Risk equation, landslide hazard and susceptibility

- Pierluigi Confuorto (Earth Science Department, University of Florence)

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Who I am

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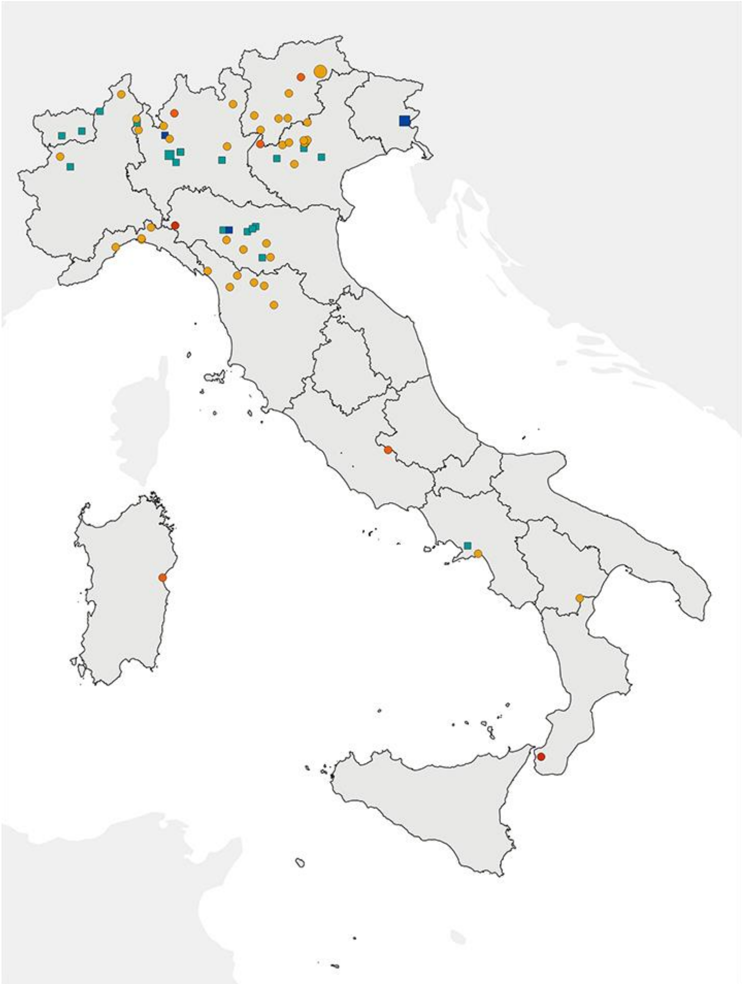
- Currently a fixed-term researcher at the Earth Science Department of the University of Florence in Physical Geography and Geomorphology.

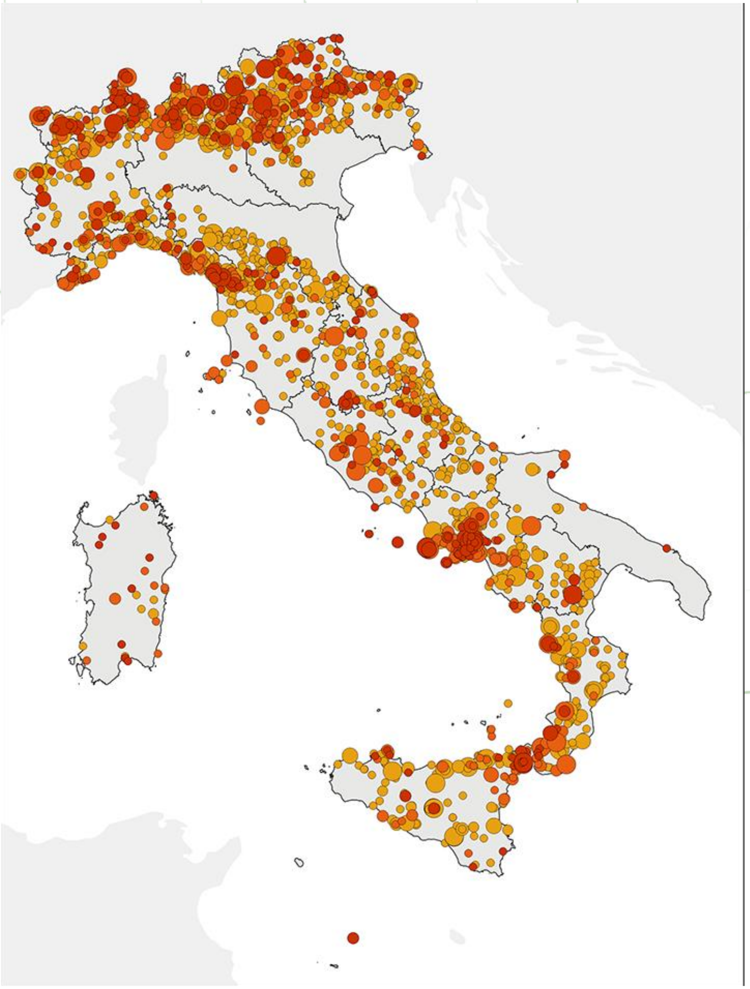
- Graduated in 2012 and PhD in Analysis of Environmental Systems in 2016 at the Federico II University of Naples (Italy).
- Visiting student at the German Aerospace Center (DLR) and at the Technical University of Munich (TUM) in 2014 and 2015
- Since 2019, post-doc researcher at the Earth Science Department of the University of Florence.
- Main researches topics: landslide and subsidence monitoring by spaceborne remote sensing methods (DInSAR, multi- and hyper-spectral imagery), landslide and soil erosion susceptibility assessment through ML methods.

What’s going on in Italy

2 victims and 5 injuries due to landslides in Italy in the first semester of 2024



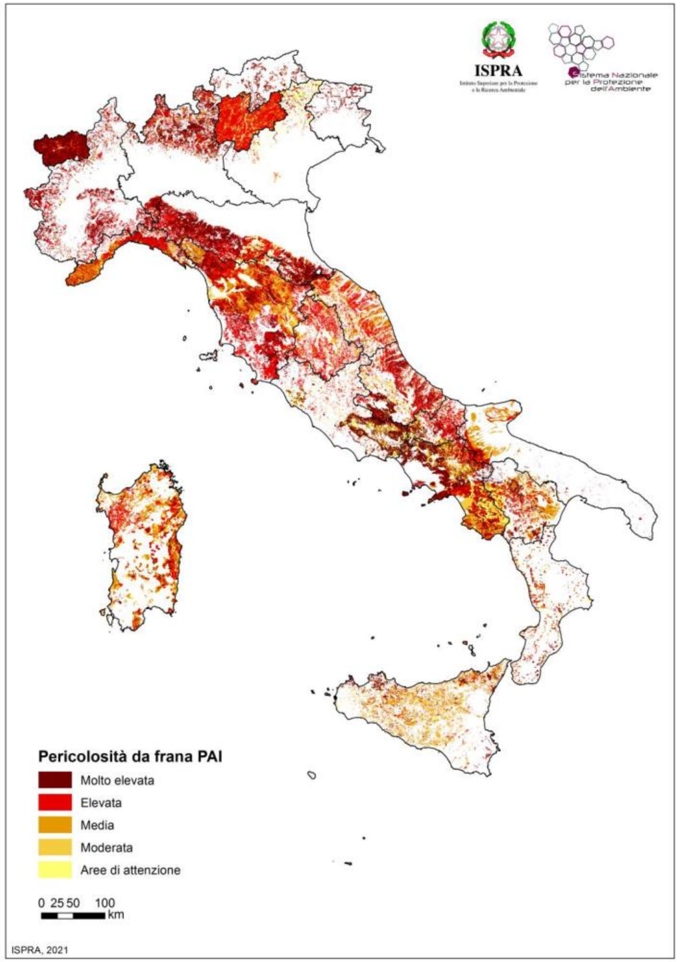
1060 victims and 1442 injuries due to landslides in Italy in the last 50 years



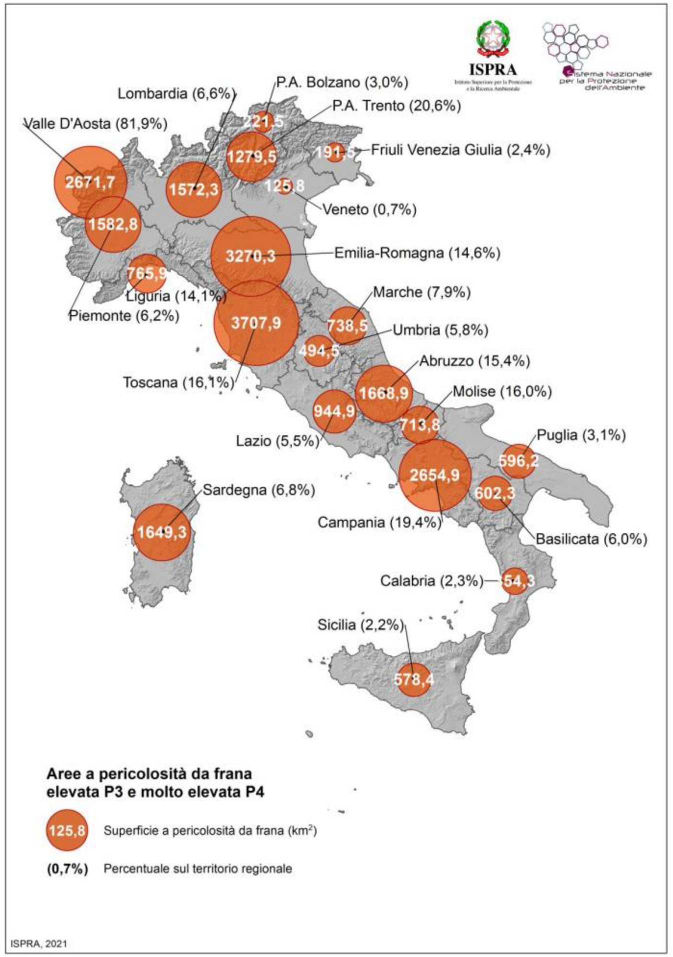
Source: IRPI Polaris

What's going on in Italy

60'481 km^2 (20% of the national territory) is the total extent of hazardous areas in Italy



Tuscany, Emilia-Romagna, Valle d'Aosta, Campania regions have the higher extent of high and very high hazardous areas to landslides



Source: ISPRA

What’s going on in Italy

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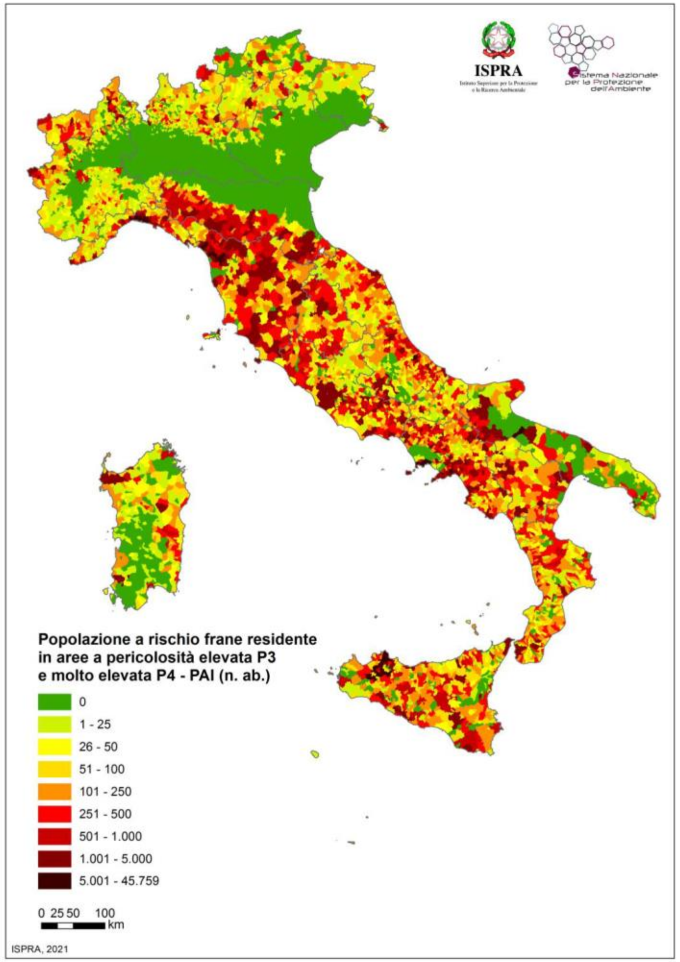
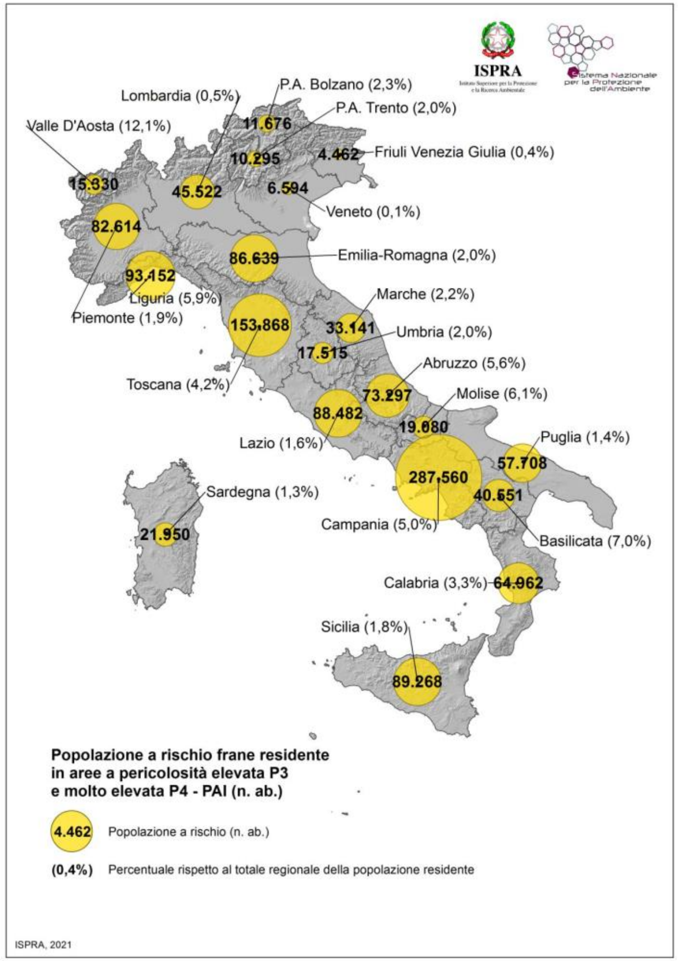
5.7 millions of people lives in landslide risk area. Of these, 500k in very high hazardous areas

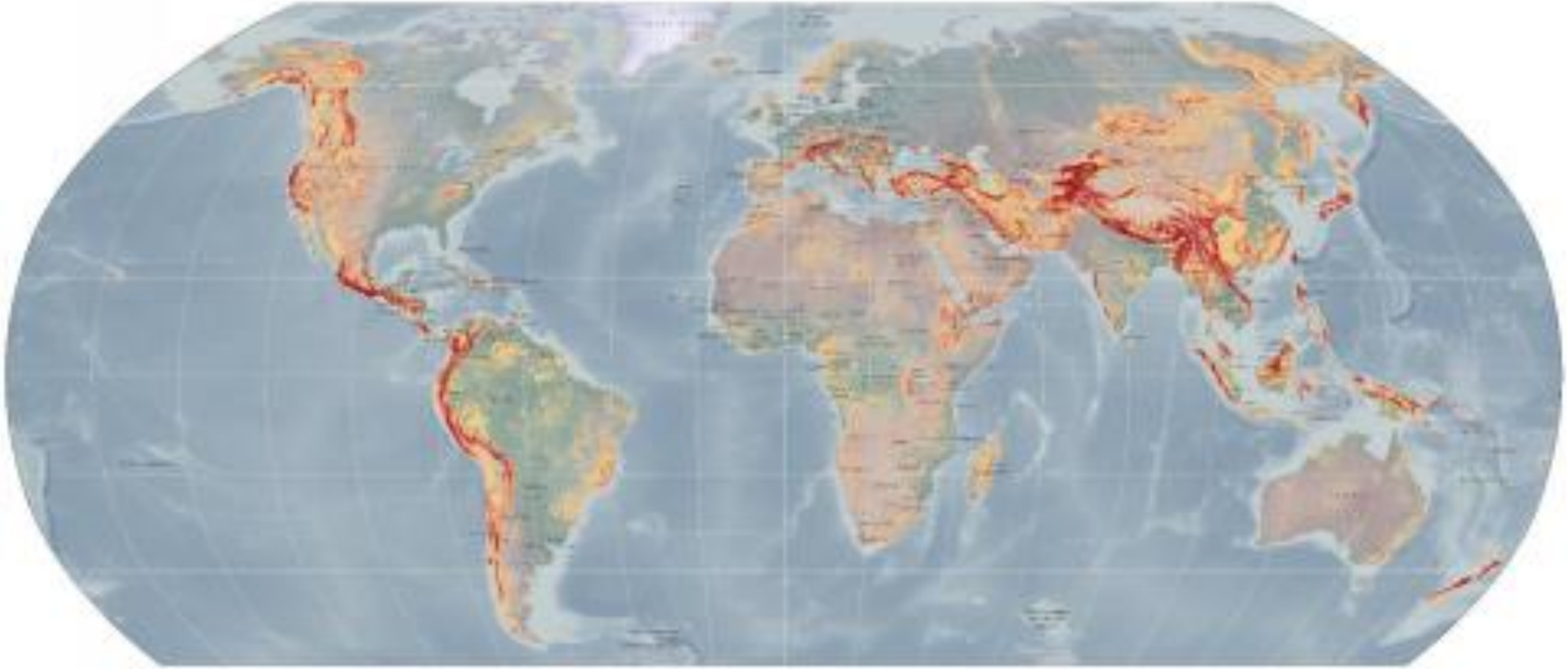


Campania, Tuscany, Liguria and Sicily regions have the highest number of people exposed to landslide risk



Source: ISPRA

Landslide hazard in the world



Exec Table 1 – Estimated average annual number of significant rainfall-triggered landslides (1980-2018)

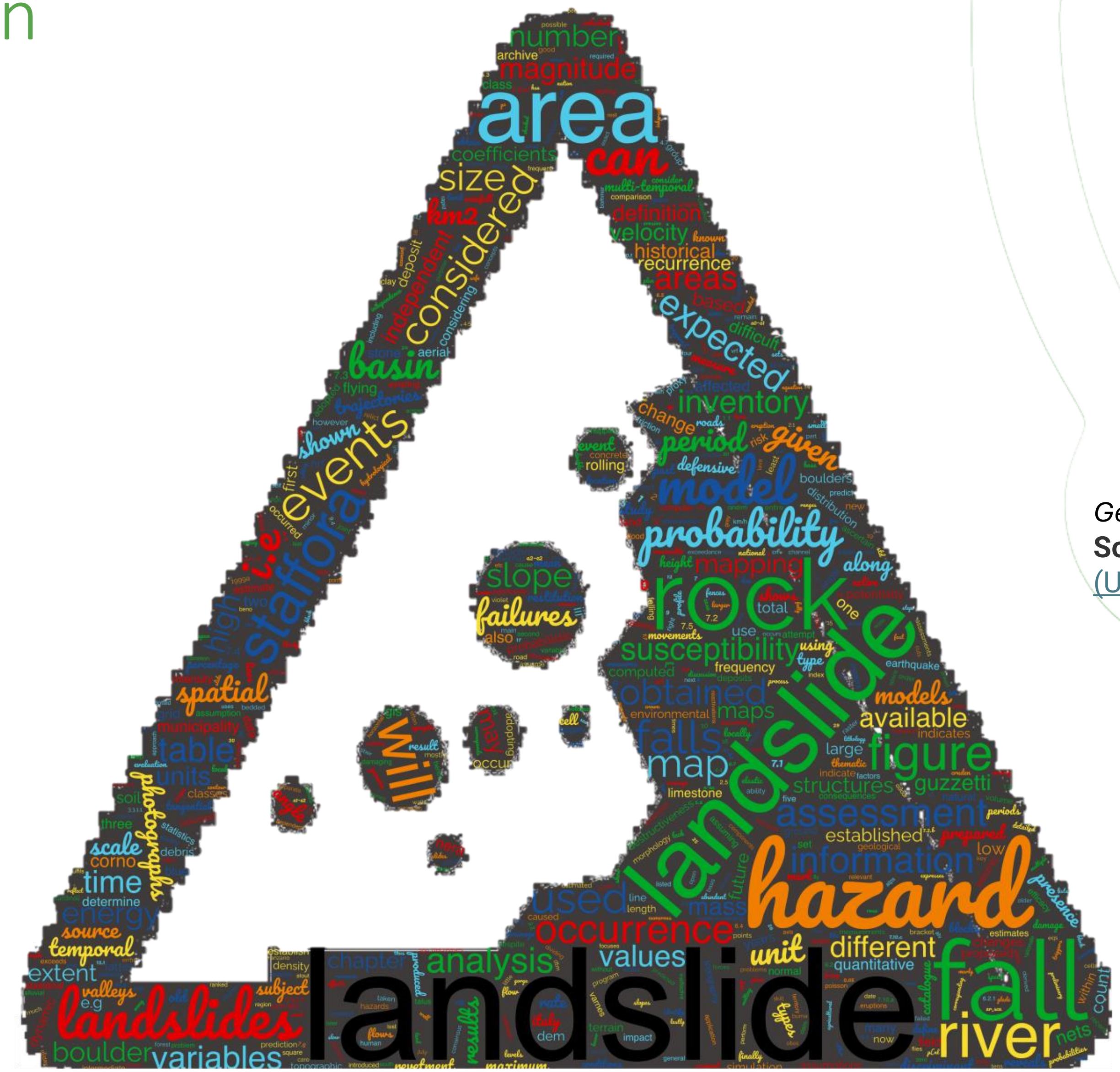
Country	Country code	Estimated average annual number of significant rainfall-triggered landslides (1980-2018)
United States of America	259	36,150
China	147295	35,280
India	115	31,430
Philippines	196	23,110
Indonesia	116	22,220
Russian Federation	204	18,340
Myanmar	171	15,080
Brazil	37	13,360
Canada	46	11,780
Vietnam	264	11,490

Exec Table 3 – Estimated average annual number of significant earthquake-triggered landslides

Country	Country code	Estimated average annual number of significant earthquake-triggered landslides
China	147295	20,950
Kyrgyz Republic	138	11,070
United States of America	259	10,710
Turkey	249	9,270
Mexico	162	7,510
Islamic Republic of Iran	117	6,580
Russian Federation	204	6,290
Tajikistan	239	5,810
Afghanistan	1	4,990
Nepal	175	4,550

Source: World Bank

Introduction



Generated from **Landslide hazard and risk assessment**
Source: [United Nations Office for Disaster Risk Reduction (UNDRR)]

Risk equation

$$R = H \cdot V \cdot E$$

Risk = expected loss

Hazard = probability of occurrence

Vulnerability = loss degree

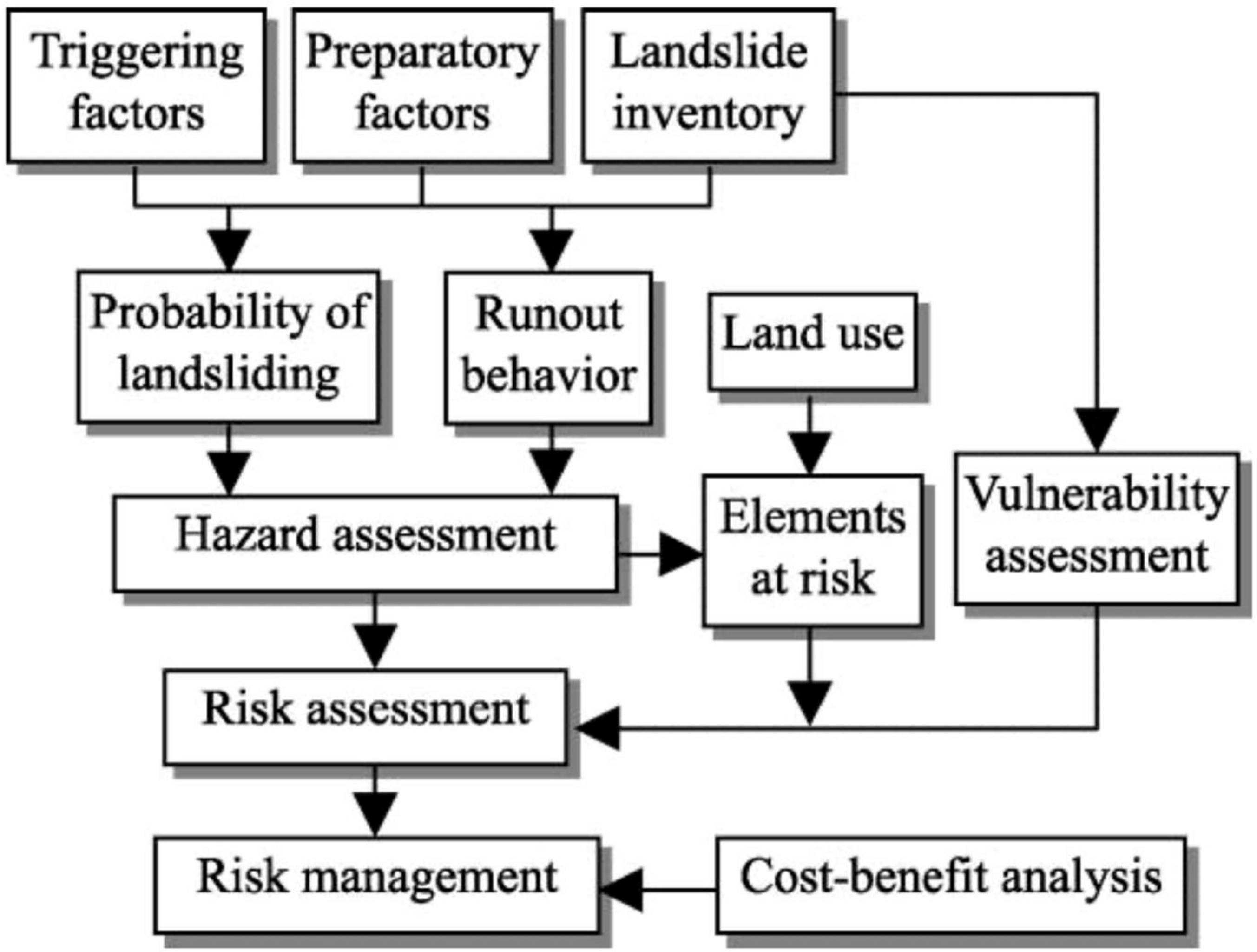
Elements at risk = value

Definitions

- **Total risk (R)**: expected loss, i.e. expected number of lives lost, persons injured, damage to property, disruption of economic activity due a particular phenomenon, and is therefore the product of specific risk Rs and elements at risk E
- **Hazard (H)**: probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon of given intensity
- **Vulnerability (V)**: degree of loss to a given element or set of elements at risk resulting from the occurrence of a natural phenomenon of given intensity. It is expressed on a scale from 0 (no damage) to 1 (total loss)
- **Element at risk (E)**: population, properties, economic activities, including public services etc. at risk in a given area
- **Specific risk (Rs)**: expected degree of loss due to a particular natural phenomenon. It may be expressed by the product of H times V

Varnes & IAEG (1984) modified

Risk framework



Dai et al. (2002)

Risk assessment

- **Qualitative methods**:probability and losses expressed in qualitative terms
- **Semi-quantitative methods**: indicative probability, qualitative terms
- **Quantitative methods (QRA)**: probability and losses quantified

Depends on the desired accuracy of the outcome and the nature of the problem, and should be compatible with the quality and quantity of available data

Risk equation

$$R = H \cdot V \cdot E$$

Risk = expected loss

Hazard = probability of occurrence

Vulnerability = loss degree

Elements at risk = value

Hazard H

- **Hazard** is defined as the probability of occurrence of a geomorphological process with intensity I on a given area in a given time span.

- Hazard prediction is made difficult by the fact that most of the underlying processes are only partially known, and systems are not deterministic in behavior.

