Brief Overview of Research Interests
II. Landslides
III. Wildfires
IV. Multi Hazards
V. Other Hazards
  a) Tornadoes
  b) Time Series
  c) Earthquakes & Prediction
VI. Closing Remarks

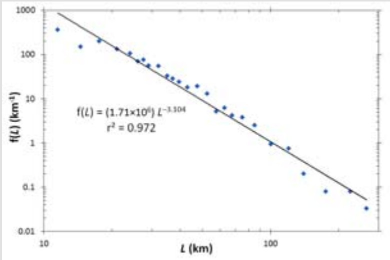
Va. Other Hazards: Tornadoes

Malamud, Turcotte (2012) **Statistics of severe tornadoes and severe tornado outbreaks.** *Atmospheric Chemistry & Physics.*

Va. Other Hazards: Tornadoes

Malamud, Turcotte (2012) **Statistics of severe tornadoes and severe tornado outbreaks.** *Atmospheric Chemistry & Physics.*

- Frequency densities as a function of path length L
- L = Path length of individual severe tornadoes ($L \geq 10$ km).
- $f(L)$ = frequency density = # of tornadoes in 'unit' size bins.
- Continental USA Tornadoes, $L \geq 10$ km, 1981–2010



Vb. Other Hazards: Landslide Time Series

Creating historical landslide series in time, and examining the statistical distribution of 'events'.

Rossi, Witt, Guzzetti, Malamud, Peruccacci (2010) **Analysis of historical landslide time series in the Emilia-Romagna region, northern Italy.** *Earth Surf. Proc. Land.*

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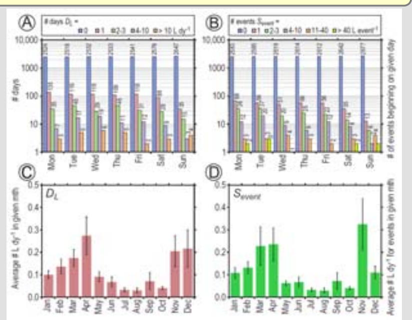
Summary statistics for 1951–2002 landslide intensity time series in Emilia-Romagna Region, northern Italy:

- D_L (# landslides per day)
- S_{event} (# landslides per event)



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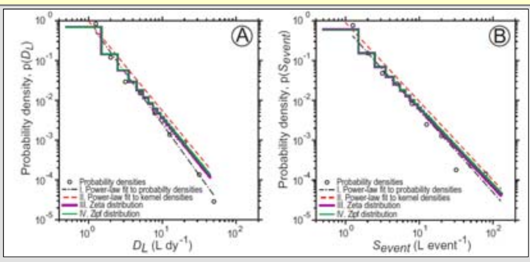
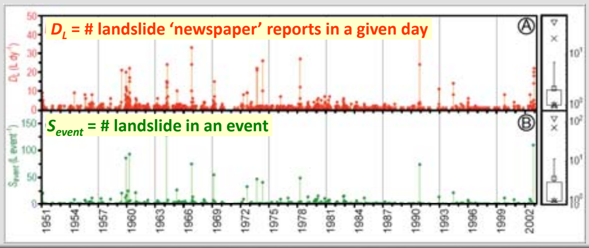


Fitting probability densities of (A) D_L (# landslides per day) and (B) S_{event} (# landslides per event). *Probability densities estimated using normalized histograms with log bins. Zeta and Zipf distributions obtained through maximum likelihood estimation.*

Vb. Other Hazards: Landslide Time Series

Approach for examining correlations in time series that are strongly non-Gaussian and unequally spaced in time.

Witt, Malamud, Rossi, Guzzetti, Peruccacci (2010) **Temporal correlation and clustering of landslides.** *Earth Surf. Proc. Land.*



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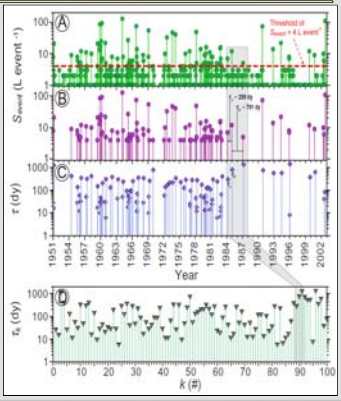
Inter-event occurrence times, τ, constructed from subset of the original Emilia-Romagna Region study area landslide intensity event time series ($S_{event} \geq 1$ L event^{-1}, 1951–2002).

Dashed horizontal line represents the ϑ threshold, $S_{event} = 4$ L event^{-1}.



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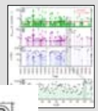
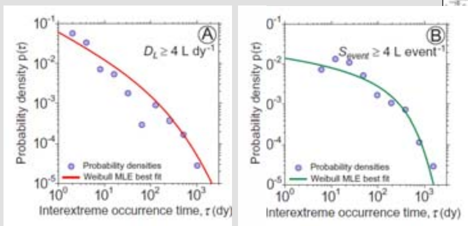


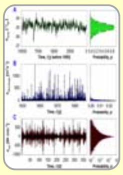


Probability densities of the inter-event occurrence times, τ. (Tells us if the events are correlated or not in time, in this case they are NOT uncorrelated).

IVb. Other Research: Time Series

Approach for examining correlations in time series that are strongly non-Gaussian and unequally spaced in time.

Witt, Malamud, Rossi, Guzzetti, Peruccacci (2010) Temporal correlation and clustering of landslides. *Earth Surf. Proc. Land.*



Review paper systematically examining techniques for looking at correlations in time series using benchmarks.

Witt, Malamud (2013) Quantification of Long-Range Persistence in Geophysical Time Series. *Surveys of Geophysics* (111 pages)

Vc. Other Hazards: Earthquakes & Prediction

Research paper examining claims of earthquake prediction by other authors.

Blackett M, Wooster MJ, Malamud BD (2011) Exploring land surface temperature earthquake precursors: A focus on the Gujarat (India) earthquake of 2001. *Geophysical Research Letters*

'Precursor' → Earthquake?
[Earthquake follows precursor]

Also need to take into account...
[Earthquake occurs, but no 'precursor']
[Precursor occurs, but no earthquake]

VI. Closing Remarks

- Single Events vs. Populations
- Multi-Hazard Interactions
- Prediction of Hazards
- Clustering of Hazards in Time & Space
- Synthetic Data
- Computer Model Simulations
- Visualization and Uncertainty

VI. Closing Remarks

Questions and Comments

bruce.malamud@kcl.ac.uk