- For the most part, the starting point is the study of the recent past to understand which processes are taking place and why. It is clear that a good database of the past process is an area that may lead to good predictions and vice versa for a poor database

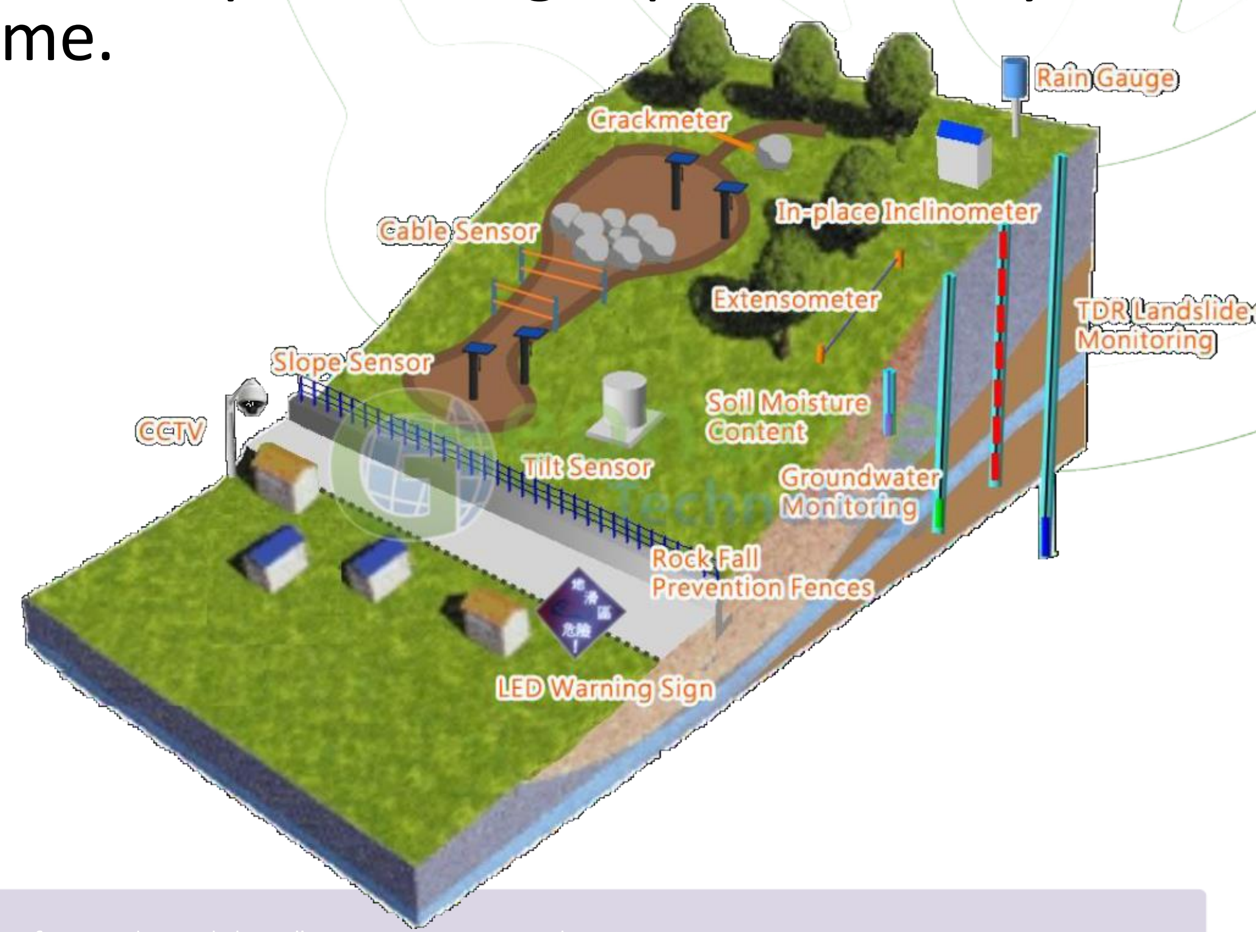
- Hazard prediction may be of various types: **typological**, **spatial**, **temporal**, **intensity**, and of the **runout**.

Slope scale vs Basin scale

- For landslide analyses at the slope scale, a geomorphic process is easy to control due to the many available monitoring tools and modeling methods. It is not difficult to inspect carefully the entire slope with high spatial density and high frequency of observations in time.

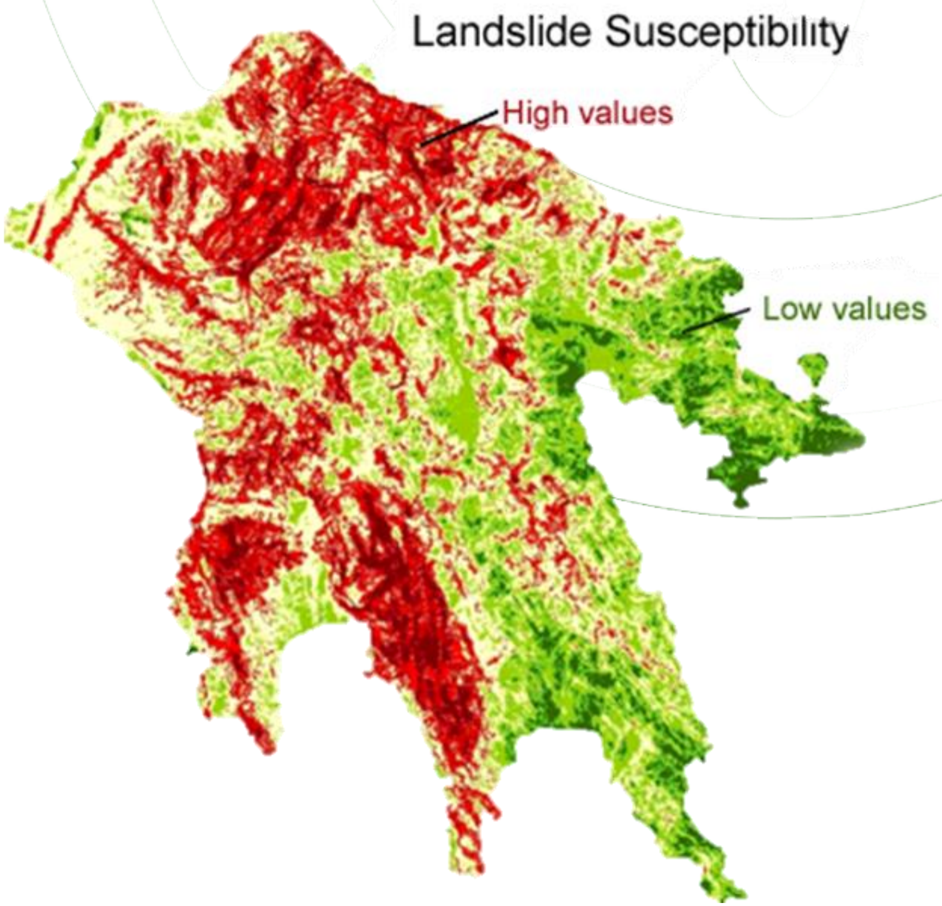
- Most of the terrain parameters are all directly measurable by recurring to specific tools with costs compatible with results in case we have elements at risk exposed and impending failure.

- What if we have 100 situations like this?



Hazard at Basin scale

- To work at a much larger scale we need to start from basic knowledge of the region, by collecting data on the state of the nature.
- Some of the required basic documents for this are the geological maps, the landcover maps, the river network, the topographical maps or DEM, the rainfall distribution (in both space and time), the geomorphological map.
- In the geomorphological map, in particular, we must have a good quality inventory of the known occurrences of the target process we want to be able to forecast (e.g., a landslide inventory map). This map will represent our known observable.



Susceptibility vs Hazard

- The term hazard refers to the probability that one or more landslides of a certain intensity will trigger in a given time interval and at a specific location.

- What size?

- When?

- Where? → **Susceptibility**

Susceptibility definition

- Landslide susceptibility is the likelihood of a landslide occurring in an area on the basis of local terrain conditions (Brabb, 1984)

- As reported in Reichenbach et al. (2018)…

"Susceptibility does not consider the size e.g., the length, width, depth, area, or volume of the landslides, but susceptibility assessments can be prepared for different-sized landslides (Carrara et al., 1995). We note that the definition of landslide susceptibility adopted in this work differs from the definition given by Fell et al. (2008a)."

- In mathematical language, landslide susceptibility can be defined as the probability of spatial occurrence of slope failures, given a set of geo-environmental conditions (Guzzetti et al., 2005). Susceptibility measures the degree to which terrain can be affected by future slope movements. In other words, it is an estimate of "where" landslides are likely to occur (Guzzetti, 2006).

- Susceptibility evaluation represents the first step towards a hazard and risk assessment, but can also coincide with an end product for spatial planning or environmental impact studies.

Susceptibility estimation

- The basic principle of hazard analysis is that the causes that produced a process in the past are likely the same that will produce the process in the future. This is only valid if processes are in equilibrium with the landscape and for short time frames in geological terms.

- For example, it is not correct to predict a glacial erosion process in a mountain valley in the Apennines since the glacial landforms we see today are only relics of a past climate.

- It is correct, instead, to predict that the Arno river could flood Florence since the same as happened only a few decades ago, which is quite no time, in geological terms.

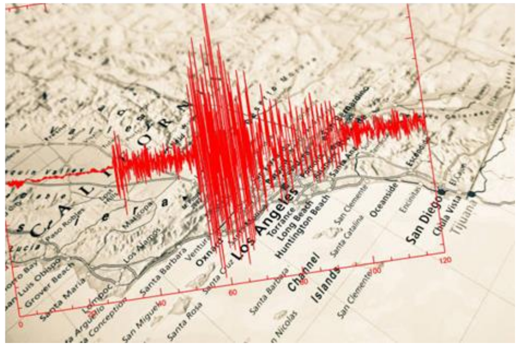
Susceptibility estimation

- The first step is therefore to understand which are the possible causes of recent landslides or active processes. Then, we collect maps and data relative to such causes, at the best possible resolution and accuracy.
- Causes may be of two types:

• **<u>Predisposing</u>**: causes that made the slope susceptible to mass wasting and that are necessary (but not sufficient) to develop slope instability.

• **<u>Triggering</u>**: causes that actually are responsible of the actual failure or, in any case, able to bring the impending process to start or to change its kinematics. Typical triggering causes for slope processes are:

1. *Rainfall, water-related in general*
2. *Earthquakes*
3. *Human activity*



Susceptibility scale

Scale description	Indicative range of scales	Examples of zoning application	Typical area of zoning
Small	< 1:100,000	Landslide inventory and **susceptibility** to inform policy makers and the general public.	>10,000 square kilometres
Medium	1:100,000 to 1:25,000	Landslide inventory and **susceptibility** zoning for regional development or very large scale engineering projects. Preliminary level hazard mapping for local areas	1000 – 10,000 square kilometres
Large	1:25,000 to 1:5,000	Landslide inventory, **susceptibility** and hazard zoning for local areas. Intermediate to advanced level hazard zoning for regional development. Preliminary to intermediate level risk zoning for local areas and the advanced stages of planning for large engineering structures, roads and railways.	10-1000 square kilometres
Detailed	> 5,000	Intermediate and advanced level hazard and risk zoning for local and site specific areas and for the design phase of large engineering structures, roads and railways.	Several hectares to tens of square kilometres

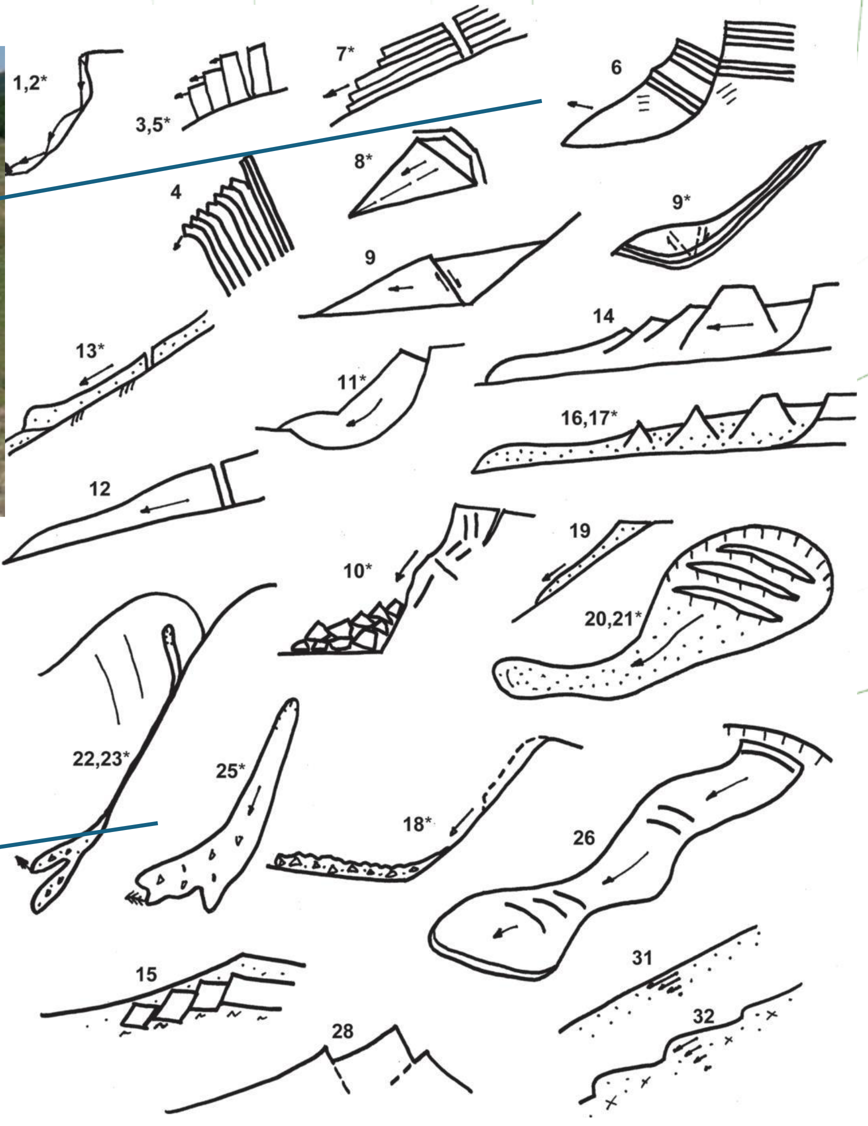
Fell et al., 2008

Susceptibility – type of landslide

- There is **no unique procedure** capable of estimating the potential of failure of each type of landslide and its expected travel distance.

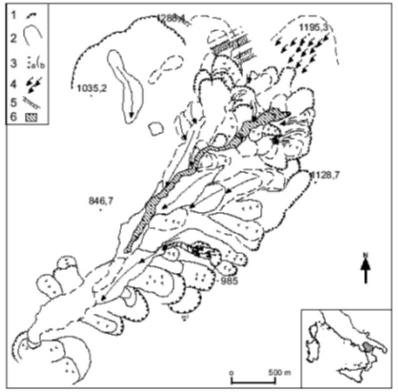
- In fact, the conditioning factors (i.e., slope angle, lithology, groundwater conditions, …) are specific for each landslide mechanism. Because of this, it will often be necessary to assess separately susceptibility, hazard, and risk, for the **different types of landslides** affecting the area (i.e. for rockfalls, small shallow landslides, and deep-seated large landslides) and to present the results in **specific zoning maps** as the recommendations of the statutory obligations to mitigate the risk might differ for the different landslide types.

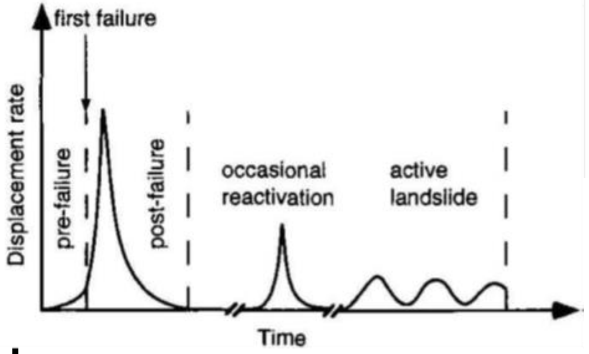
- These maps may be **combined into one map**. In this case, it must be taken into account that, for instance, the same hazard level may be obtained from different combinations of landslide types, volumes, intensities and frequencies. It may also be necessary to produce separate maps for landslides from natural slopes and constructed slopes.

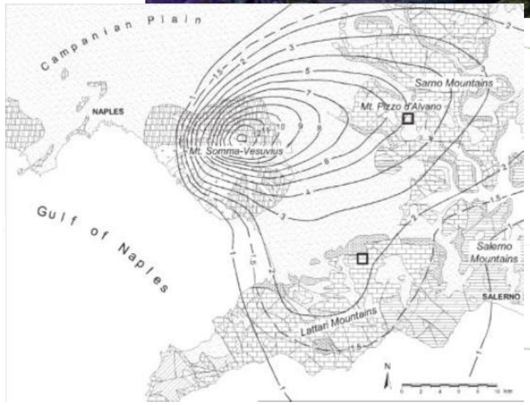


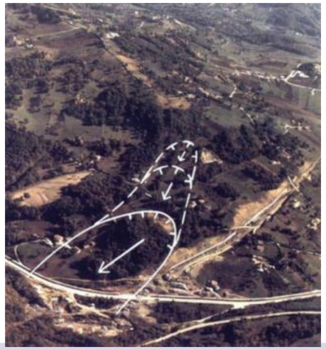
Susceptibility – Starting point

- Individuation of the area where first-failure phenomenon or landslide reactivation can occur
- Geomorphological sketch-map
- Knowledge of the territory
- State of activity of landslides
- Classification, areal extent and volume









Susceptibility – Starting point – Landslide inventory

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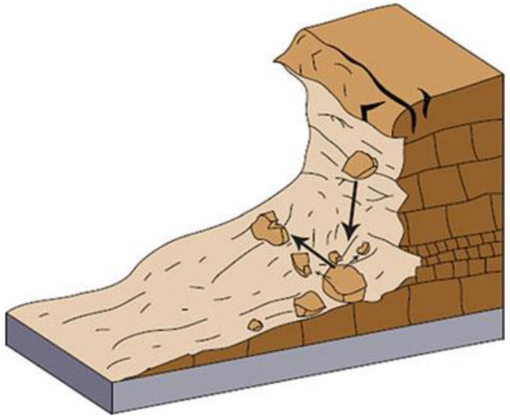
Know your inventory!

Who did it and how?

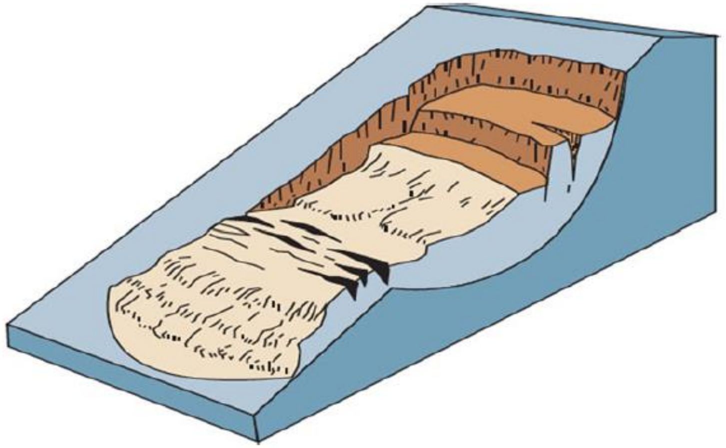
What landslide types?

Different landslide types have different predisposing factors

In a good LSM, it is mandatory that only a specific landslide type is considered



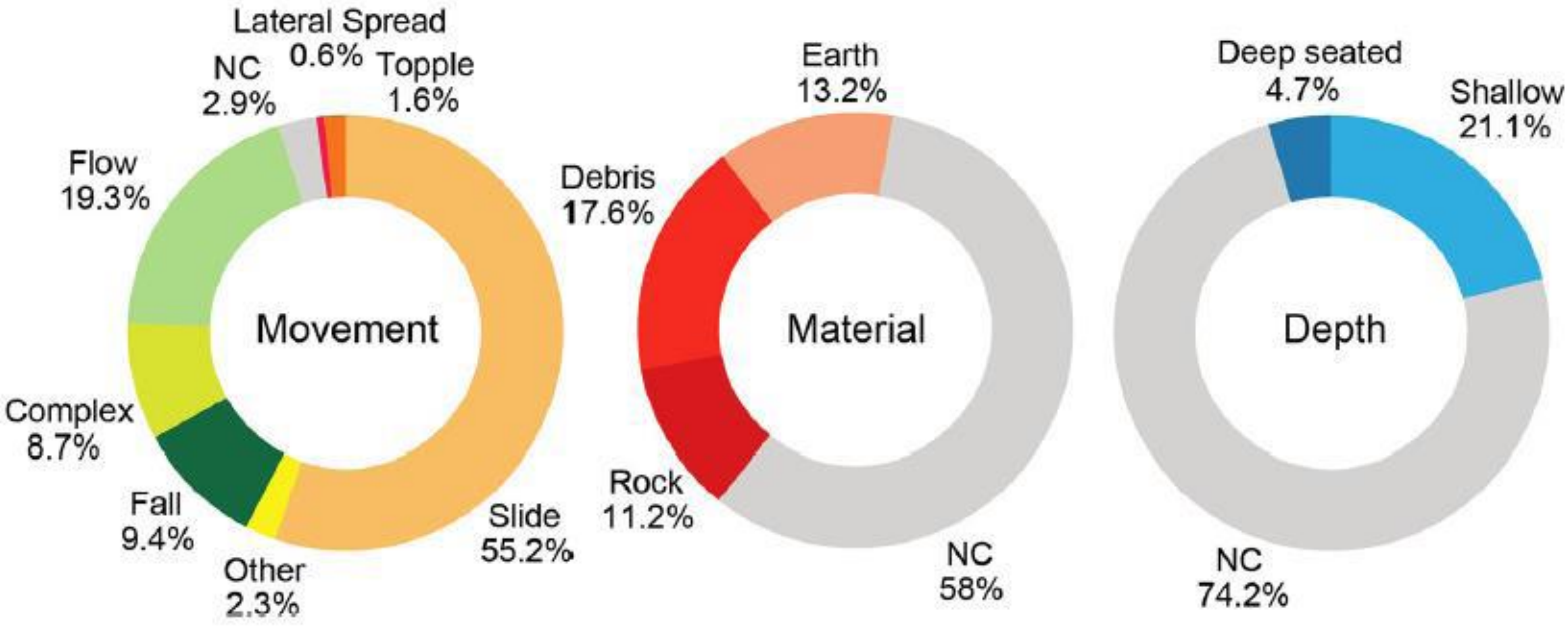
Falls



Slides

Flows

Susceptibility – Starting point – type of landslide



Reichenbach et al., 2018

Susceptibility – Starting point – Landslide inventory

- Know your inventory!

Who did it and how?

What landslide types?

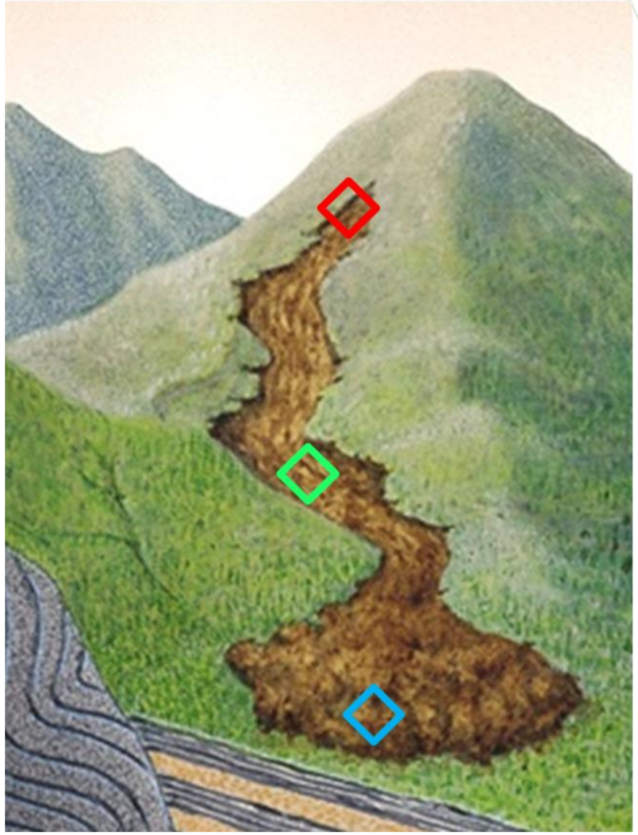
How mapped?

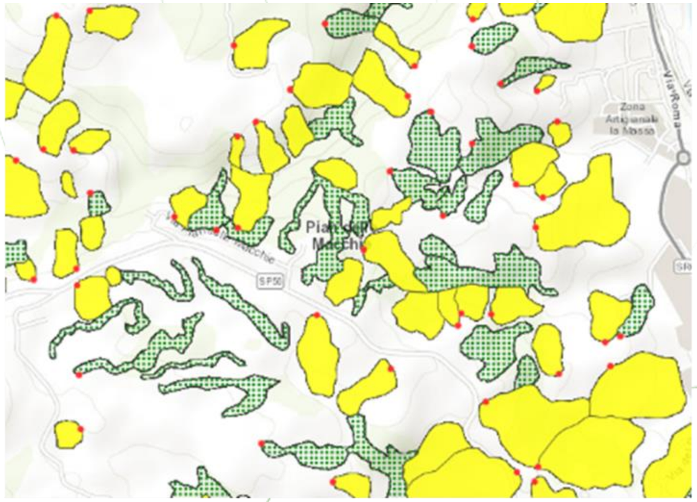
- Polygon
- Point

source area

centroid

Impact point



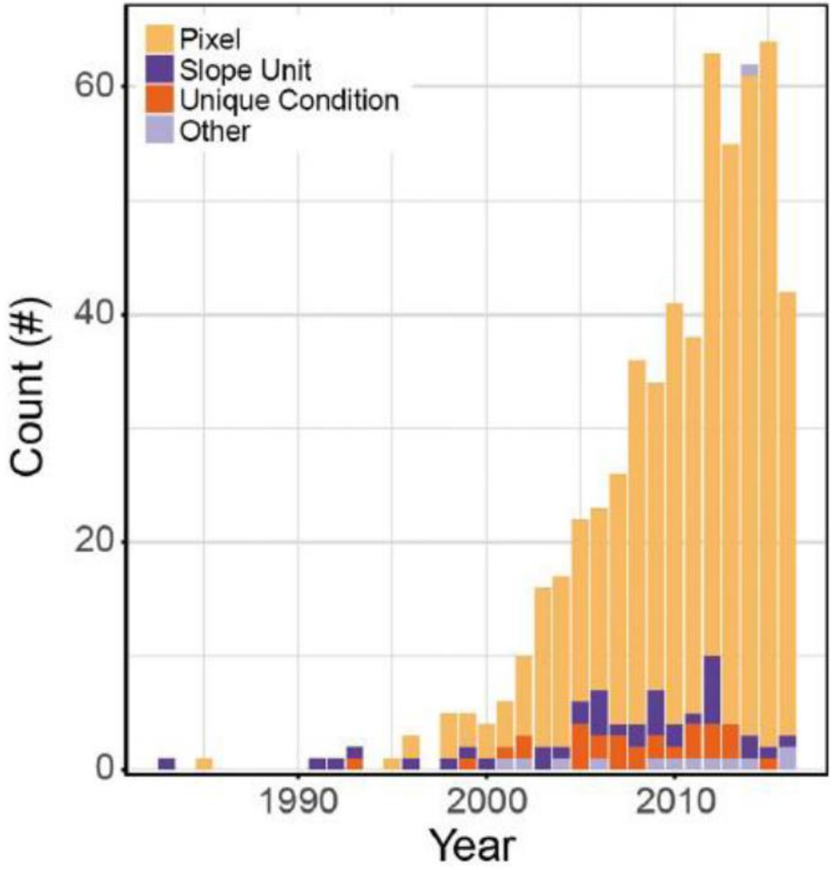


https://idrogeo.isprambiente.it/app/

Susceptibility – Starting point - Terrain units

- A terrain unit (or "mapping unit") is a portion of the land surface characterized by a set of ground conditions that differ from the adjacent units across distinct boundaries (Hansen, 1984). At the scale of the analysis, a mapping unit is a geographical domain that maximizes the unit internal homogeneity and the between-unit heterogeneity (Guzzetti, 2006).

- All the mapping units proposed in the literature for landslide susceptibility assessment fall into one of the following seven groups (Reichenbach et al., 2018)



(i)Grid cells ("pixels")

(ii)Terrain units

(iii)Unique condition units

(iv)Slope units

(v)Geo-hydrological units

(vi)Topographic units

(vii)Political or administrative units.

Susceptibility – Starting point - Terrain units

The main ones are:

- regular cells: provide very accurate information on predisposing factors (high spatial resolution), but do not take into account the geomorphological context

- slope units: have a coarser resolution, but outline the geomorphological context. They can represent single slopes or groups of slopes.

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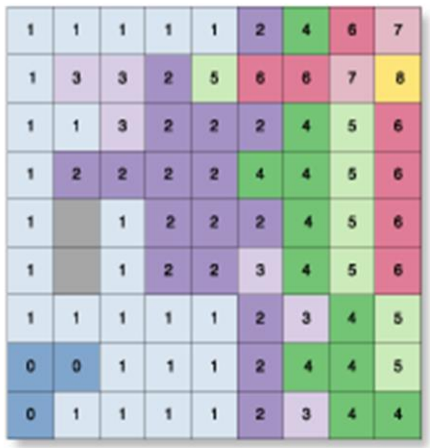

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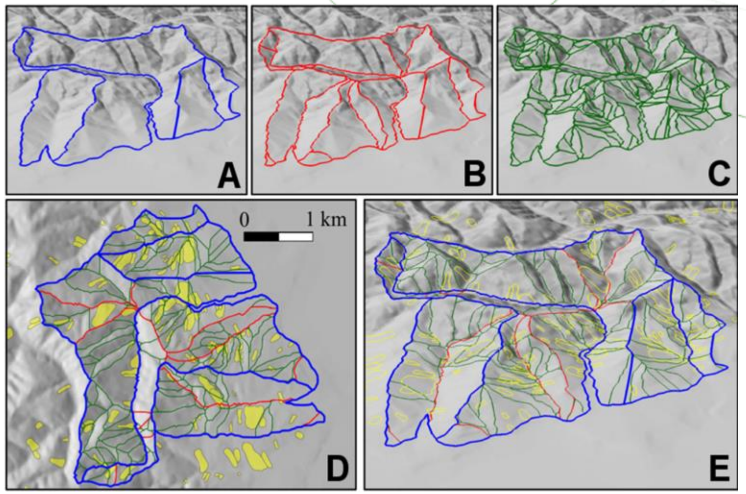
SLOPE UNITS

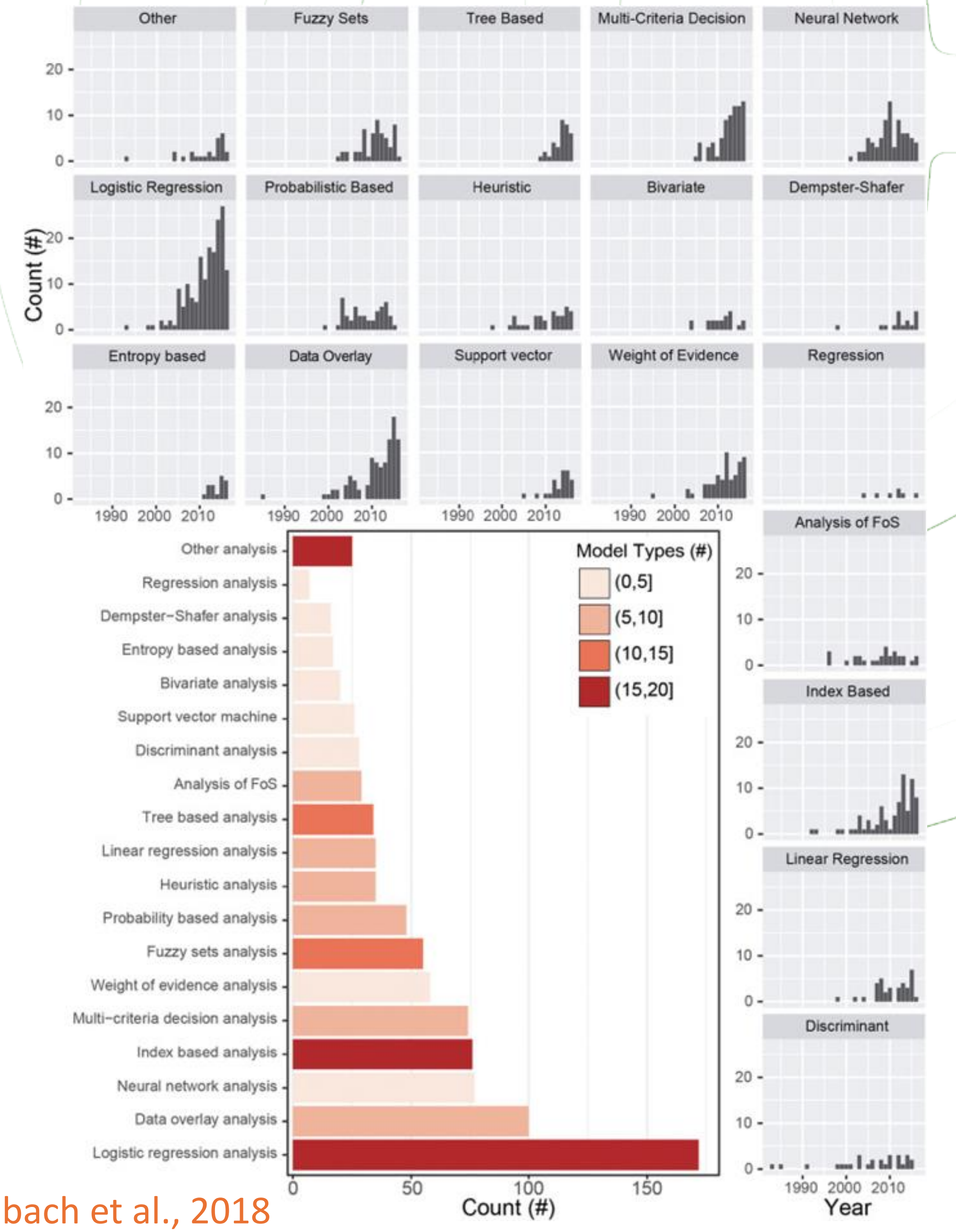


https://www.irpi.cnr.it/focus/slope-units/

Statistical methods

- Statistically-based landslide susceptibility models are constructed to describe the functional (statistical) relationship between instability factors, described by sets of geo-environmental (independent) variables, and the known distribution of landslides, taken as the dependent model variable. The functional relationship is then used to ascertain the propensity of the terrain to generate landslides and to predict susceptibility.
- In the literature, the majority of the models employs one of several possible classification methods that can be clustered into six main groups:

1. Classical statistics (e.g., logistic regression, discriminant analysis, linear regression)
2. Index-based (e.g., weight-of-evidence)
3. Machine learning (e.g., fuzzy logic systems, support vector machines, forest trees)
4. Neural networks
5. Multicriteria decision analysis
6. Other statistics



Reichenbach et al., 2018

Maps and data for statistical susceptibility

Main information to collect to build a reliable susceptibility map for slope instability processes.

Independent variables X (predisposing factors or landslide conditioning variables):

- Geological map (better if contains any lithological or geo-mechanical information)
- Land cover or land use map (a plus if with vegetation type)
- Topographic map (better if derived from DEM)
- Hydrographic network (if not available, can be derived from DEM)
- Structural map (faulting, joints)
- Rainfall maps (from ground stations, weather radars, satellites or models)

Dependent variable Y (slope process density, probability, likelihood)

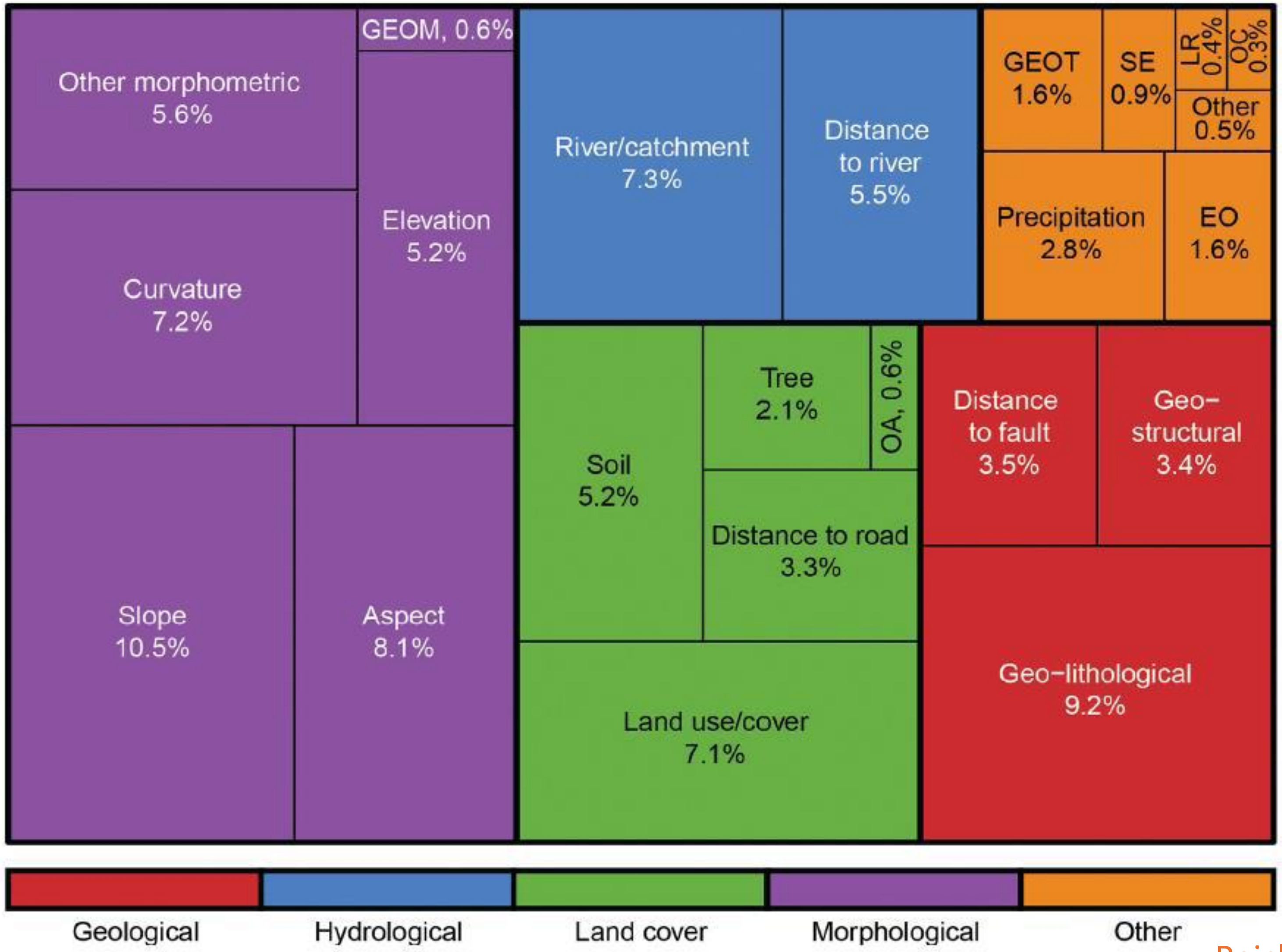
Map of slope processes (polygon of the landslides, point of the highest peak in a landslide, indications on the state of activity, etc.)

The comparison (often statistical) between effects (dependent variable) and causes (independent variables) is the key to understanding the process and forecasting it.

The basic method is to simply analyze the bivariate relationship between Y and Xi. Then we go to multi-variate analysis and then to model design, training, and testing. The final step is the validation.

Predisposing factors

Among dozens of possible parameters, how to select the optimal number? How to identify the most effective ones?



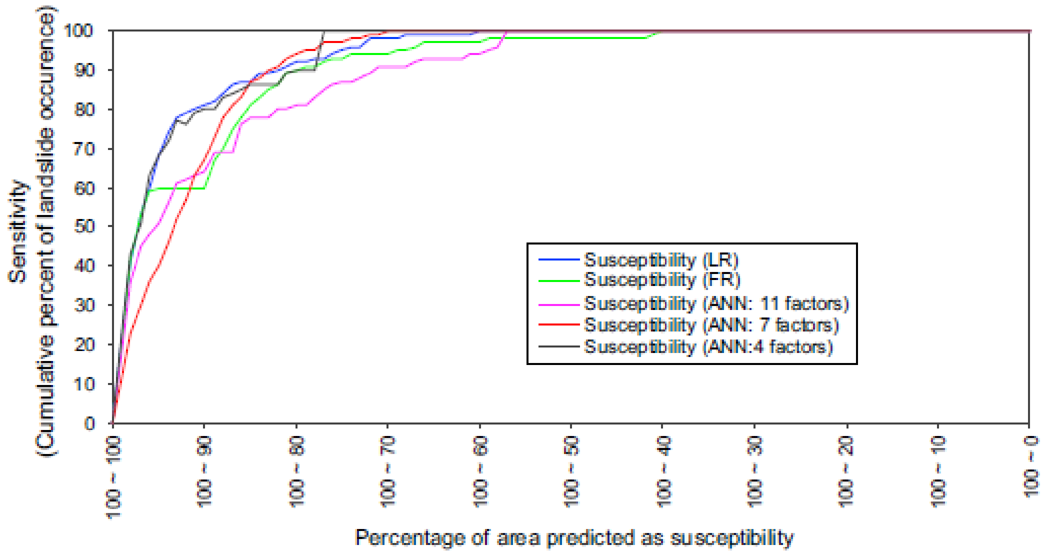
Reichenbach et al., 2018

Predisposing factors - selection

- The more, the better? Not always true!

Model configuration	AUC logistic regression	
Three parameters	0.73	Slope gradient, lithology, land cover
Four parameters	0.78	Three parameters + CN
Five parameters	0.79	Four parameters + I_a
Six parameters	0.77	Five parameters + aspect
Seven parameters	0.76	Six parameters + flow accumulation
Eight parameters	0.76	Seven parameters + profile curvature

Manzo et al., 2012



Pradhan and Lee, 2010

- Model complexity may lead to worse predictions
- Some models work better with simple configurations
- Complex models may have other problems (e.g. overfitting issues)

Predisposing factors - selection

- Expert evaluation

- Collinearity tests

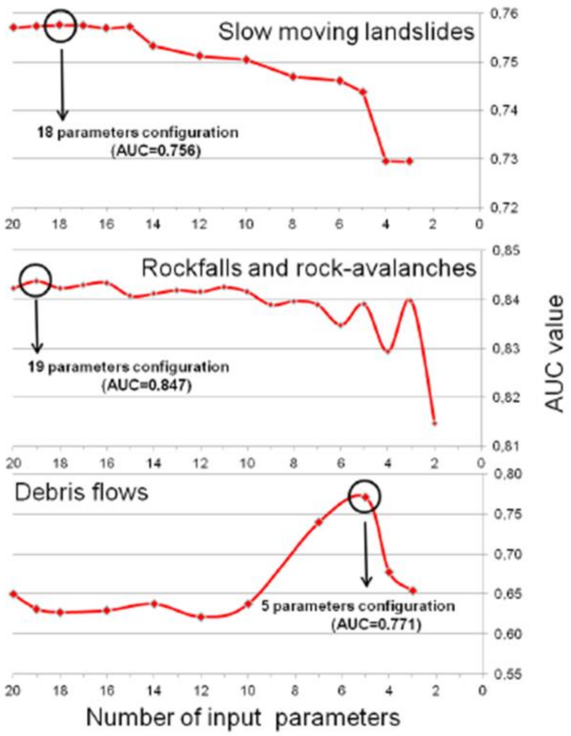
(e.g., Correlation matrix or VIF)

Predisposing factors	VIF
Altitude	2.424
Aspect	1.183
Built-up areas	1.136
Curvature	42.569
Fault	1.140
Geomorphology	1.625
LULC	1.167
Lithology	1.104
Plan curvature	17.828
Profile curvature	14.828
Road	1.149
Slope	2.334
Soil Texture	1.476
Soil bulk density	2.649
Soil clay density	2.761
Stream	1.364
TRI	2.072
TWI	2.463

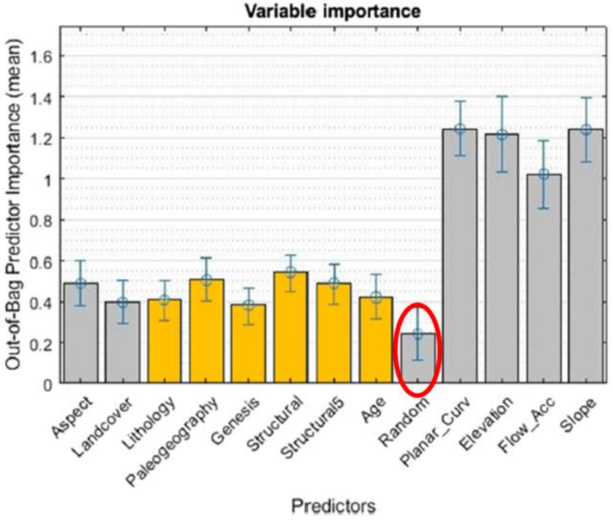
Removed 3 factors (Curvature, plan curvature, profile curvature) since VIF value is above 10

- Forward selection

(Based on the final results or on the importance score)



- Random variable



Segoni et al., 2020

Statistical methods – Methods and algorithms

Bivariate statistics

Weights of evidence

Information value

Etc.

Multivariate statistics

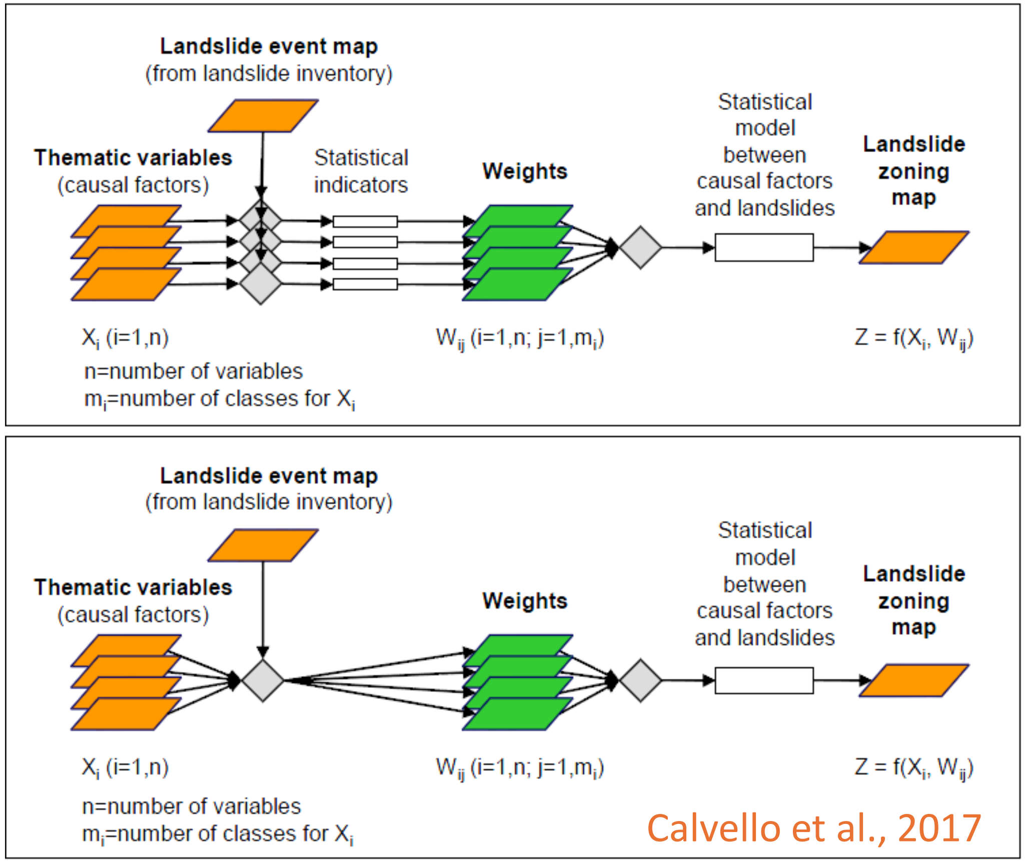
Logistic regression

Discriminant analysis

Cluster analysis

Artificial Neural Networks

Etc.



Calvello et al., 2017

- Both types of analysis rely on the information provided by a landslide event map derived from a landslide inventory, which acts in the analyses as the only dependent variable; several thematic independent variables are pre-identified as possible causal factors for landslide events. Weights are computed and assigned to the independent variables considering their statistical importance, both in absolute and relative terms, for detecting landslide events in the study area.

Statistical methods – Methods and algorithms

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Machine Learning

- Differently from statistical analyses, ML algorithms are able to learn the association between landslide occurrences and landslide conditioning factors without necessarily assuming a structural model in the data.

- The learning aspect of these methods is to develop sequences of commands or algorithms that search, in a process of iterative and gradual refinement, for associations in the data that basic descriptive statistics and the human eye may not readily detect as such (Korus and Stolle, 2014).

Three main common phases of analysis may be recognized in each ML procedure for landslide susceptibility modeling

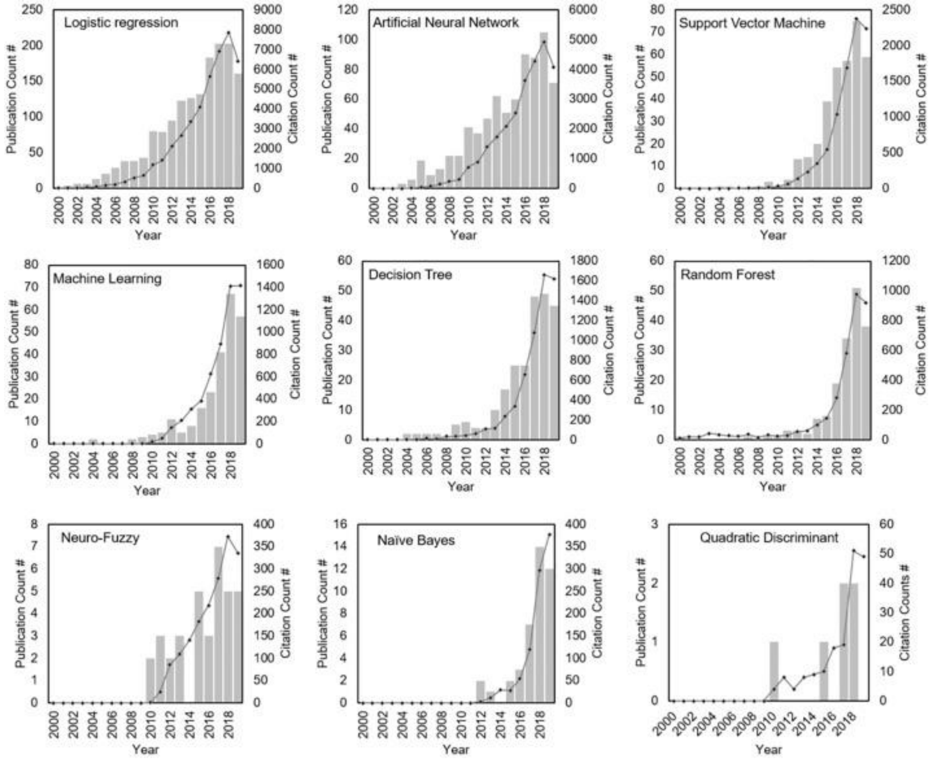
Factor analysis
- Analysis of the available information
- Selection of features and target of the ML model
- Construction of the spatial database

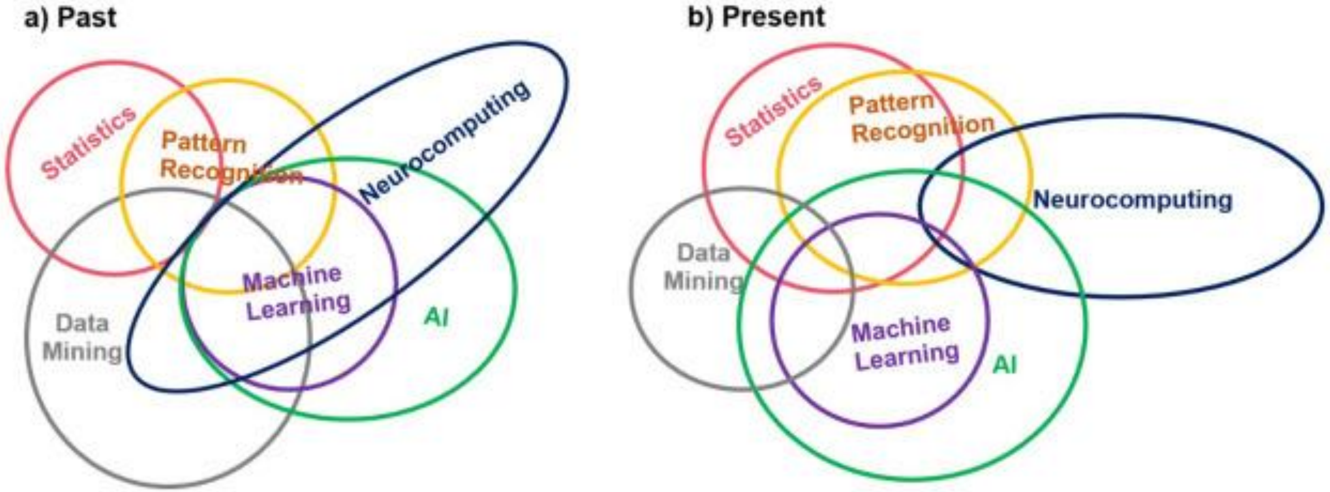
Model building
- Algorithm selection
- Model training
- Computation of landslide susceptibility map

Testing and validation
- Evaluation of model performance

Why Machine Learning

By definition, ML learns from data without banking on rules-based functions, whereas statistical modeling streamlines relationships between variables in the data by means of mathematical equations

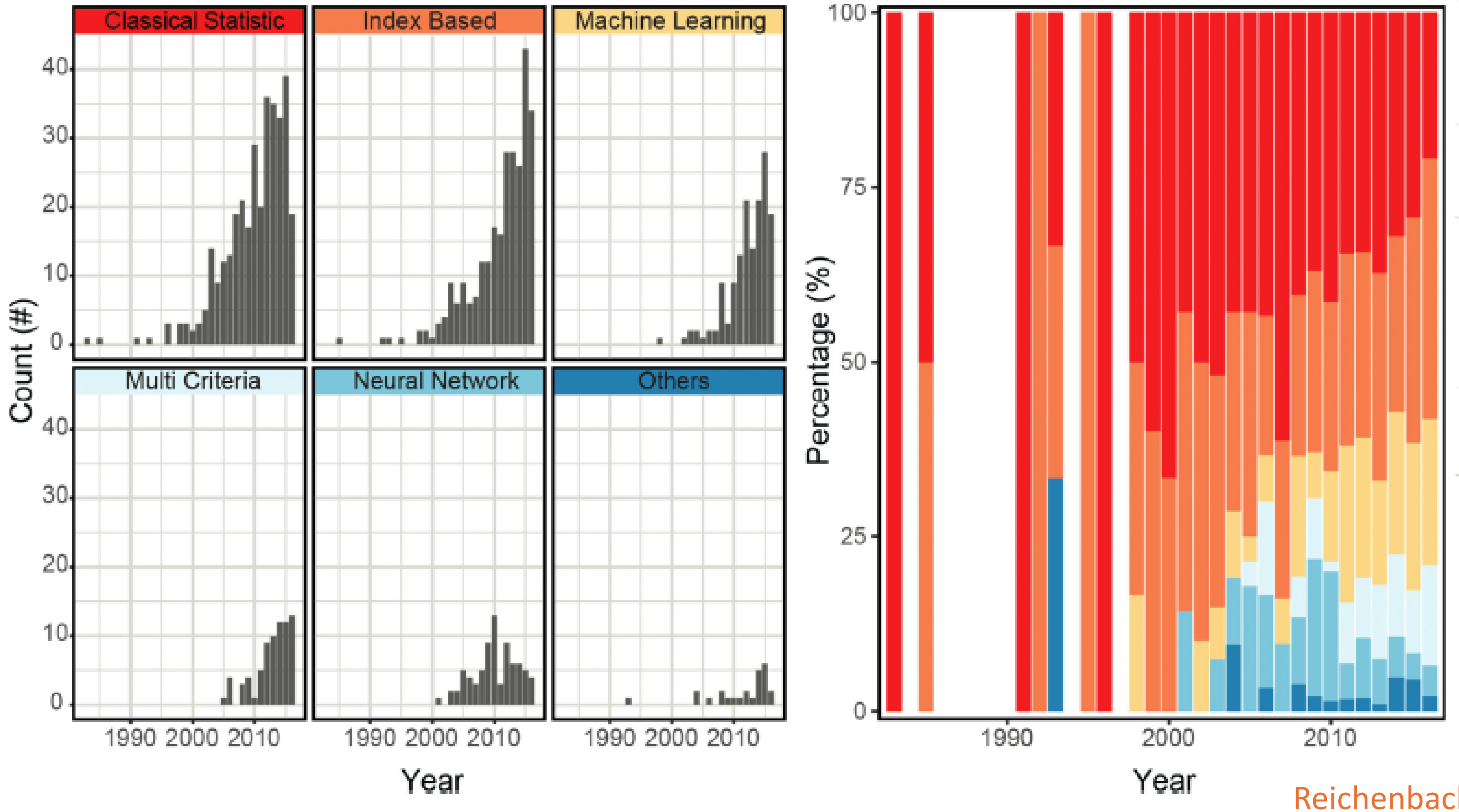




Merghadi et al., 2020

Statistical methods – Methods and algorithms

Which one to choose?

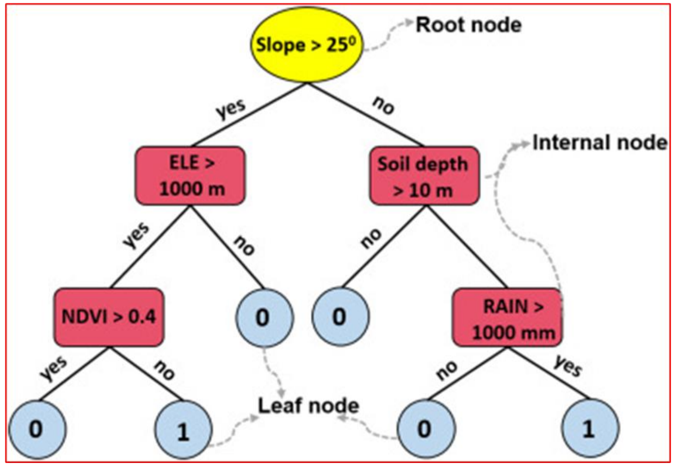


Reichenbach et al., 2018

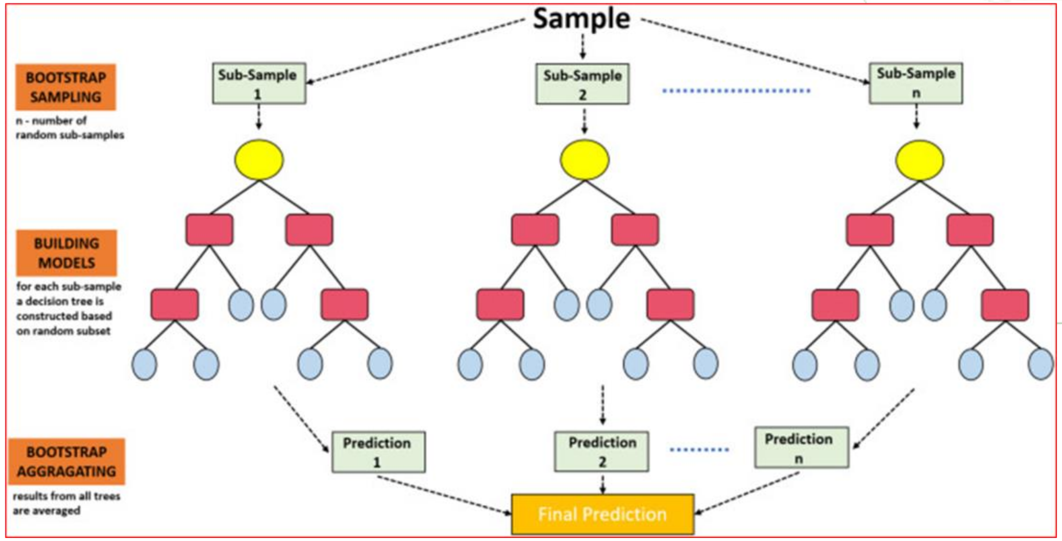
Statistical methods – Methods and algorithms

Which one to choose?

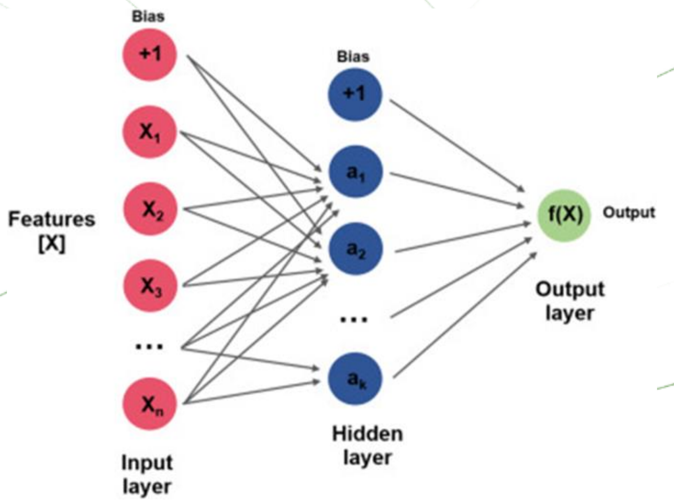
- Most methods are classification/regression algorithms to be used in programming software (Matlab, R, Python…)



Decision tree



Random Forest

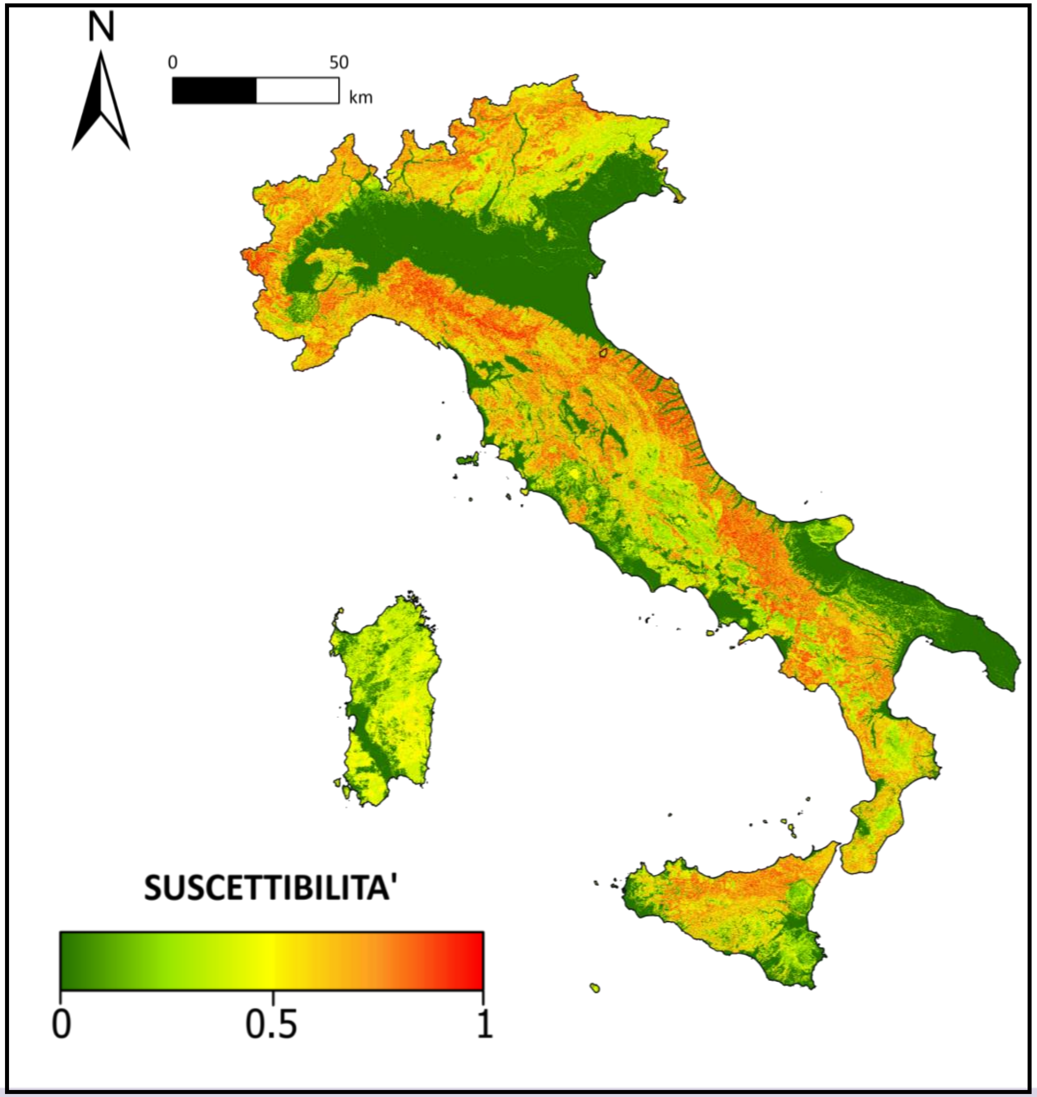


Simple multi-layer Artificial Neural Network

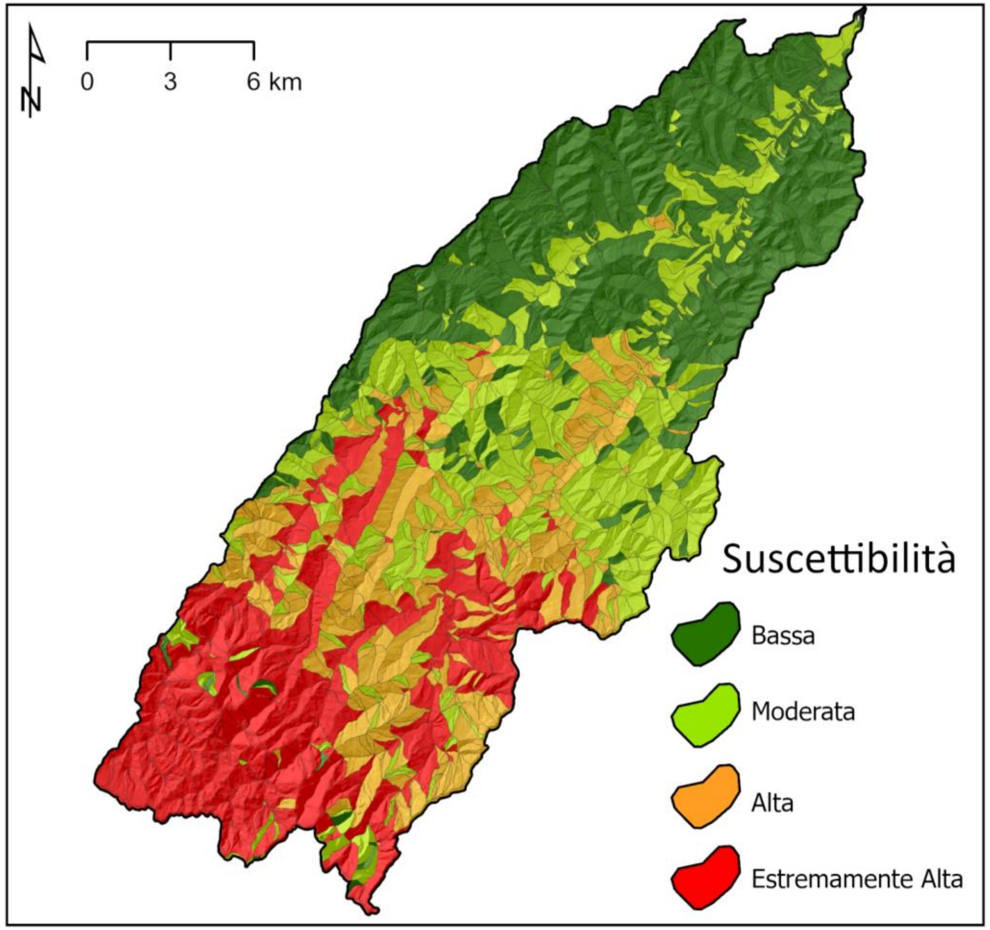
Merghadi et al., 2020

Susceptibility maps

Continuous values



Classes



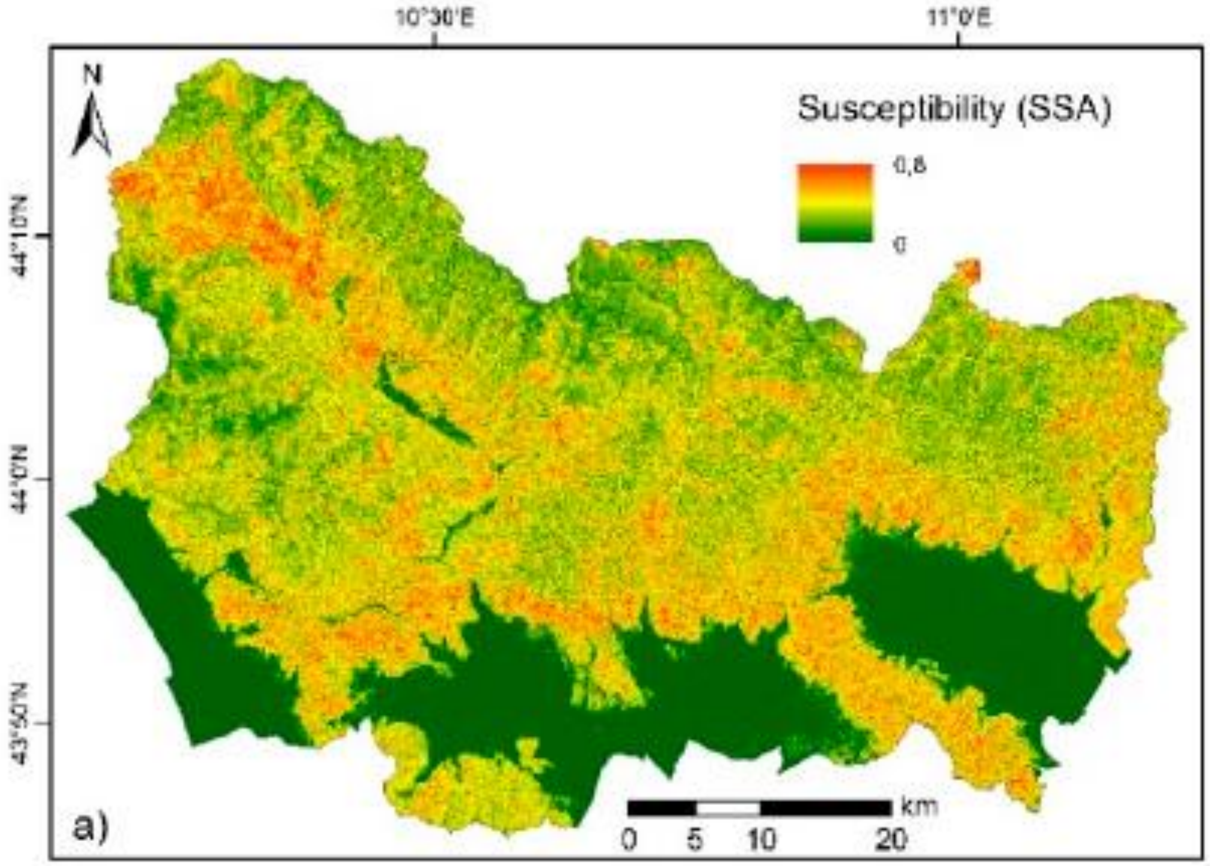
Manzo et al., 2012

Susceptibility maps

RAW MODEL OUTPUTS

Depending on the model:

- probability [0 - 1]
- adimensional index

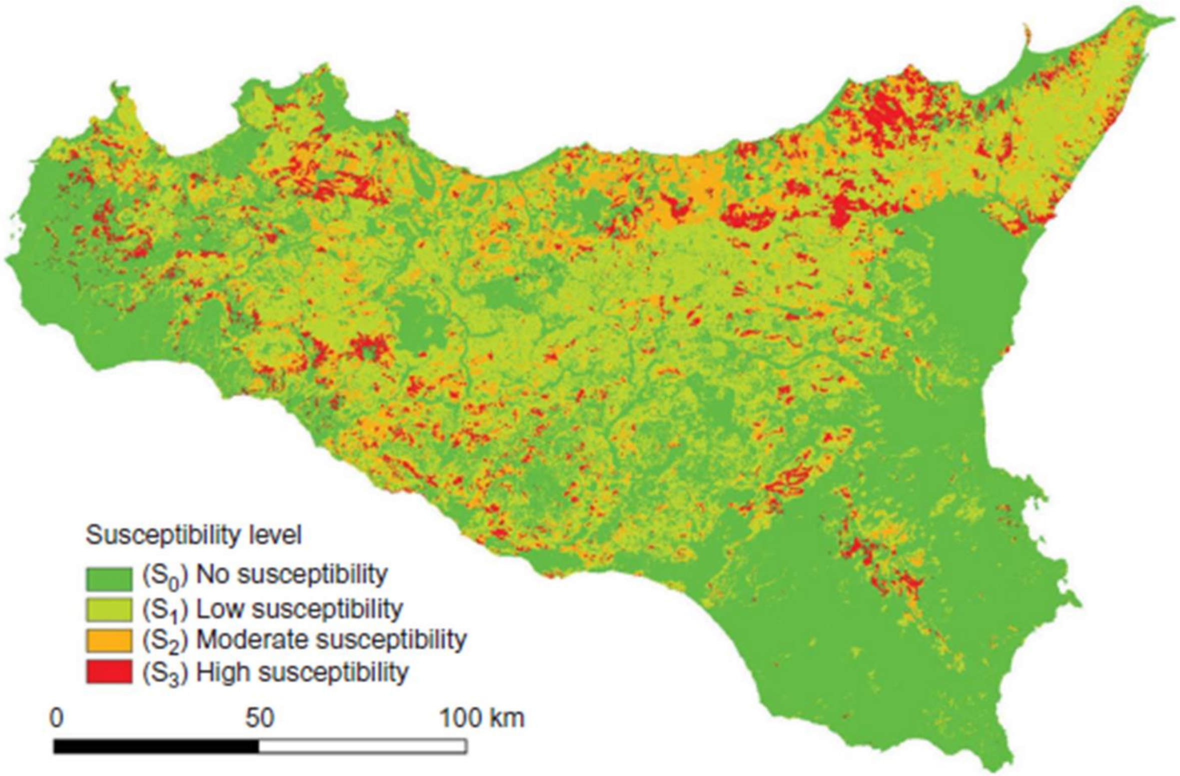


Luti et al., 2020

Susceptibility maps

RECLASSIFIED MAP

- Decide the number of classes
- Define a method to break the raw susceptibility values into classes
  - Natural breaks (Jenks)
  - Relative difference of derivates
  - Equal intervals
  - …



Manzo et al., 2012

Validation

Performance indicators

- Accuracy = (TP + TN) / (TP+FP+TN+FN)
- RMSE, R2, …
- K index
- …

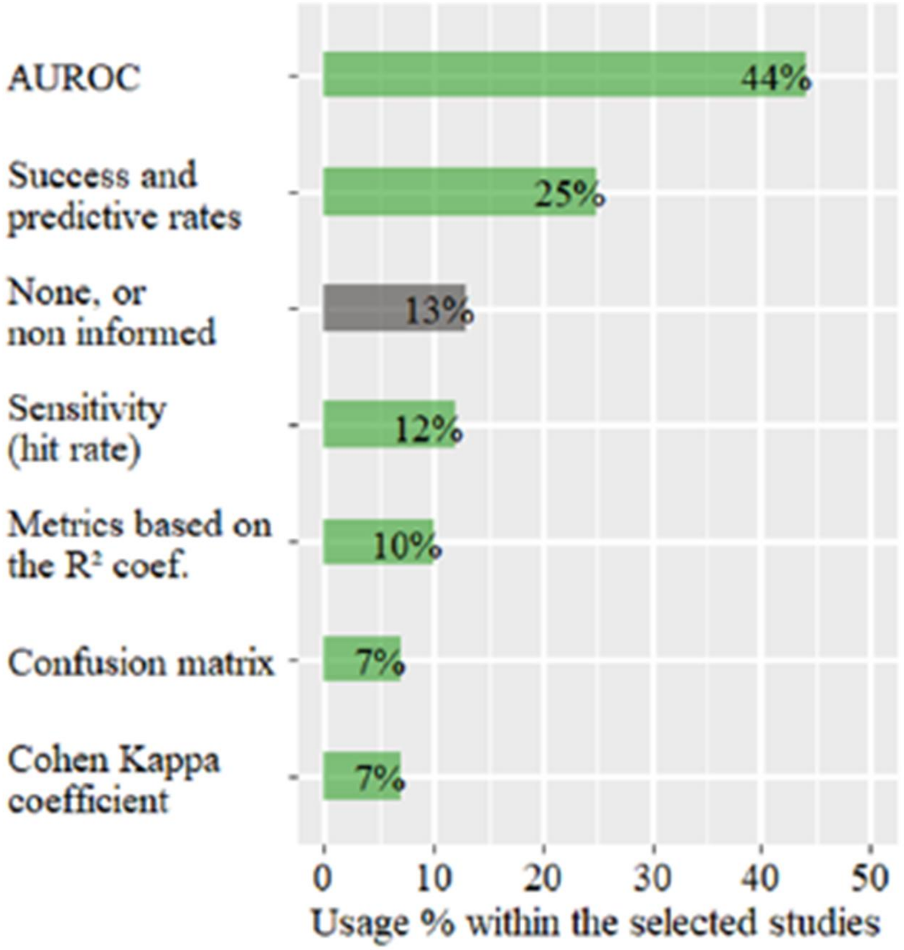
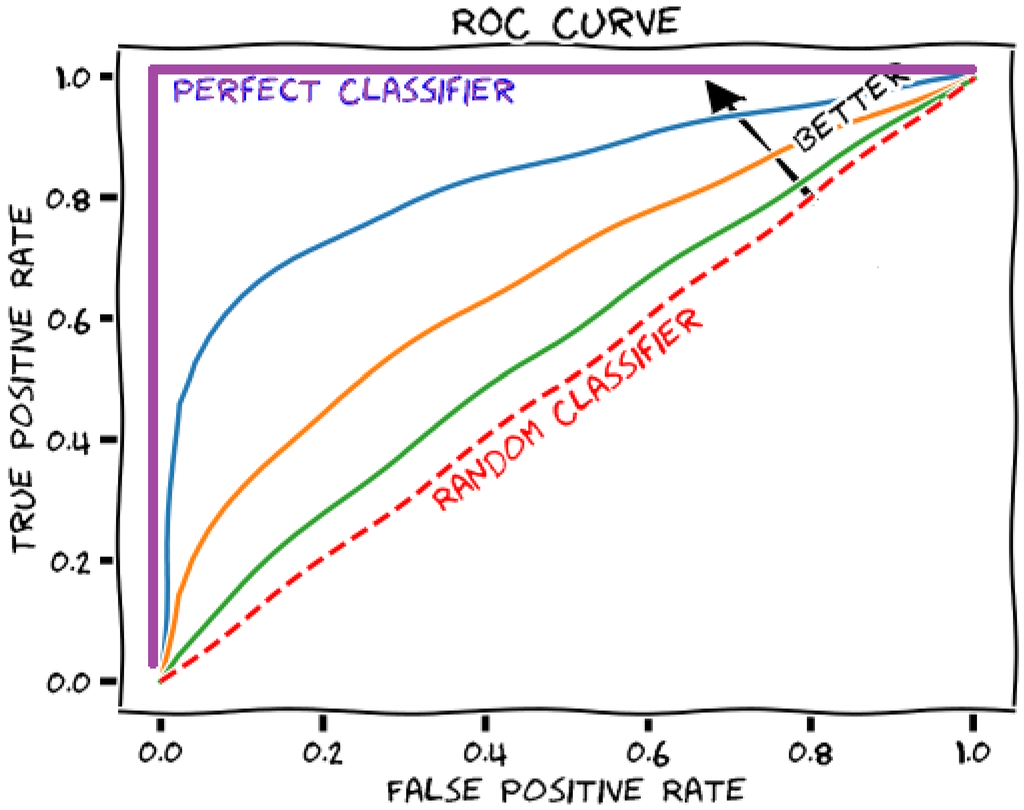


Fig. 13 Most used validation error measure techniques within the selected studies.

Validation

AUC (Area Under Receiving-Operator Curve)



A **ROC curve (receiver operating characteristic curve)** is a graph showing the performance of a classification model at all classification thresholds. This curve plots two parameters:
True Positive Rate
False Positive Rate

True Positive Rate (TPR) is a synonym for recall and is therefore defined as follows:

TPR=TP/TP+FN

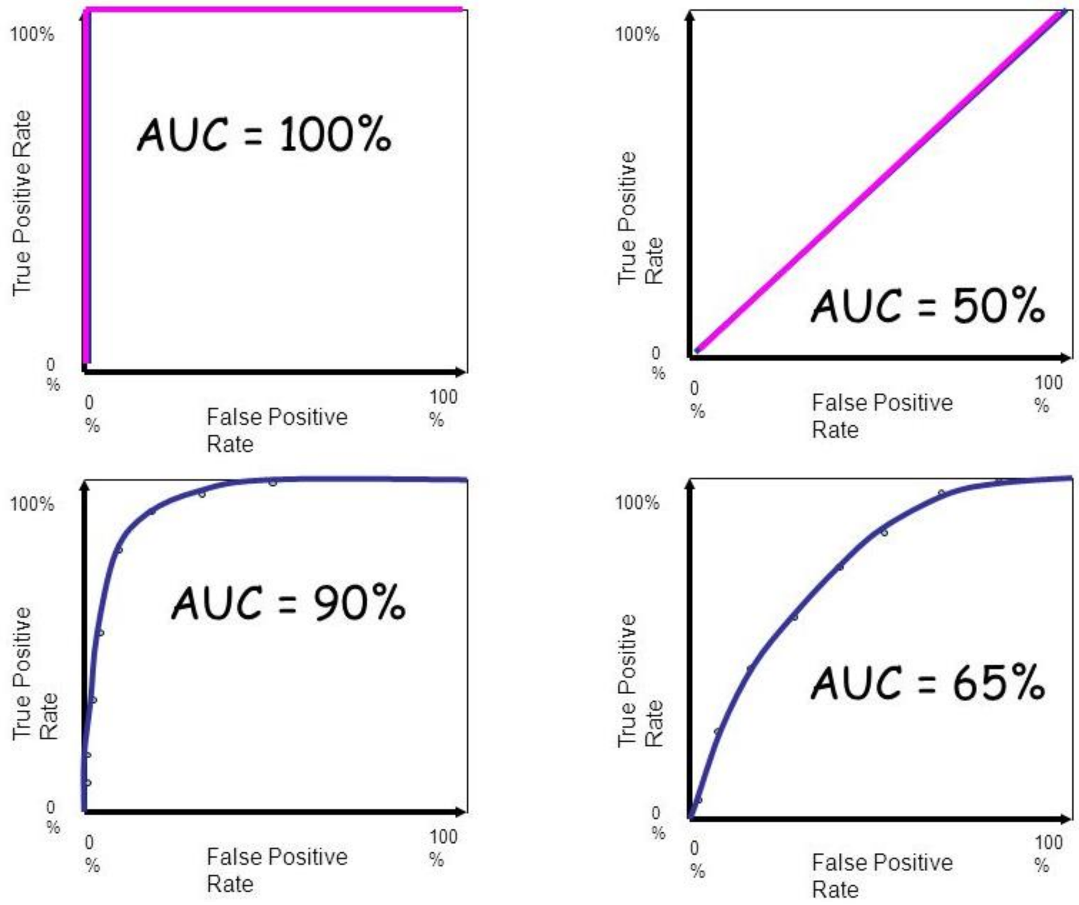
False Positive Rate (FPR) is defined as follows:

FPR=FP/FP+TN

A ROC curve plots TPR vs. FPR at different classification thresholds. Lowering the classification threshold classifies more items as positive, thus increasing both False Positives and True Positives. The following figure shows a typical ROC curve.
AUC stands for "Area under the ROC Curve." That is, AUC measures the entire two-dimensional area underneath the entire ROC curve (think integral calculus) from (0,0) to (1,1).

Validation

AUC (Area Under Receiving-Operator Curve)



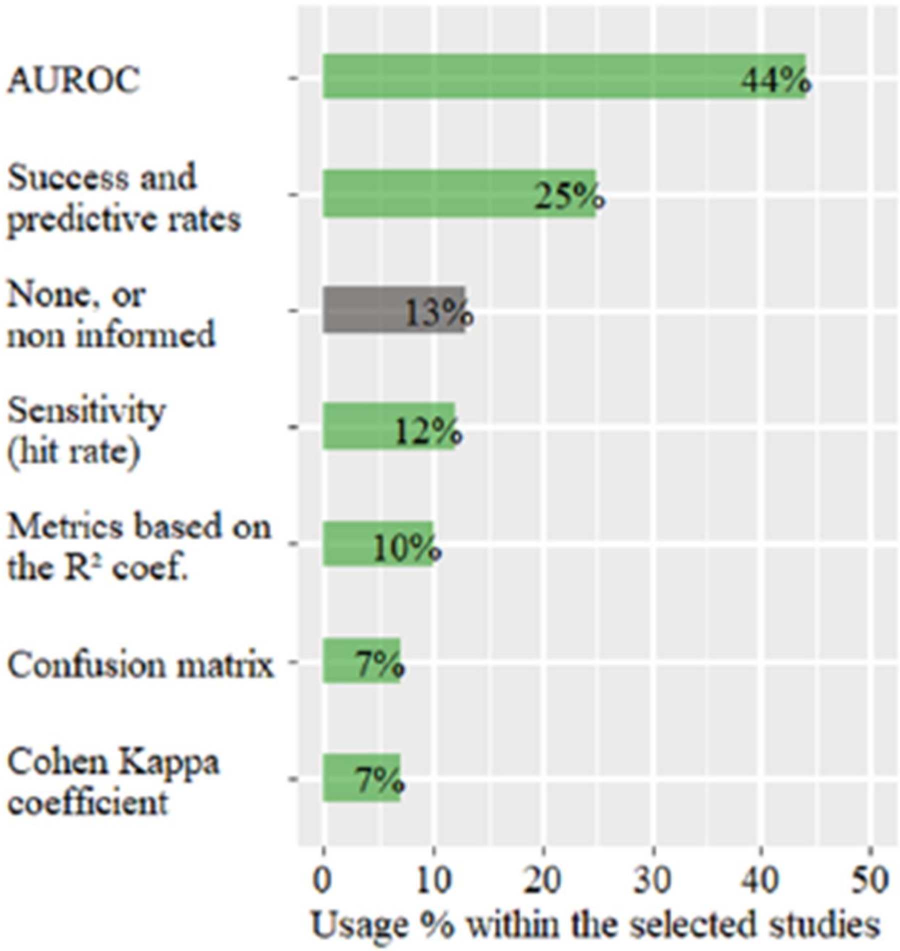


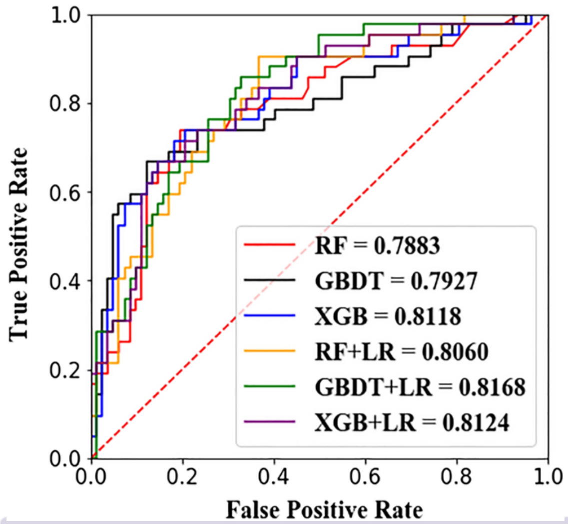
Fig. 13 Most used validation error measure techniques within the selected studies.

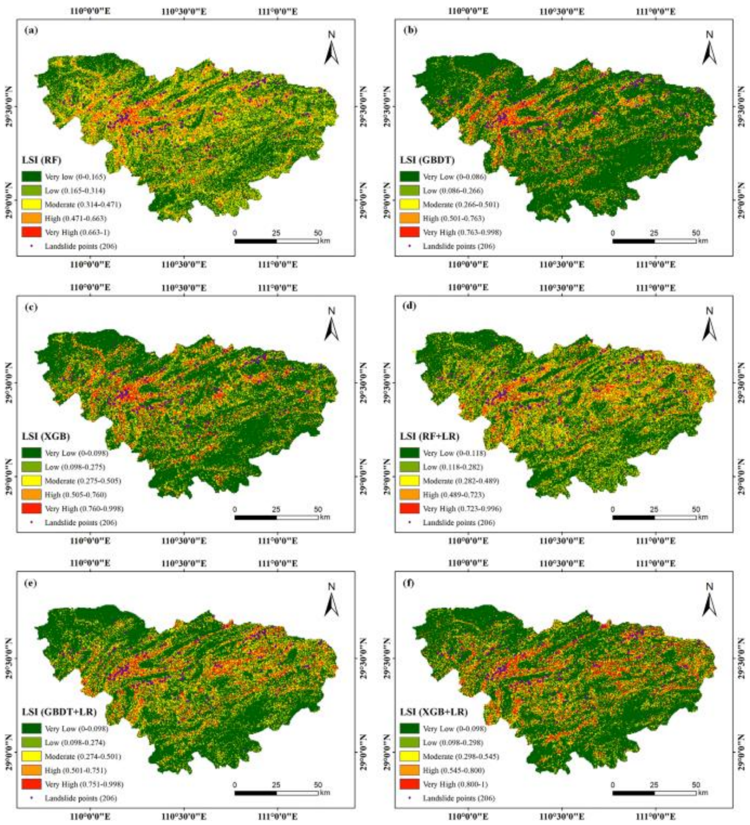
Comparison

Different models or Different configurations of the same model

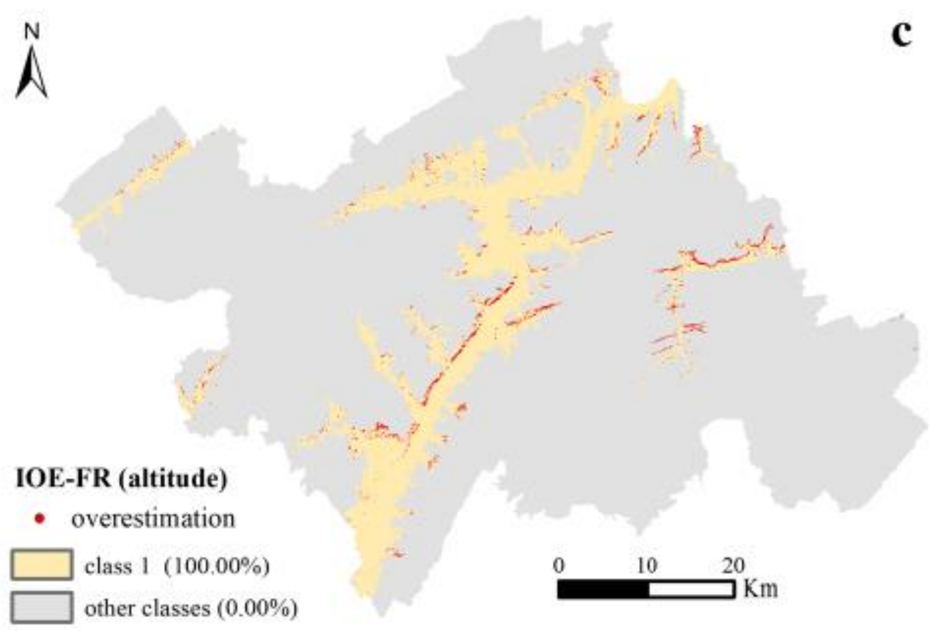
- In terms of indicators (AUC)
- Spatial patterns of differences

Huan et al., 2023

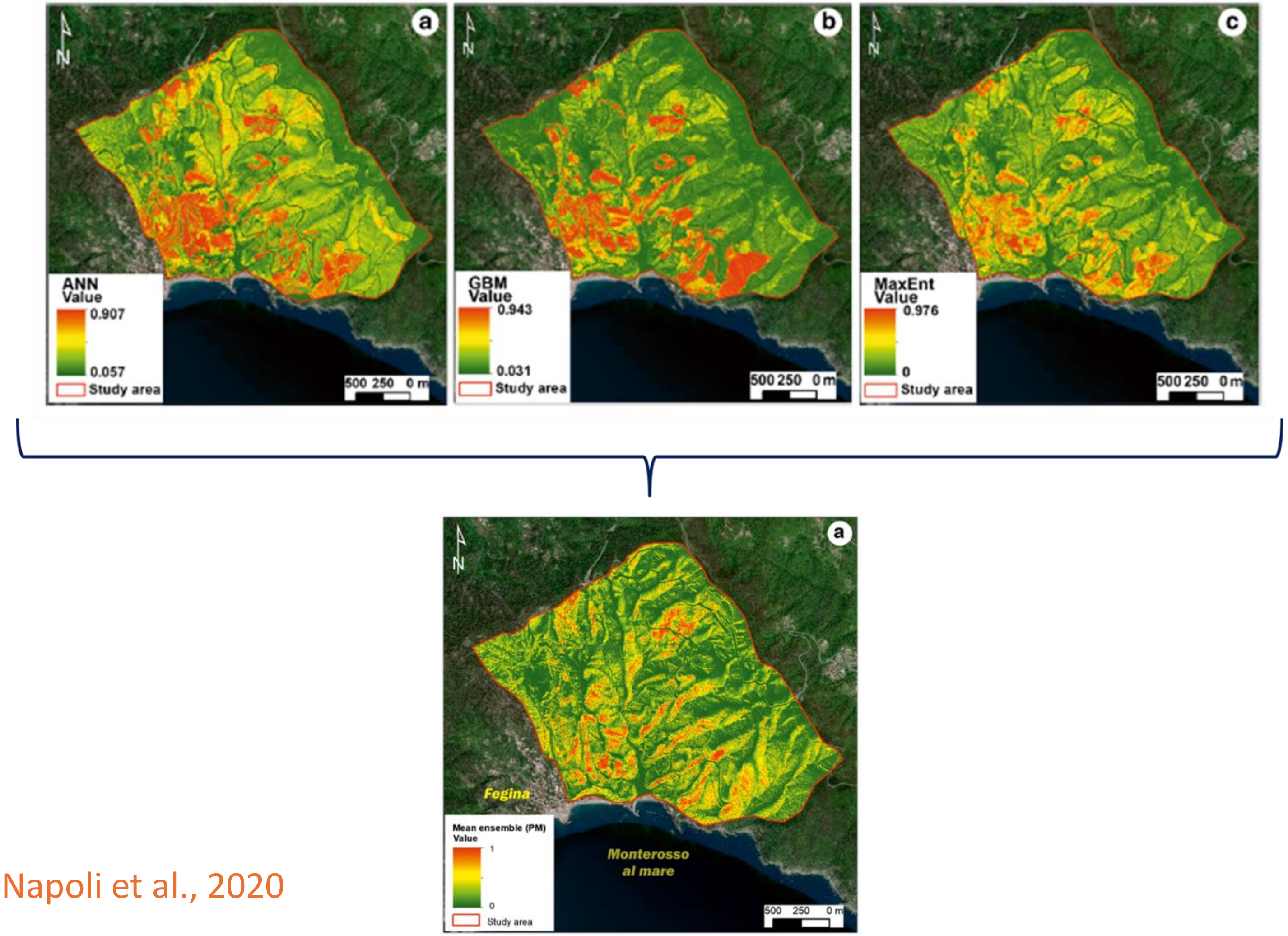




Xiao et al., 2020



Ensembling



Di Napoli et al., 2020

From **n** maps

to a **single**, comprehensive, map

(mean, median, maximum, or more complex stacking methods)

Risk equation

$$R = H \cdot V \cdot E$$

Risk = expected loss

Hazard = probability of occurrence

Vulnerability = loss degree

Elements at risk = value

Risk equation

$$R = P \times V(I) \times E$$

V (Vulnerability): degree of loss, that is, the propensity of an exposed element to suffer damage as a result of the occurrence of an event of a certain **intensity (I)**

Intensity

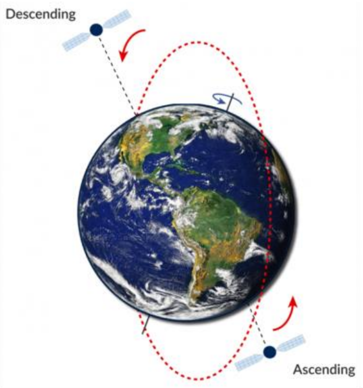
- **Landslide intensity** A set of spatially distributed parameters related to the destructive power of a landslide. The parameters may be described quantitatively or qualitatively, and may include maximum movement velocity, total displacement, differential displacement, depth of the moving mass, peak discharge per unit width or kinetic energy per unit area.
- Landslide magnitude The measure of the landslide size. It may be quantitatively described by its volume or (indirectly) by its area. The latter descriptors may refer to the landslide scar, the landslide deposit, or both.

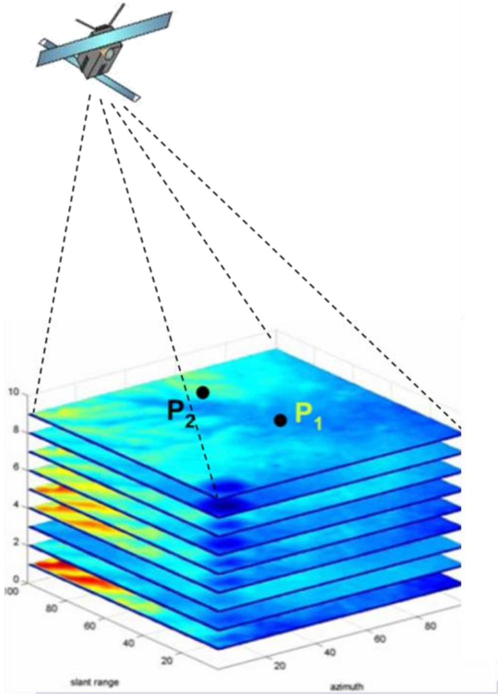
	Intensity		
Process	Low	Medium	High
Rock falls			
Kinetic energy	<30 kJ	30 - 300 kJ	>300 kJ
Slides			
Mean annual velocity	<2 cm/year	2 - 10 cm/year	>0.1 m/day
Displacement	–	–	>1 m/event
Debris flow			
Debris front thickness	–	<1 m	>1 m
Debris flow velocity	–	<1 m/s	>1 m/s
Depth of soil material (potential debris flows)	0.5 m	0.5 - 2 m	>2 m

Lateltin et al. (2005)

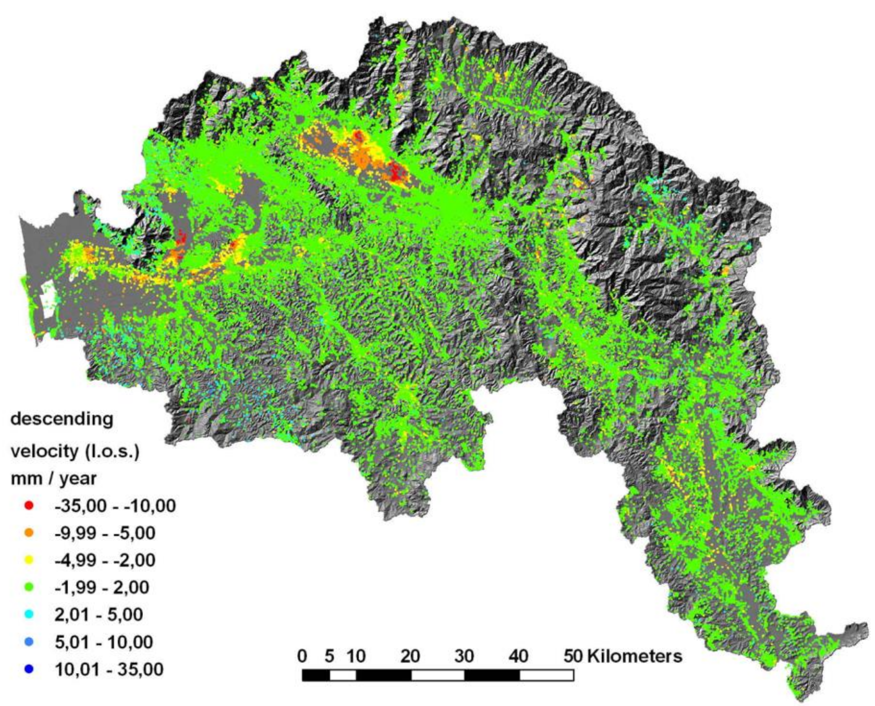
Intensity assessment at regional scale

SAR interferometry

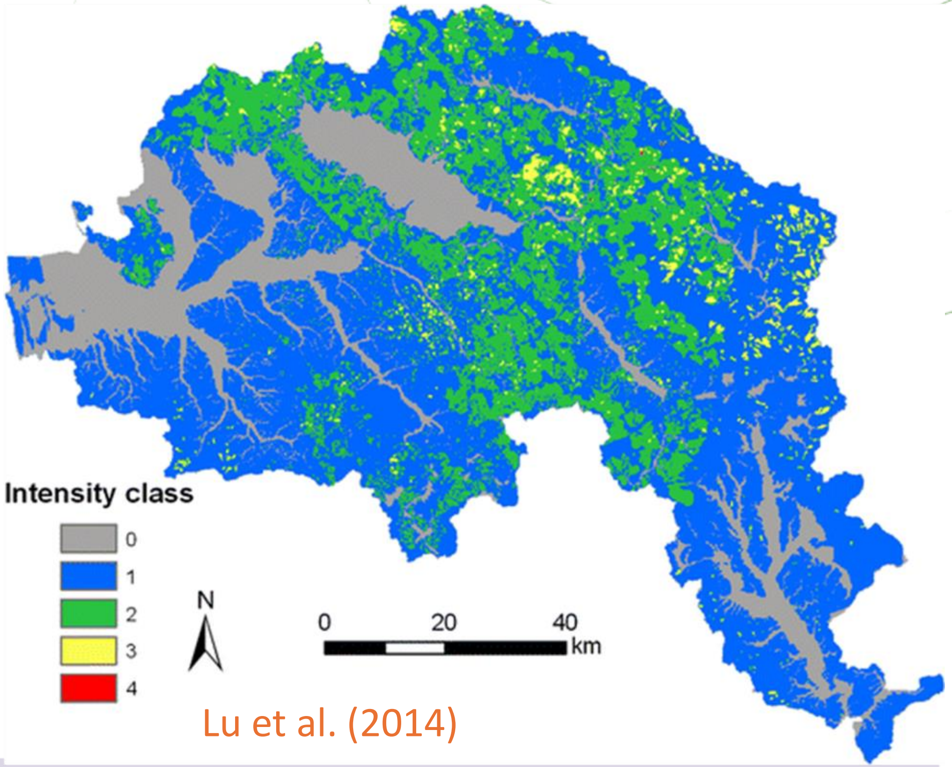




From velocity

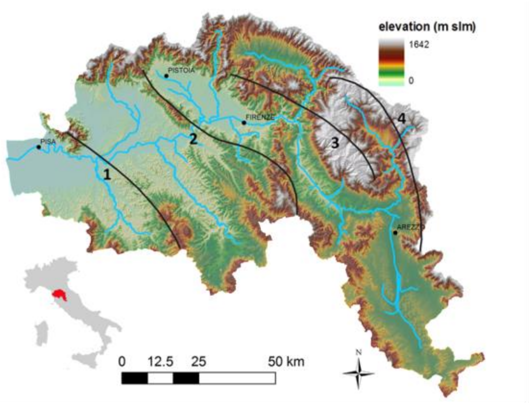


To intensity classification



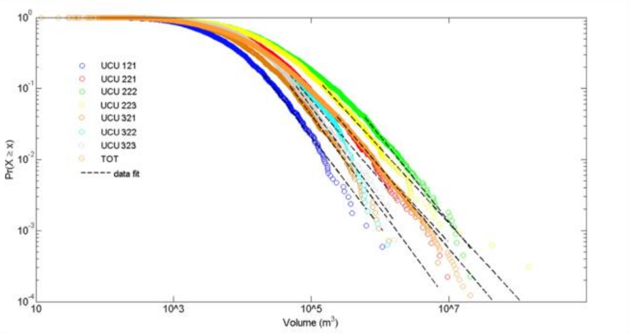
Lu et al. (2014)

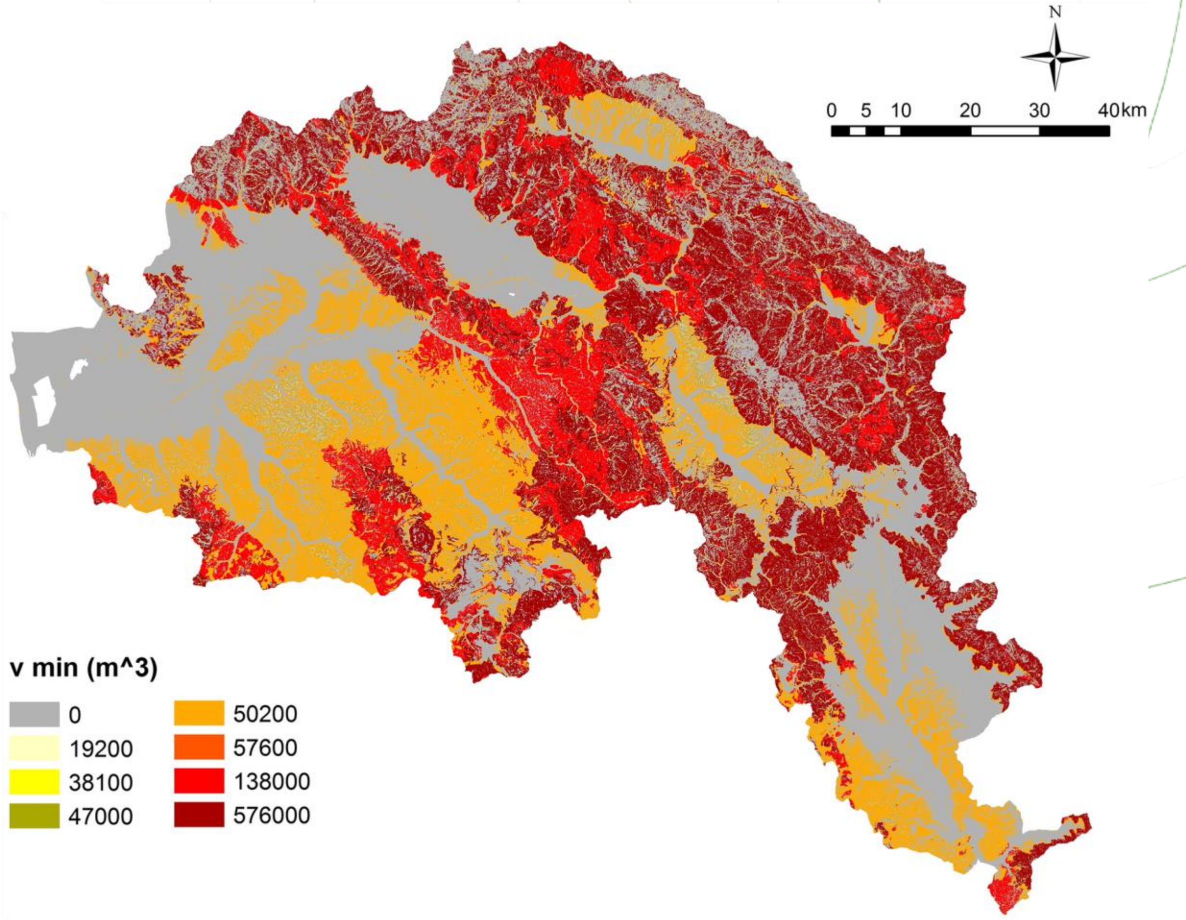
Intensity assessment at regional scale



$$V = \frac{1}{6}\pi D_r W_r L_r$$

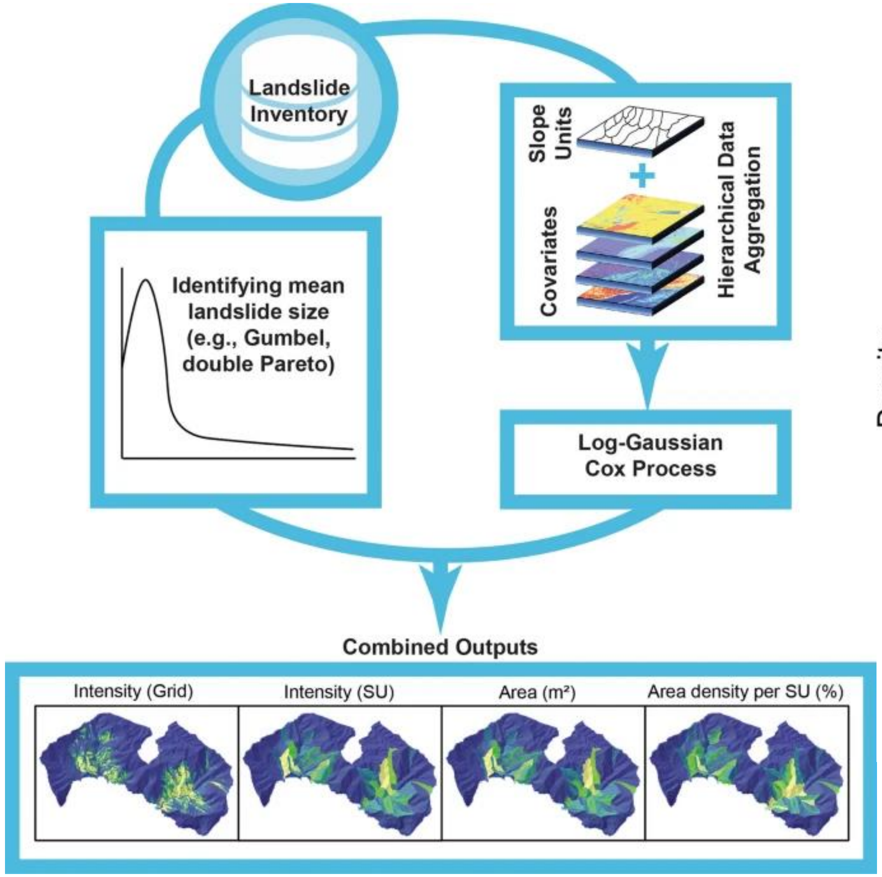
UCU	Profile curvature	Slope (°)	Lithology	Area (km^2)	Landslide #	Area landslide/area UCU
1.1.1	Concave	0–5	GCS	10.58	127	0.120
1.1.2	Concave	0–5	HR	9.61	18	0.010
1.1.3	Concave	0–5	SR	1.79	16	0.050
1.2.1	Concave	5–25	GCS	21.79	1694	0.880
1.2.2	Concave	5–25	HR	42.14	958	0.300
1.2.3	Concave	5–25	SR	4.34	608	0.170
1.3.1	Concave	>25	GCS	5.10	312	0.470
1.3.2	Concave	>25	HR	22.33	312	0.160
1.3.3	Concave	>25	SR	1.23	41	0.270
2.1.1	Planar	0–5	GCS	2612.85	208	0.002
2.1.2	Planar	0–5	HR	184.32	24	0.002
2.1.3	Planar	0–5	SR	103.47	19	0.092
2.2.1	Planar	5–25	GCS	1735.95	4486	0.070
2.2.2	Planar	5–25	HR	2312.46	4430	0.090
2.2.3	Planar	5–25	SR	911.63	3249	0.150
2.3.1	Planar	>25	GCS	103.19	360	0.020
2.3.2	Planar	>25	HR	750.36	857	0.030
2.3.3	Planar	>25	SR	50.65	76	0.020
3.1.1	Convex	0–5	GCS	11.29	189	0.190
3.1.2	Convex	0–5	HR	8.30	20	0.008
3.1.3	Convex	0–5	SR	2.44	27	0.060
3.2.1	Convex	5–25	GCS	39.85	2803	0.760
3.2.2	Convex	5–25	HR	85.05	1601	0.440
3.2.3	Convex	5–25	SR	13.73	1359	0.170
3.3.1	Convex	>25	GCS	10.53	170	0.210
3.3.2	Convex	>25	HR	55.31	374	0.100
3.3.3	Convex	>25	SR	3.74	47	0.100



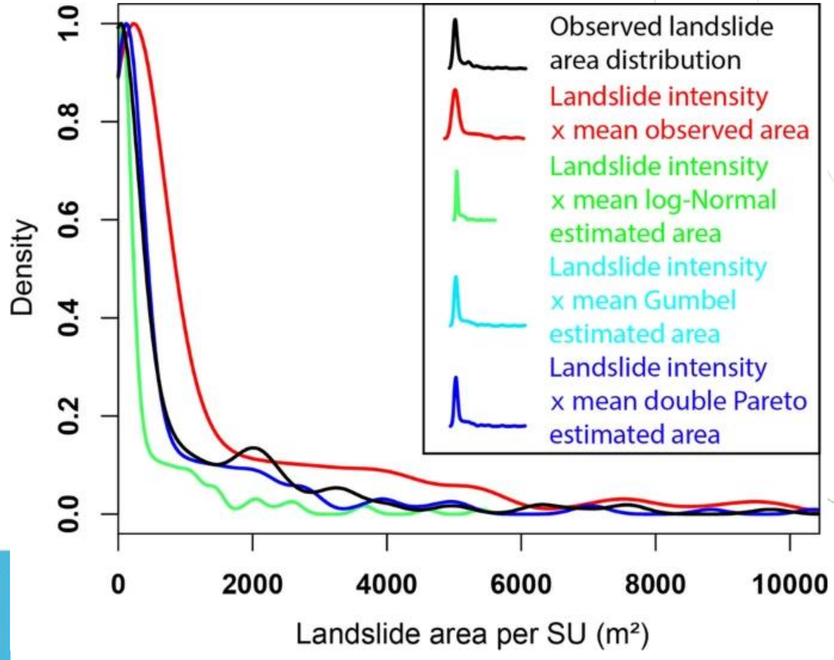


Catani et al. (2018)

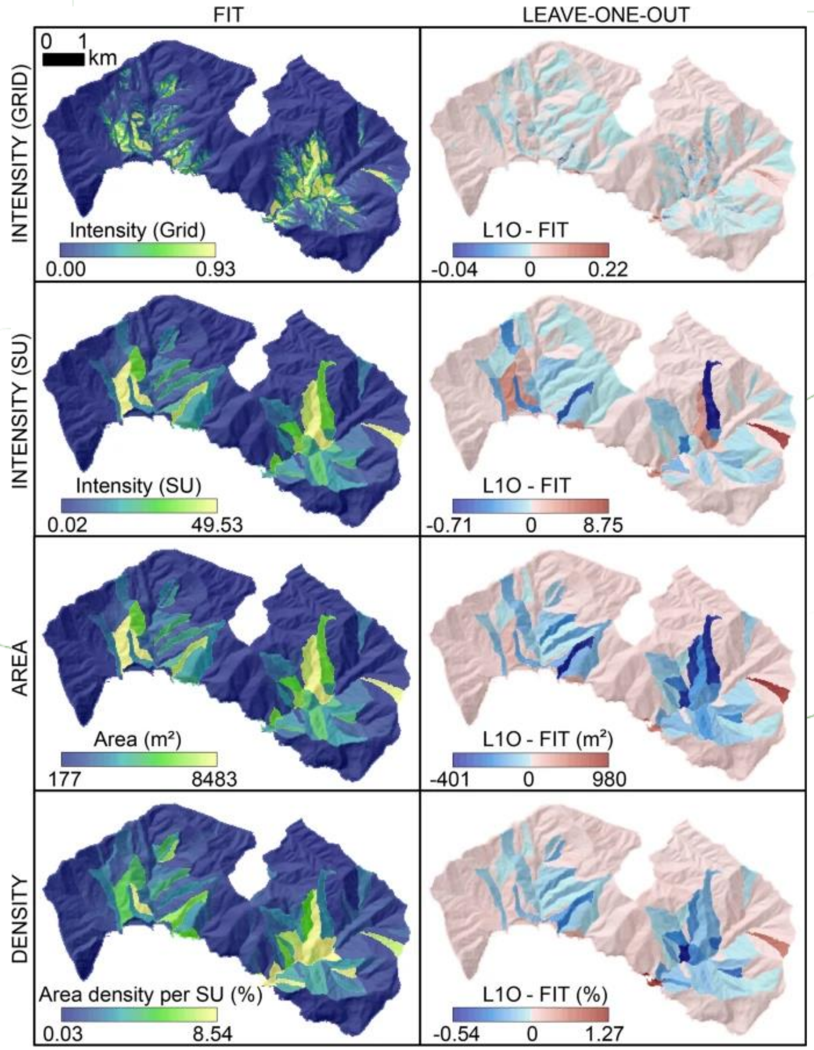
Intensity assessment at regional scale



From number of landslides per Slope Unit



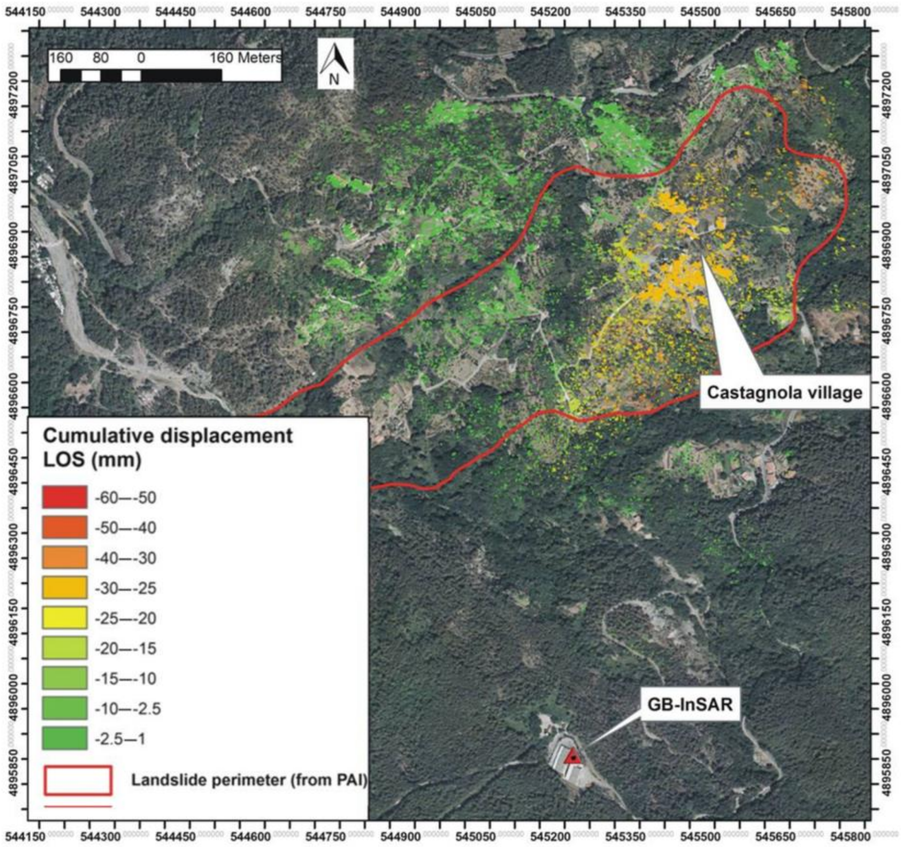
To intensity mapping



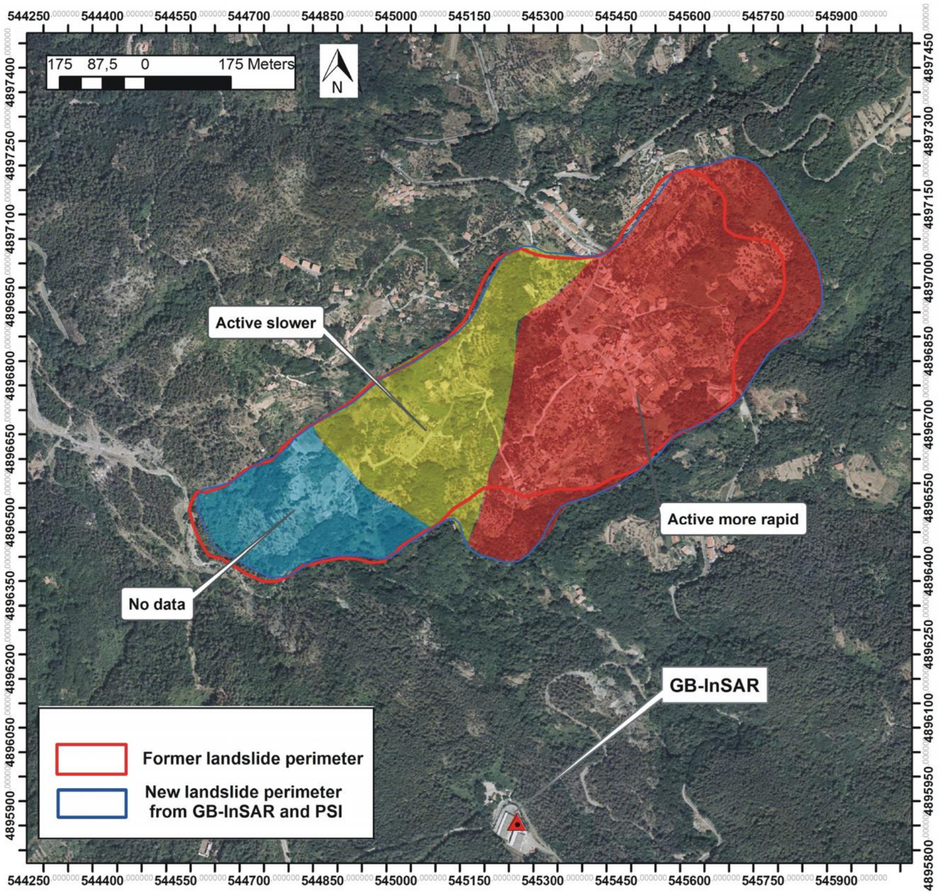
Di Napoli et al. (2023)

Intensity assessment at slope scale

From velocity



To intensity classification



Tofani et al. (2014)

Vulnerability

Vulnerability The degree of loss of a given element or set of elements exposed to the occurrence of a landslide of a given magnitude/intensity. It is expressed on a scale of 0 (no loss) to 1 (total loss).

Physical vulnerability
impact on buildings, infrastructures and utilities

Social vulnerability
determines whether a landslide event will cause injuries or fatalities

Environmental vulnerability
Direct impact on natural environment (forests, animal, plants, water)

Economic vulnerability
Indirect impact of the phenomenon on various activities

Buildings vulnerability

Depends on:

- characteristics of the building
- the landslide mechanism
- magnitude and intensity



Infrastructure vulnerability

- Partial or complete blockage of the road or track as well as structural damage, including damage to the surfacing, which is associated with the level of serviceability

Physical vulnerability assessment

ITINERIS

Vulnerability indices

Qualitative risk assessment

I	Building tipology	Observed Damages	VULNERABILITY
HIGH	All	Not considered	HIGH
MEDIUM	Strategical building	Not considered	HIGH
	Common building	YES	
	Common building	NOT	MEDIUM
LOW	Strategical building	Not considered	MODERATE
	Common building	YES	
	Common building	NOT	LOW

Cascini et al., 2005

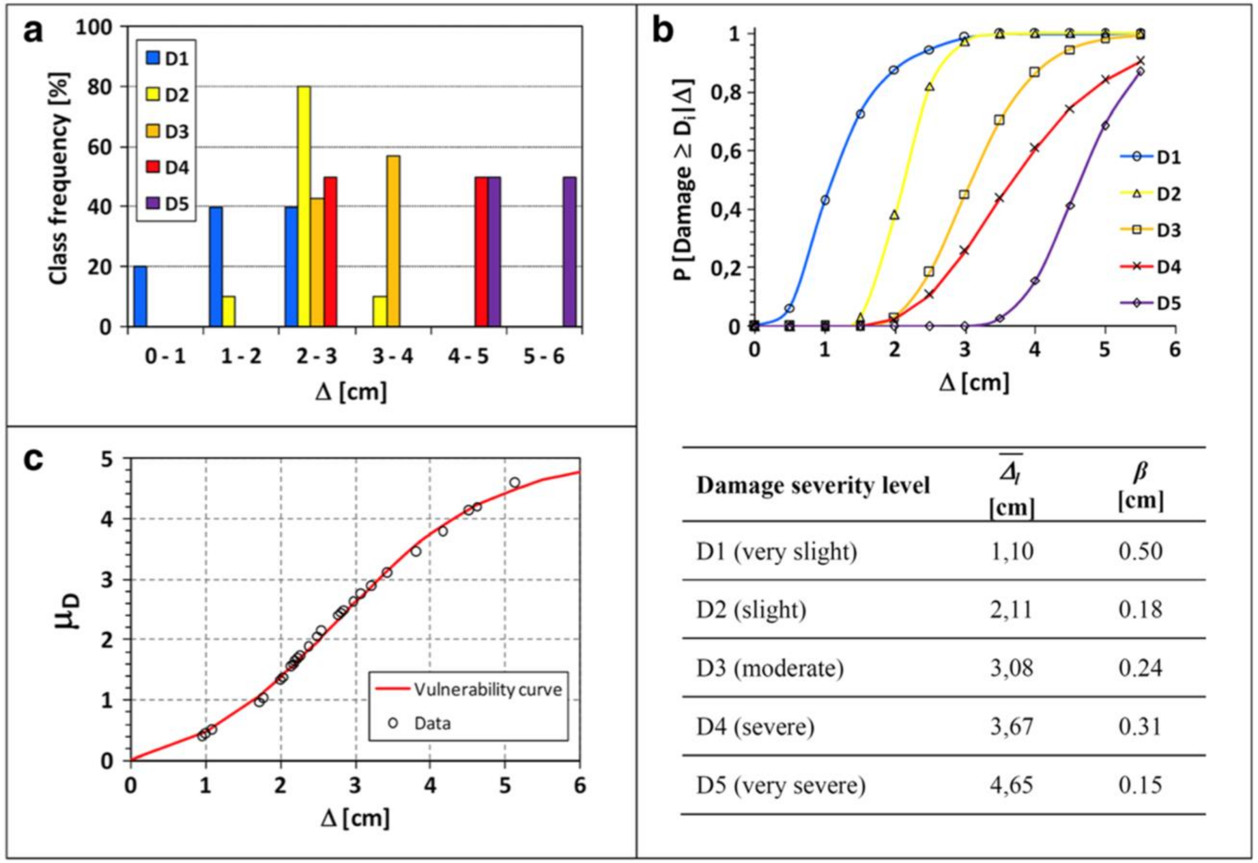
Quantitative risk assessment

Code	Description	Exposure (euro/m^2)	Vulnerability (% loss) as a function of intensity I			
			$V(I=I0)$	$V(I=I1)$	$V(I=I2)$	$V(I=I3)$
201	PUBLIC/SOCIAL/ADMINISTRATIVE BUILDING	3000	5	10	30	60
202	INDUSTRIAL/COMMERCIAL BUILDING-FACTORY	1000	5	10	20	50
203	RELIGIOUS BUILDING/BELLTOWER/TABERNACLE	4000	5	15	30	60
204	BUILDING UNDER CONSTRUCTION	100	5	15	30	40
205	ABANDONED/RUINED BUILDING	10	5	20	50	60
206	PROJECTING BODY/PORTICO/LOGGIA	100	5	10	20	40
207	SHED/KIOSK	100	5	15	50	60
208	AWNING//DORMER WINDOW	10	5	10	20	40
209	PRESSURIZED DOME	10	5	20	50	60
210	PERMANENT GREENHOUSE	10	5	20	40	60
211	TOLLGATE/RAILWAY STATION/STOPS	2000	5	10	30	50
212	POWER STATION/POWER SUBSTATION/POWER SHED	2000	5	10	20	50
213	MONUMENT	100	5	15	40	50
215	NURSERY GREENHOUSE	10	5	20	40	60
216	STABLE/BARN/BREEDING FARM	10	5	15	40	60
217	TOWER/CHIMNEY	100	5	15	40	50
218	SILO	10	5	15	40	50
219	CROSS/TABERNACLE	10	5	10	40	40
223	HOSPITAL COMPLEX	4000	5	10	50	70
224	SCHOOL COMPLEX	4000	5	20	50	70
225	SPORT FACILITIES	100	5	10	25	50
226	RELIGIOUS BUILDING COMPLEX	4000	5	15	50	70
227	CIVIL COMPLEX	4000	5	15	30	50
228	CEMETARIAL COMPLEX	100	5	10	30	50
229	CAMPGROUND/RESORT	100	5	20	50	80
301	TOLLROAD/HIGHWAY	200	5	30	50	80
302	STATE HIGHWAY/PROVINCIAL HIGHWAY	100	5	40	60	100
303	PROVINCIAL ROAD	50	5	50	80	100
304	LOCAL ROAD	50	5	60	80	100

Catani et al., 2005

Physical vulnerability assessment

Vulnerability/fragility curves



Damage severity level	$\overline{\Delta}_i$ [cm]	β [cm]
D1 (very slight)	1,10	0.50
D2 (slight)	2,11	0.18
D3 (moderate)	3,08	0.24
D4 (severe)	3,67	0.31
D5 (very severe)	4,65	0.15

Peduto et al., 2017

Structural resistance

$$R_{\mathrm{str}} = \left(\xi_{\mathrm{sfd}} \cdot \xi_{\mathrm{sty}} \cdot \xi_{\mathrm{smn}} \cdot \xi_{\mathrm{sht}}\right)^{\frac{1}{4}}$$

Structural typology	Field name	ξ_{sty}
Lightest structures (simple timber constructions)	LT	0.10
Light structure	LS	0.20
Mixed structure (concrete and timber)	MS	0.40
Brick walls, concrete	BC	0.80
Reinforced concrete	RC	1.30
Reinforced	RF	1.50

State of maintenance	Field name	ξ_{smn}
Very poor	VP	0.10
Poor	P	0.40
Medium	M	0.80
Good	G	1.20
Very good	VG	1.50

Height	Field name	Number of storey	ξ_{sht}
Single-storey	S	1	0.10
Low-rise building	L	2	0.40
Medium-rise building	M	3,4,5	0.90
High-rise building	H	6+	1.50

Li et al., 2010

Risk equation

$$R = H \cdot V \cdot E$$

Risk = expected loss

Hazard = probability of occurrence

Vulnerability = loss degree

Elements at risk = value

Exposure of elements at risk

- The exposure of an element is determined by its position relative to the path of the landslide, which varies depending on the landslide kinematics

- **Population exposure**: the quantification is based on the number of human lives exposed

- **Physical assets** (buildings, infrastructure, or agricultural areas): exposure is determined by their monetary value

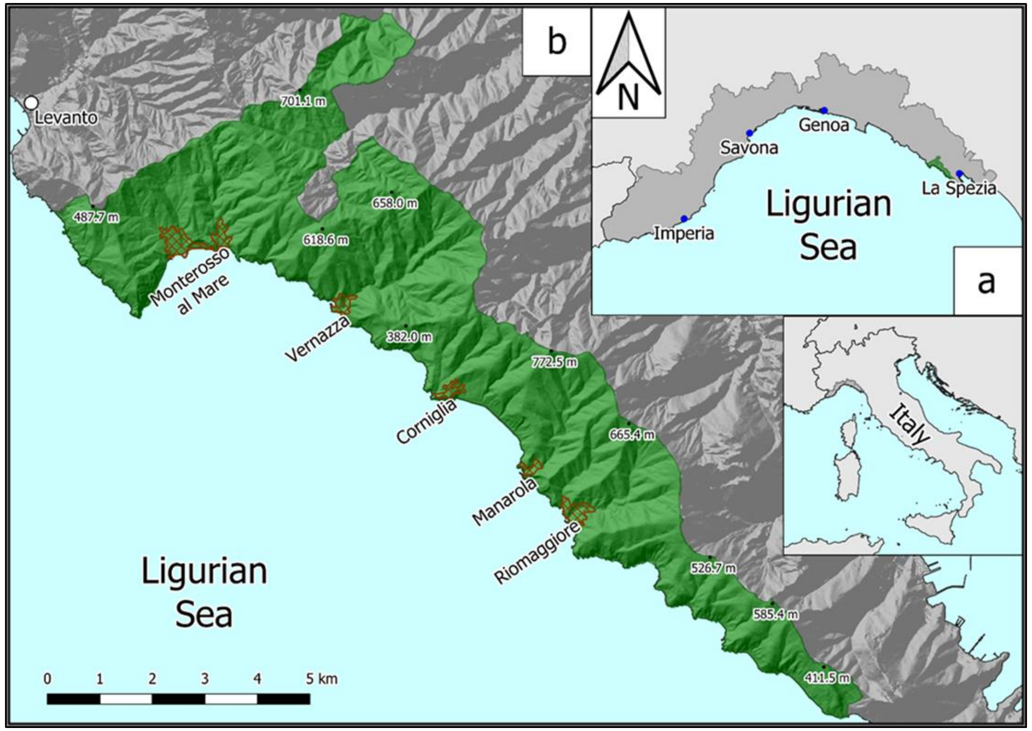
Case studies

- Susceptibillity analysis

- Risk analysis at regional scale

- Risk analysis at national scale

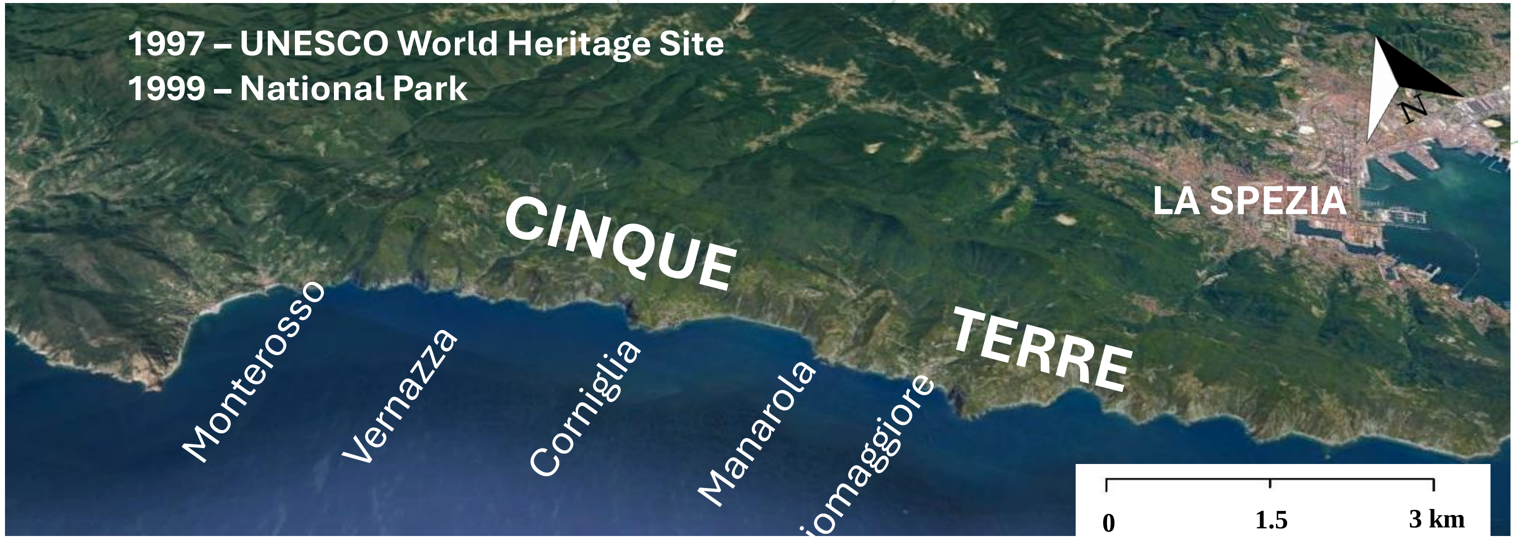
Case studies –Landslide susceptibility



Di Napoli et al., 2021

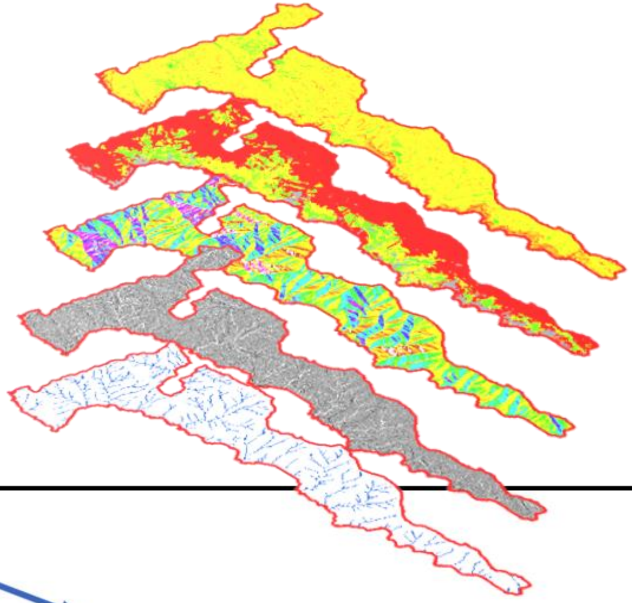
Cinque Terre National Park

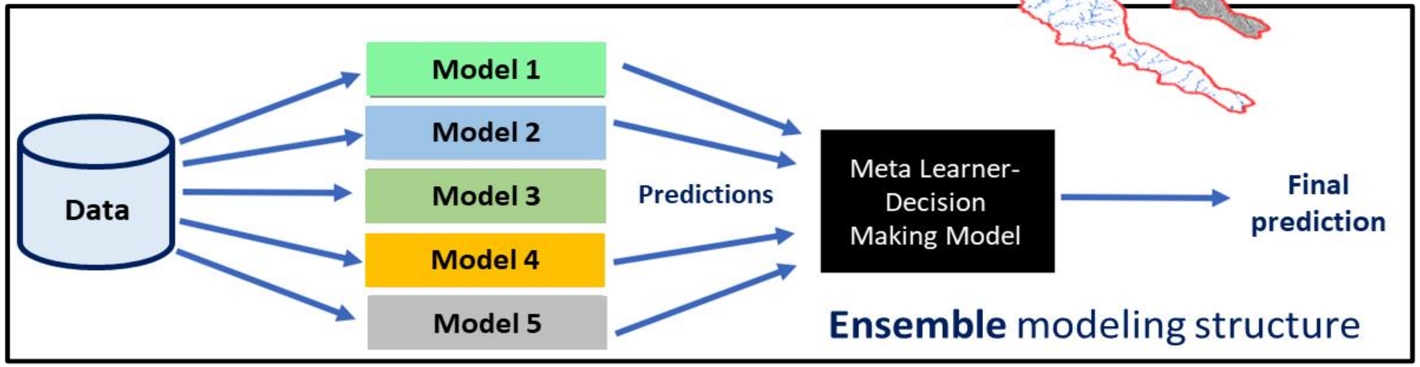
- Area: 38.44 km2
- 5 hamlets (Monterosso, Vernazza, Corniglia, Manarola, Riomaggiore)
- Residents: 4373
- Millions of tourists visit the Cinque Terre every year

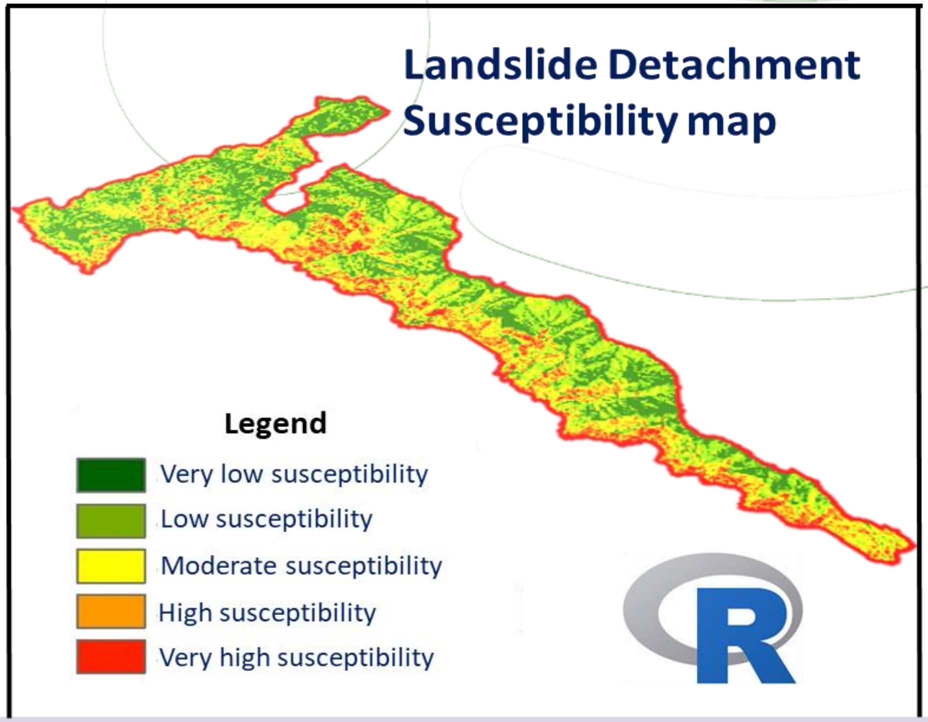


Case study – Cinque Terre – Machine learning

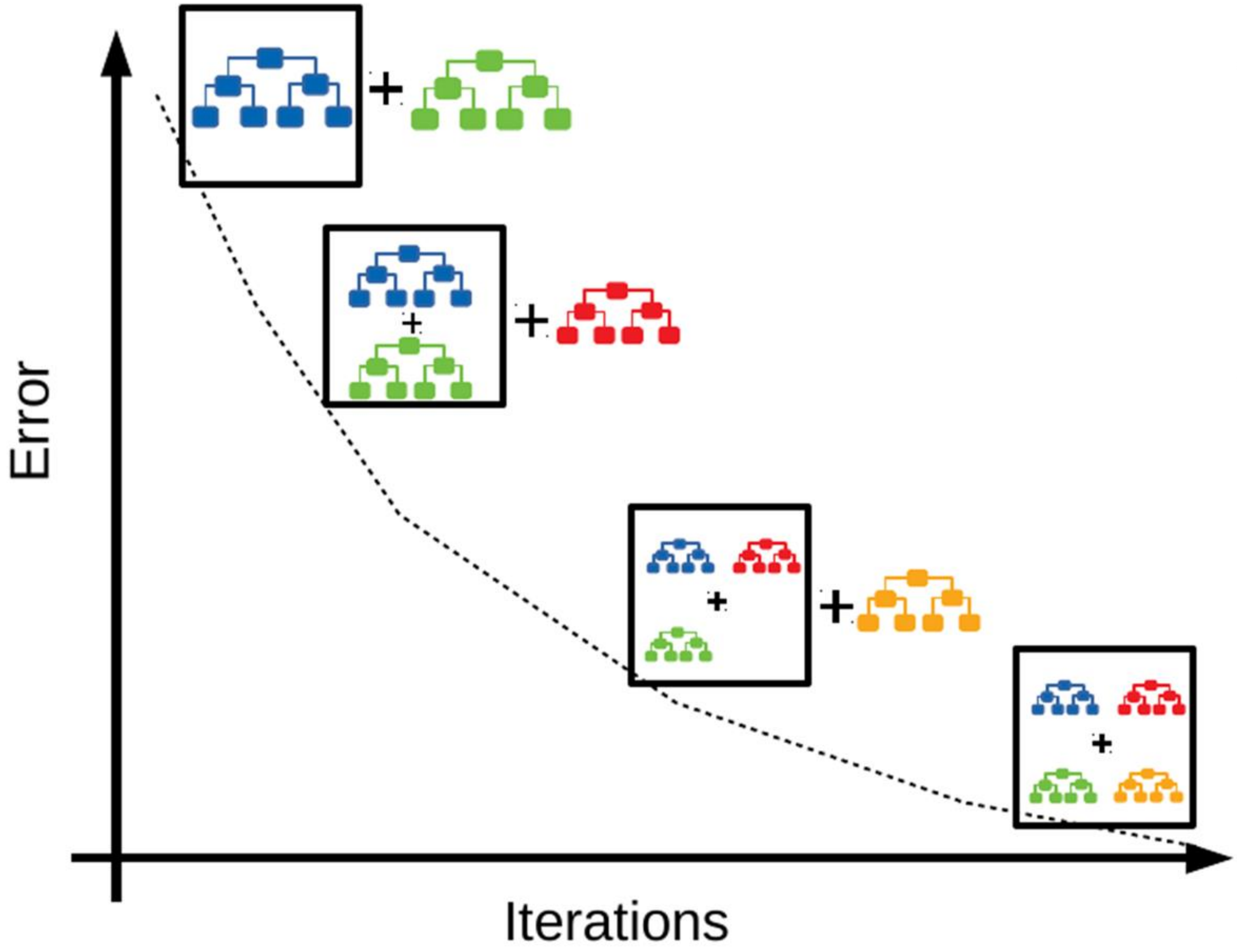
- Y = Response or dependent variable (landslide inventory map)
- X = Independent or predisposing variable (slope, aspect, drainage density, soil moisture index, degree of abandonment of agricultural terraces)
- Machine Learning models:
- Generalized Boosting Model
- Artificial Neural Network
- Maximum Entropy (MaxEnt)

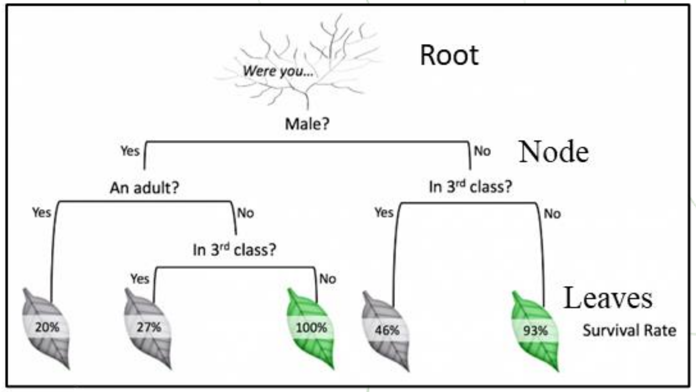






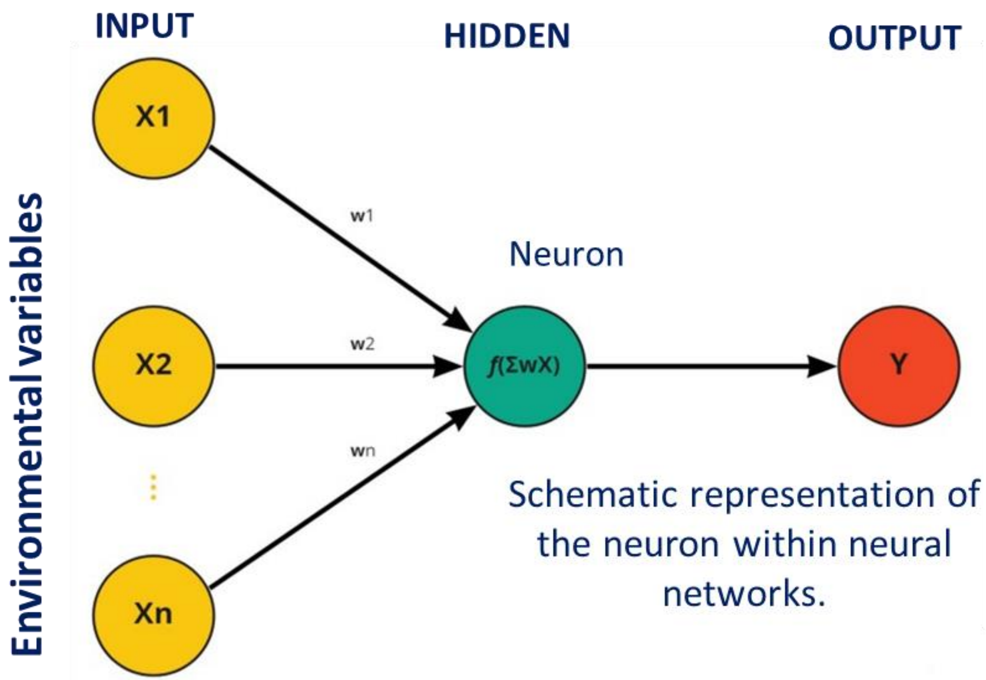
Case study – Cinque Terre – GBM



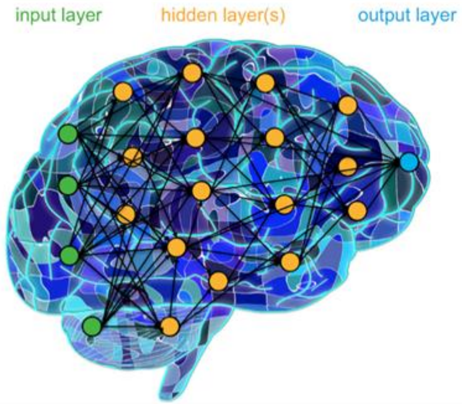


- Generalized Boosting Models repeatedly fit many decision trees to improve the accuracy of the model.

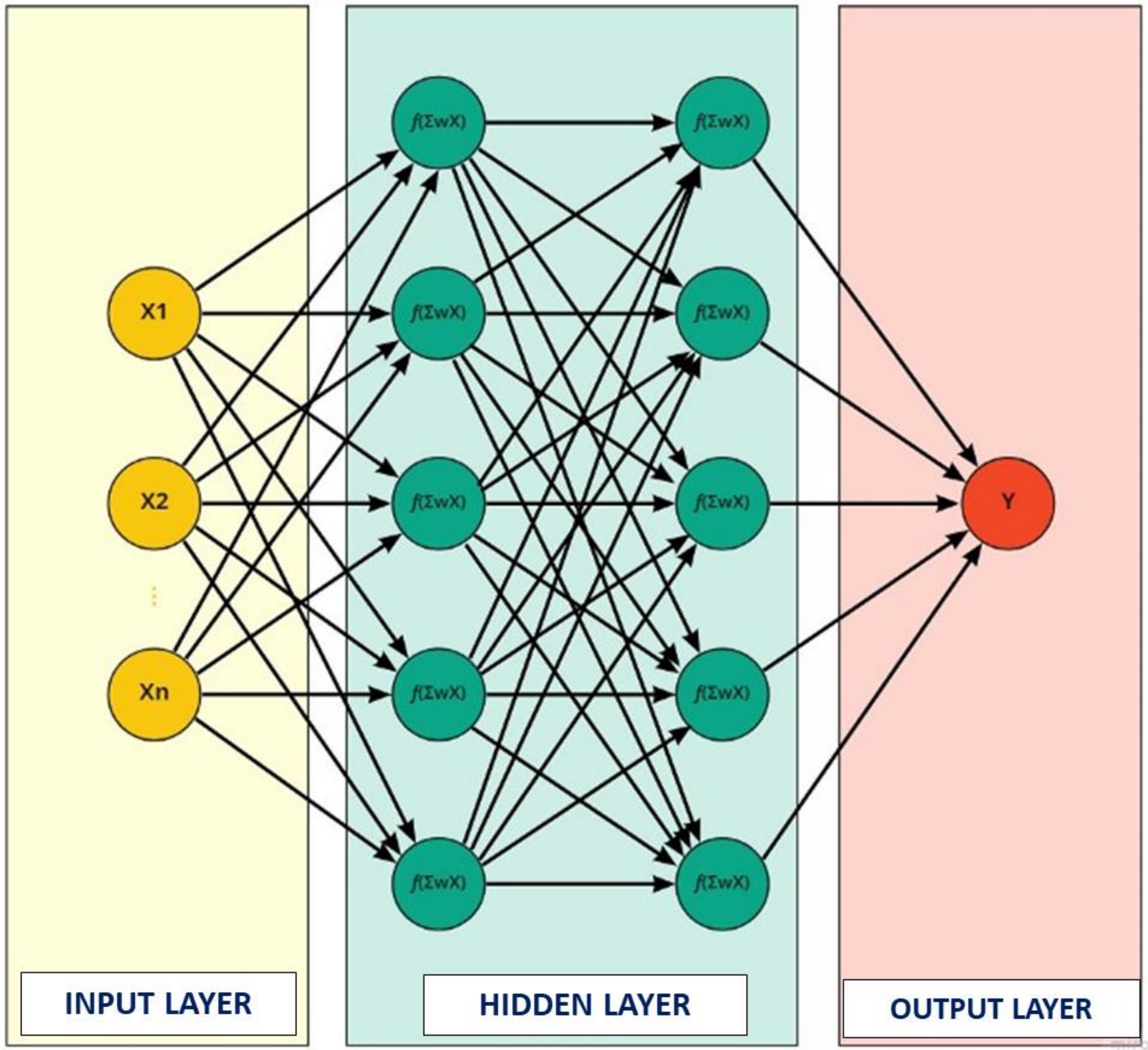
Case study – Cinque Terre – ANN



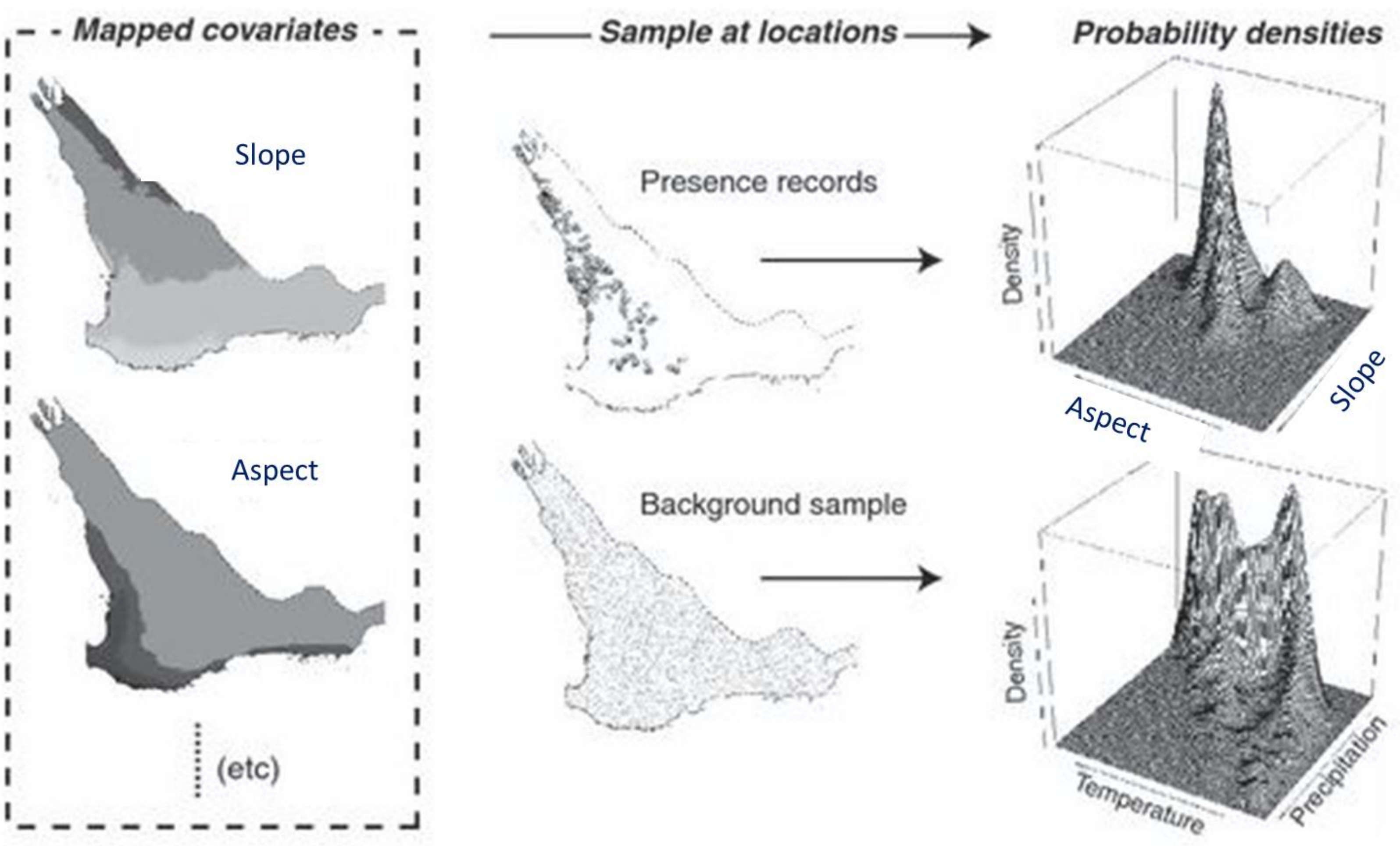
Schematic representation of the neuron within neural networks.



Neural network structure.

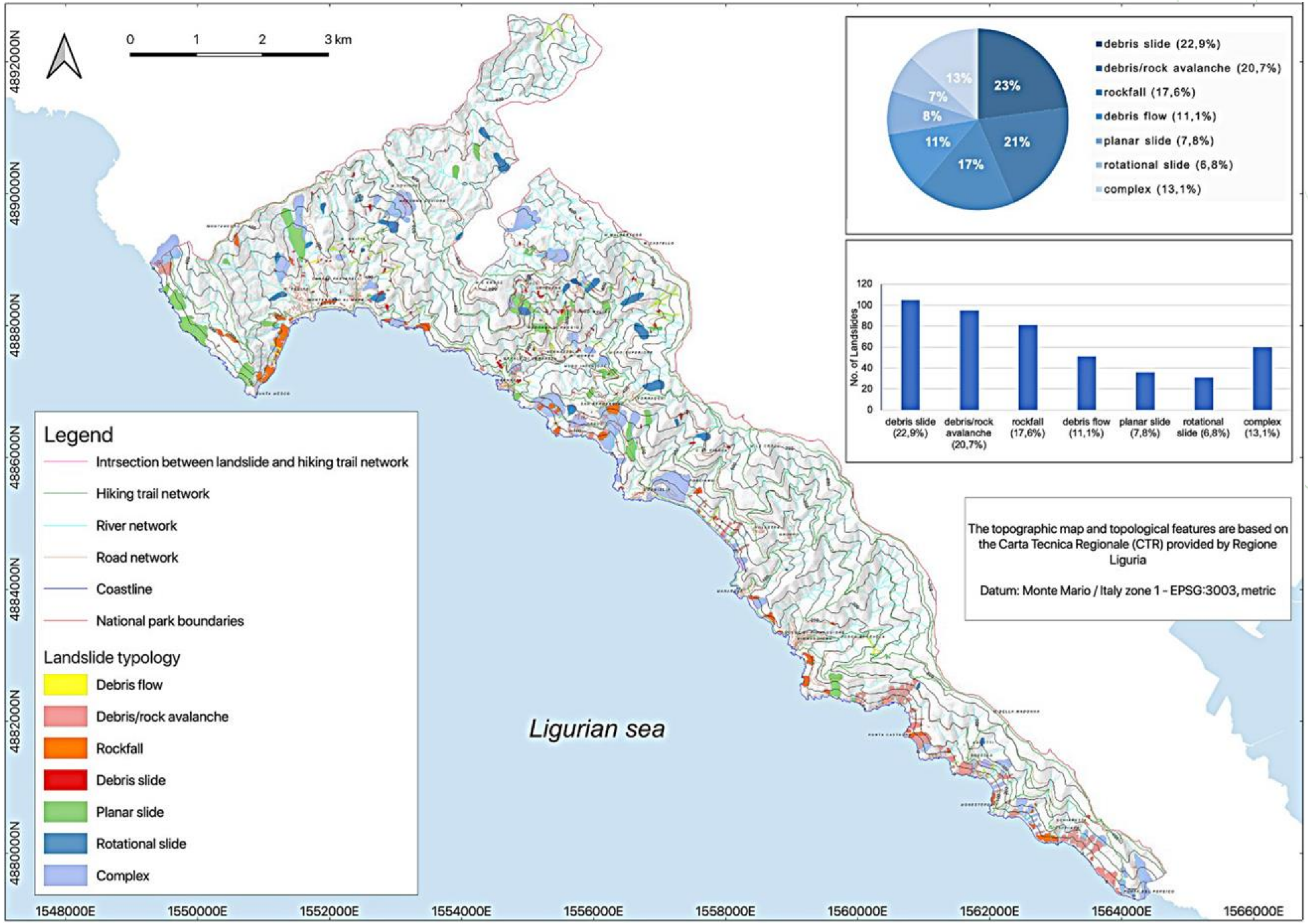


Case study – Cinque Terre – MAXENT



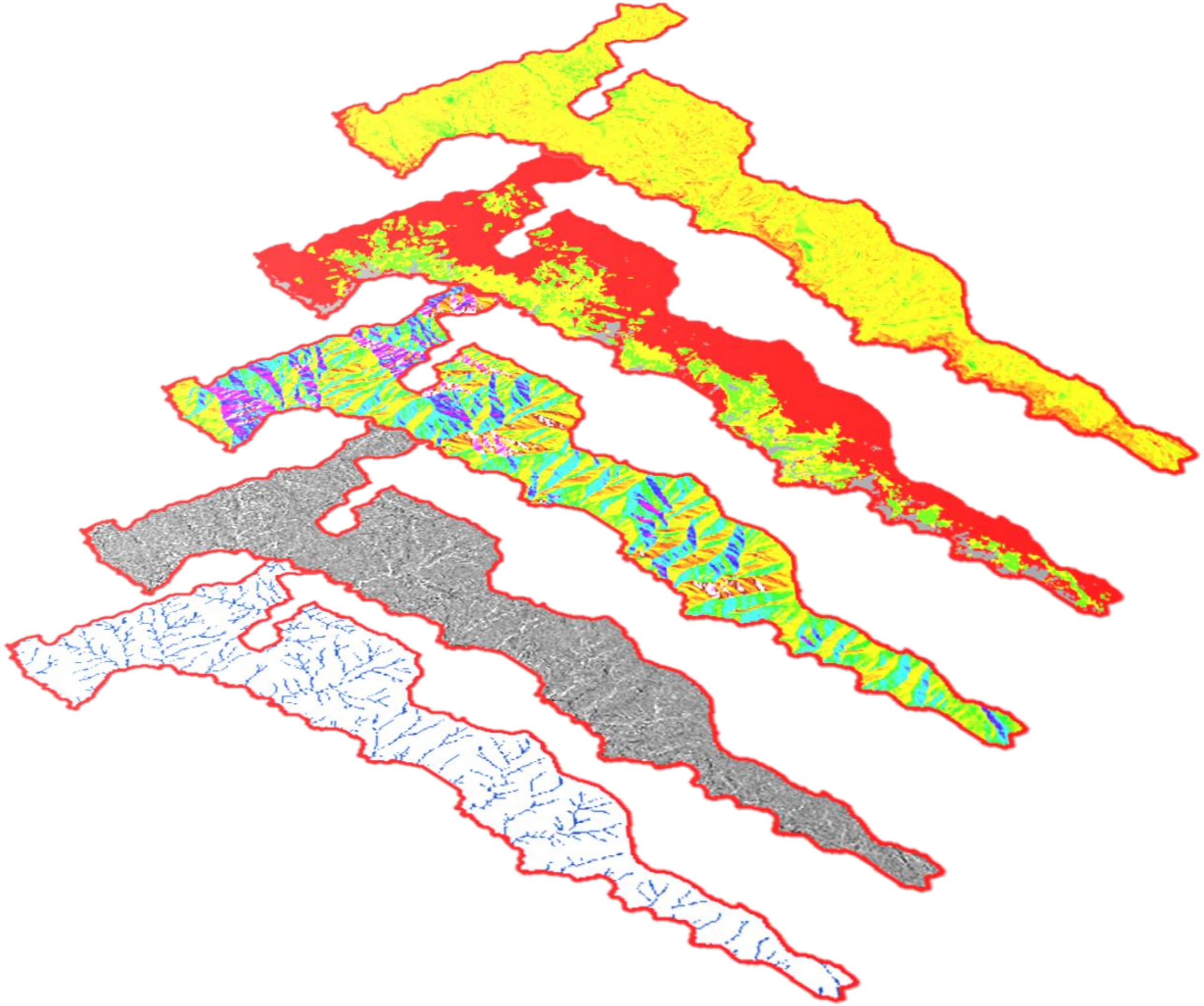
- Schematic representation of the MaxEnt algorithm.

Case study – Cinque Terre – Landslide Inventory



Landslide inventory of the Cinque Terre National Park and diagrams showing the percentage of catalogued landslides for each typology (from Raso et al. 2019).

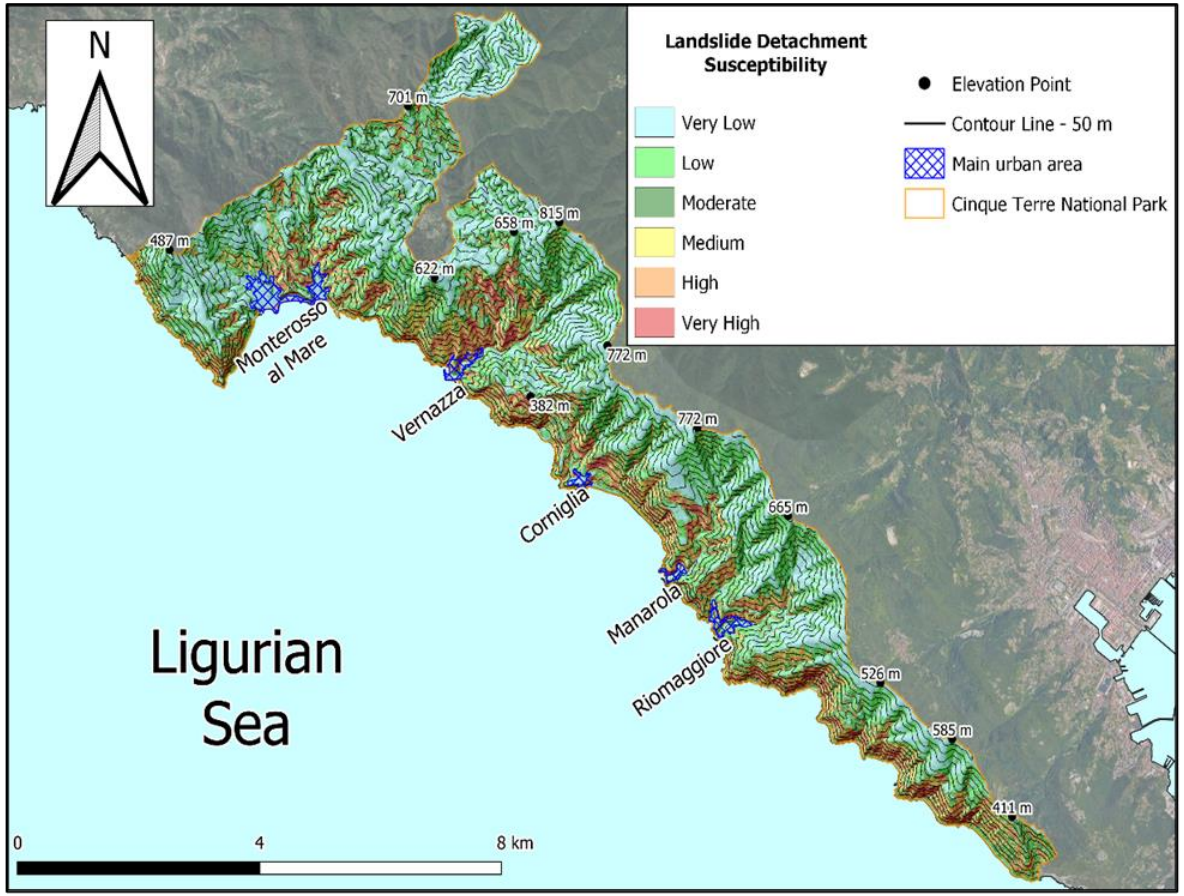
Case study – Cinque Terre – Predisposing factor



Predisposing factors:

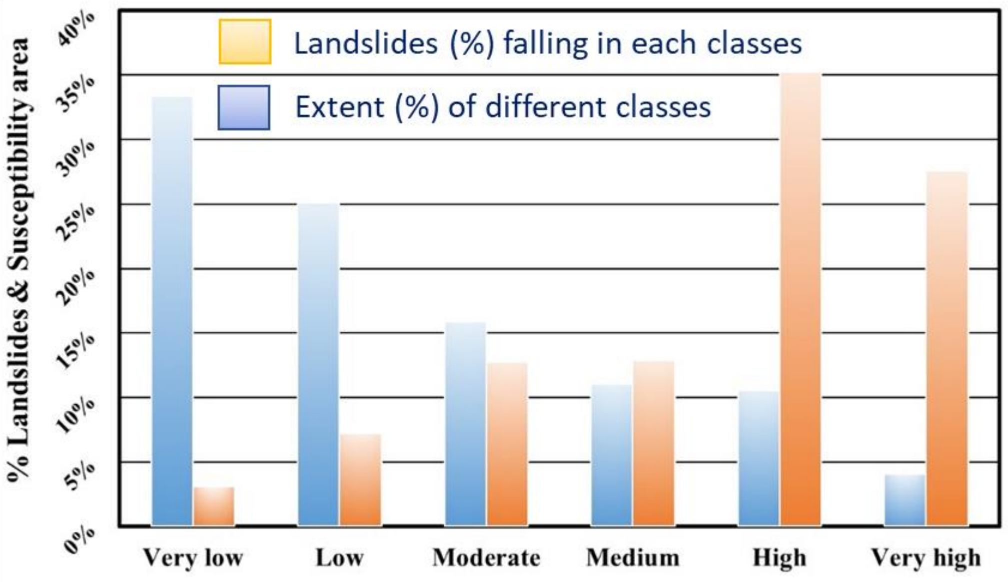
- Slope angle;
- Slope aspect;
- Planform curvature;
- Profile curvature;
- Distance to roads;
- Distance to streams;
- Agricultural terraces state of activity;
- Land use;
- Geolithological map.

Case study – Cinque Terre – Ensembled map



Landslide Detachment Susceptibility (LDS) map of the Cinque Terre National Park obtained with Machine Learning algorithms

Results of the statistical analysis (Ensemble Weighted mean method)



Stand-alone methods	AUC
GBM	0.78
ANN	0.74
MaxEnt	0.80
Ensemble methods	AUC
Mean	0.89
CA	0.86
Median	0.87
Wmean	0.90

AUC values for Machine Learning algorithms used for both stand-alone and ensemble methods

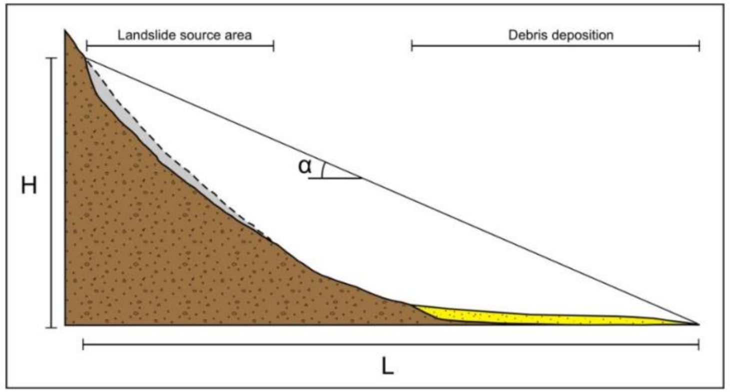
Case study – Cinque Terre – Variable importance

		Stand-alone models		
		GBM	ANN	MaxEnt
Predisposing factors	aspect	0.23	0.4	0.25
	plan_curv	0.11	0.2	0.13
	prof_curv	0.032	0.11	0.07
	slope	0.24	0.28	0.23
	geological	0.035	0.07	0.08
	terraces	0.38	0.37	0.31
	land_use	0.087	0.11	0.06
	streams	0	0.03	0.02
	roads	0	0.01	0.012

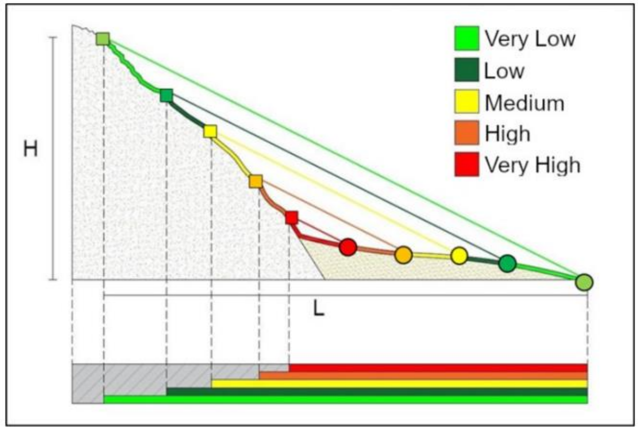
		Ensemble models		
		Mean	Wmean	Median
Predisposing factors	aspect	0.24	0.24	0.25
	plan_curv	0.12	0.12	0.12
	prof_curv	0.04	0.04	0.04
	slope	0.22	0.22	0.245
	geological	0.04	0.04	0.05
	terraces	0.38	0.38	0.37
	land_use	0.06	0.06	0.06
	streams	0	0	0
	roads	0	0	0

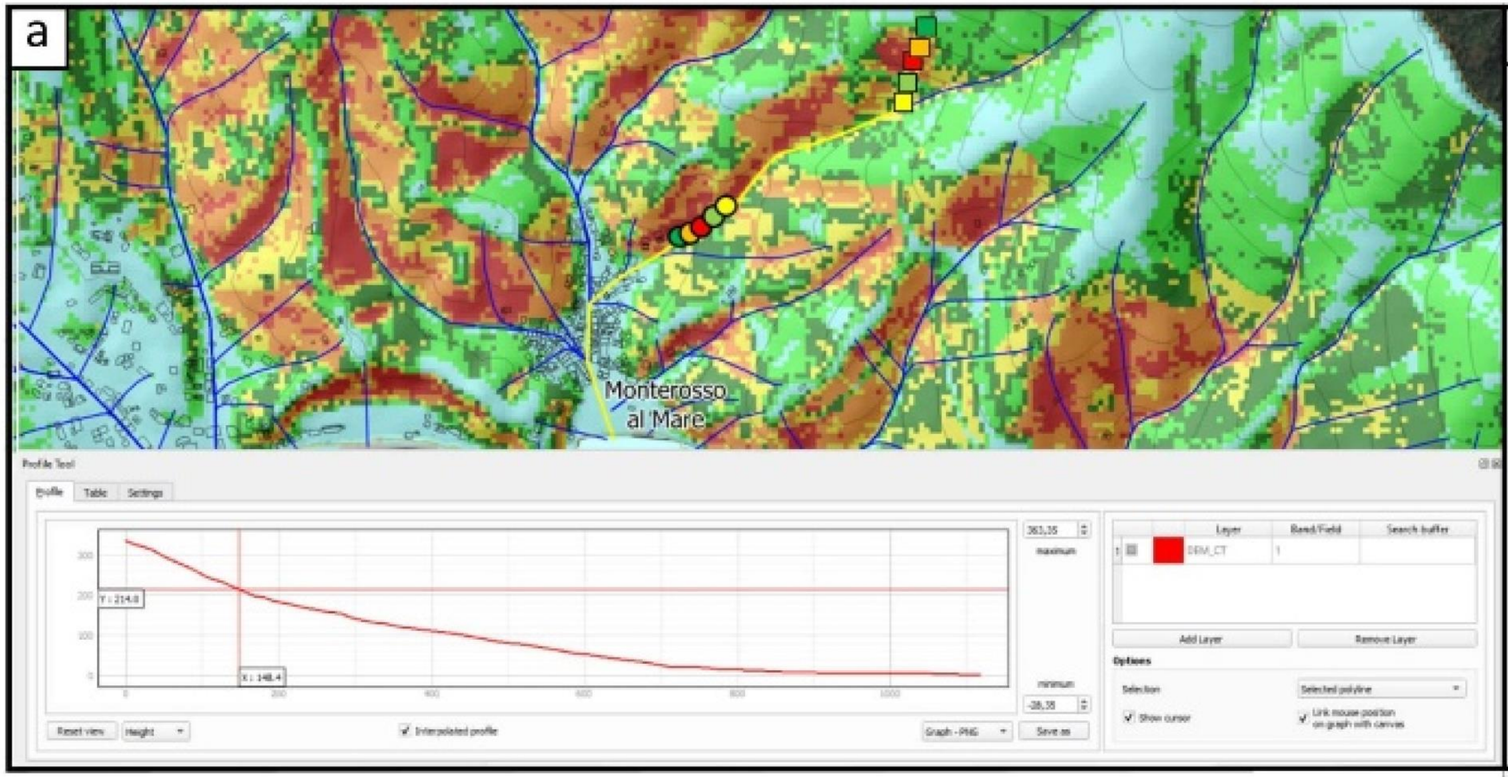
- Variables' importance values of stand-alone and ensemble models.

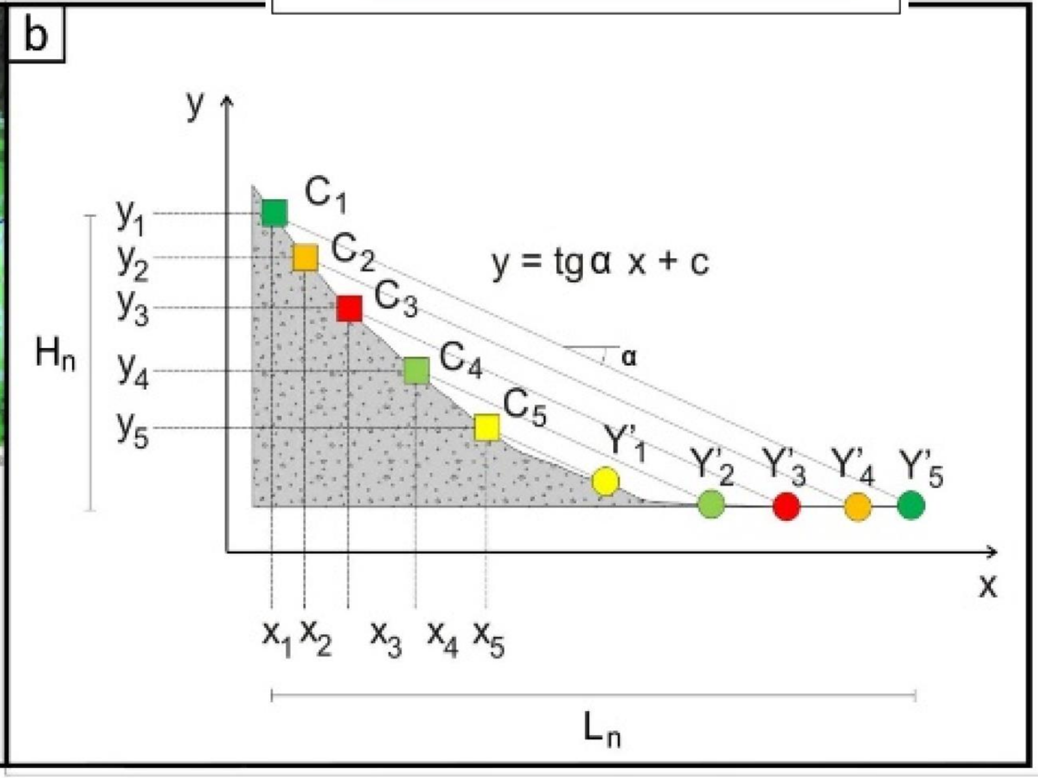
Case study – Cinque Terre – Run-out estimation



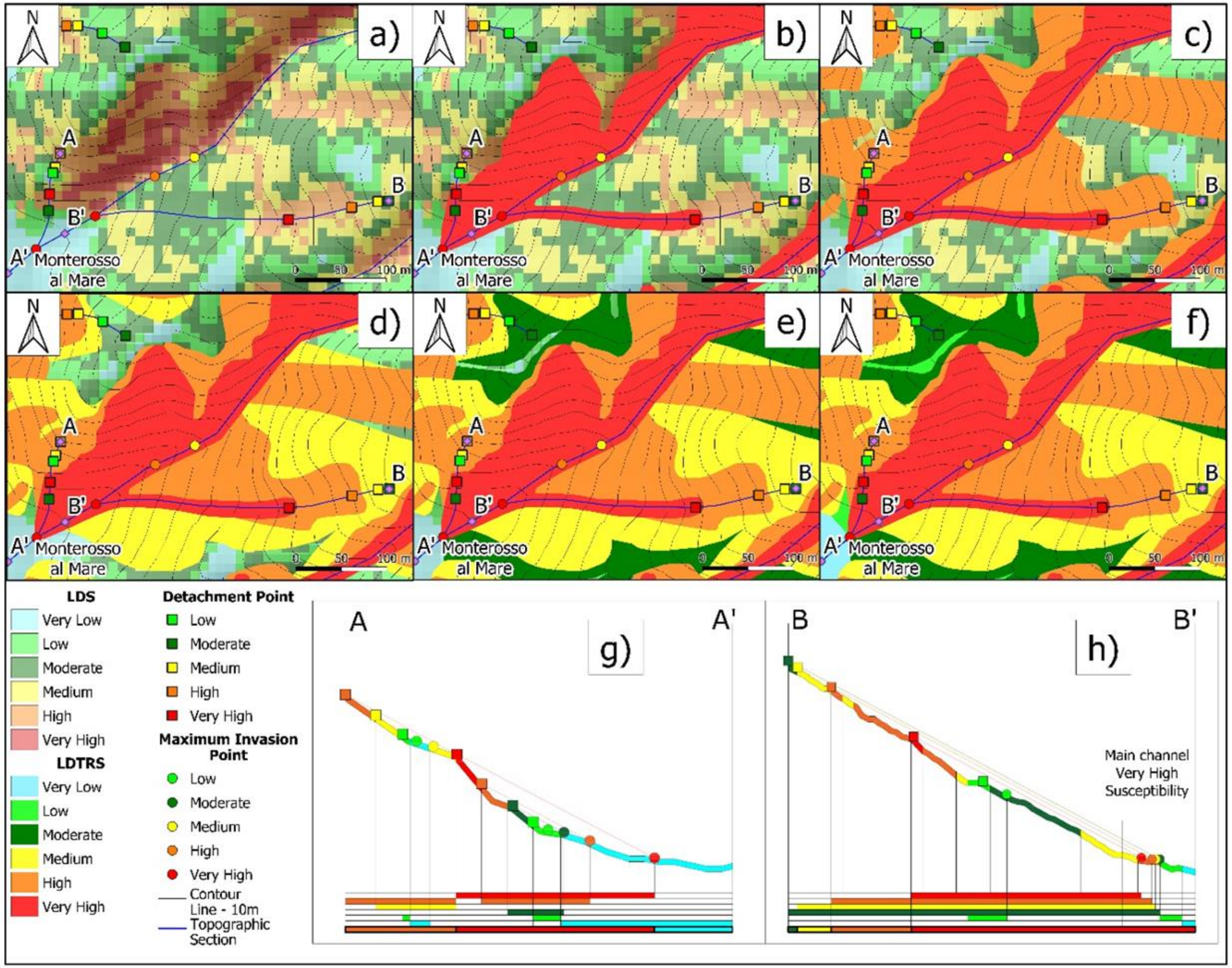
Reach angle method



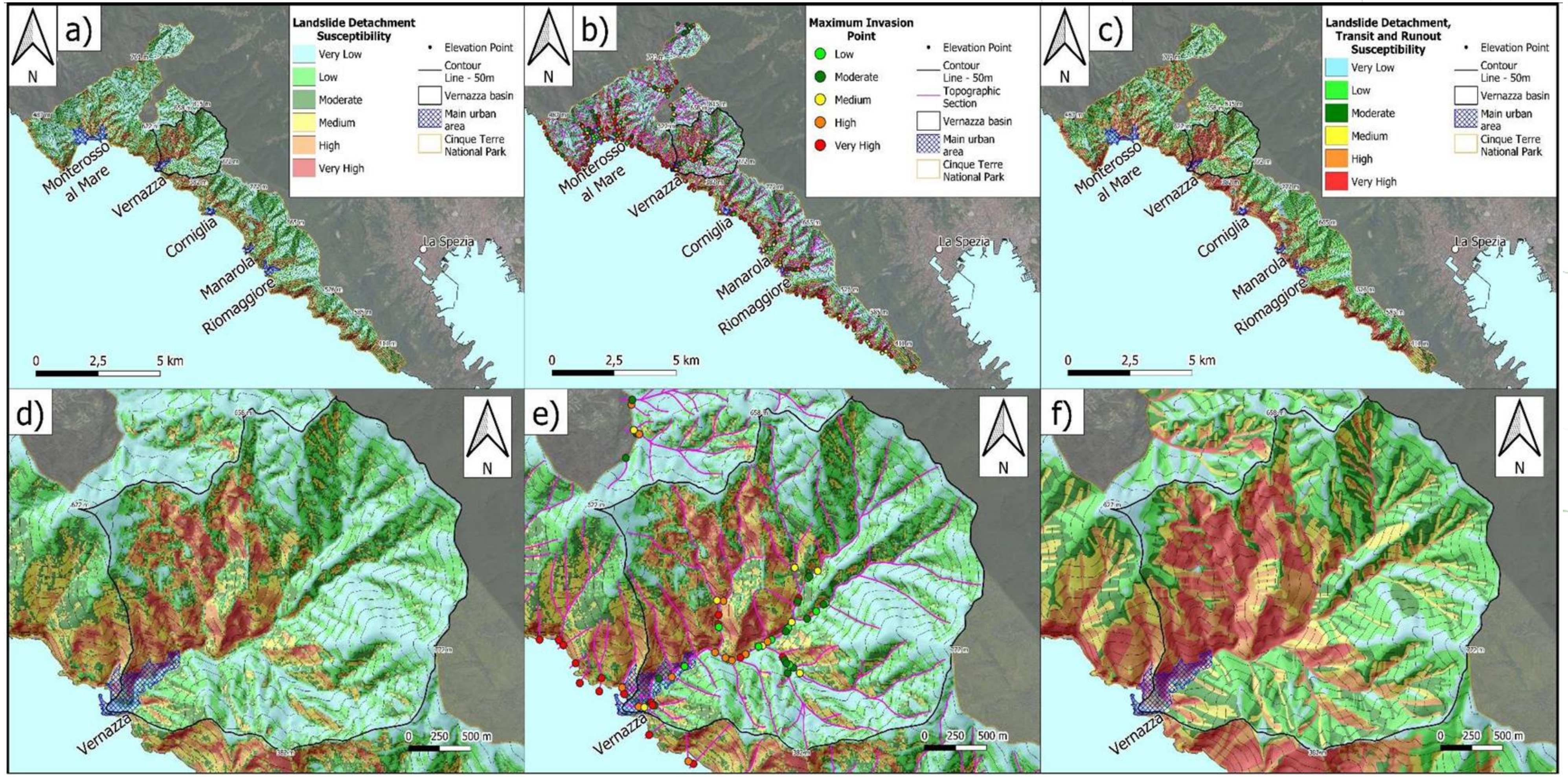




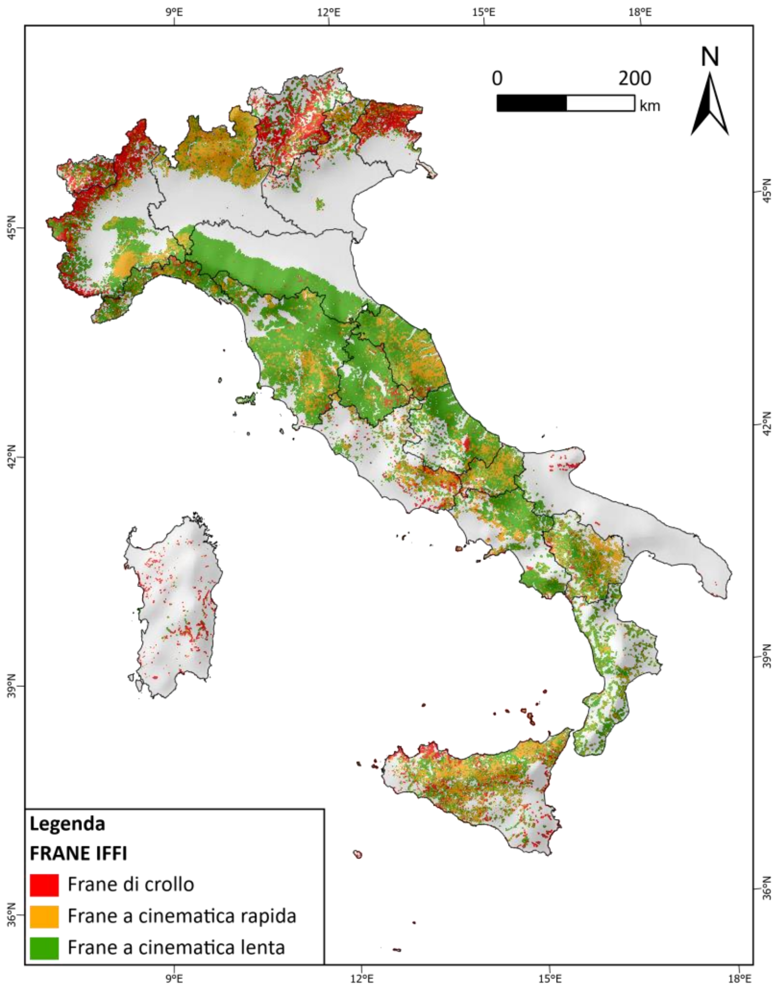
Case study – Cinque Terre – Run-out estimation

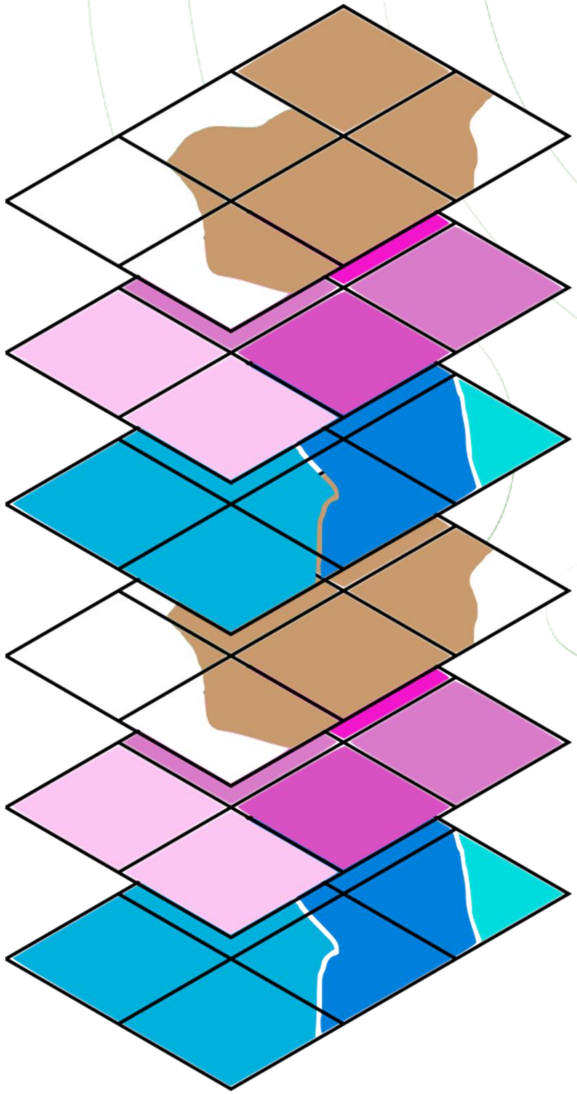


Case study – Cinque Terre – Run-out estimation



Landslide susceptibility and risk at national scale





QRA at basin scale
Italy
Caleca et al. 2022

Arno basin case study

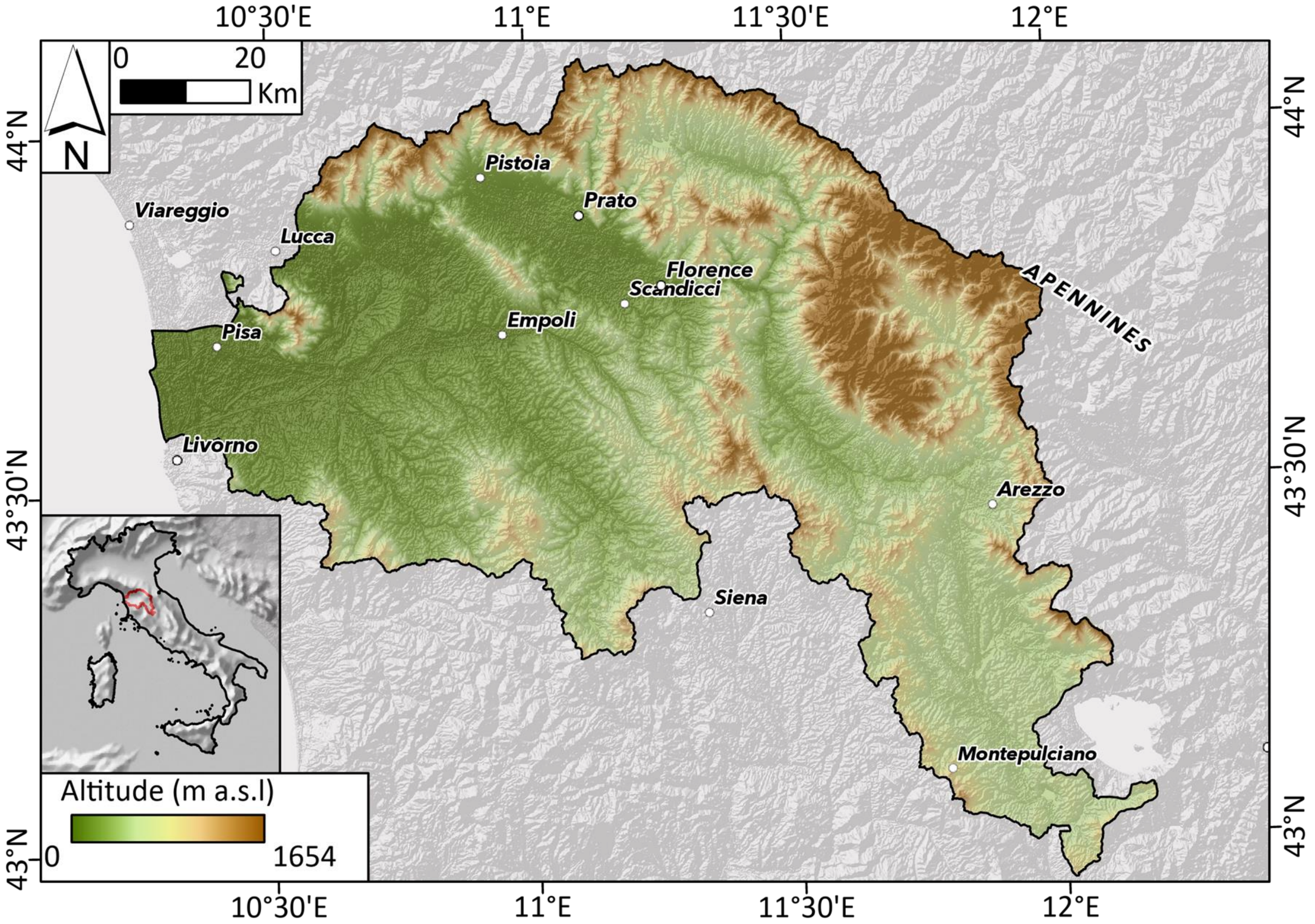
Objectives

- Implement an approach to quantitatively assess risk for slow-moving landslides in terms of possible economic losses to buildings and land use
- Define a replicable nationwide (Italy) methodology
- Verify the soundness of outcomes

Motivation and research question

- Risk assessment is a powerful tool for measuring the severity of landslides to properties and population, allocate resourses and define priorities of intervention
- QRA studies are generally focused on site specific or limited area cases
- Can we go beyond this ‘’limit’’ of the scale of analysis?

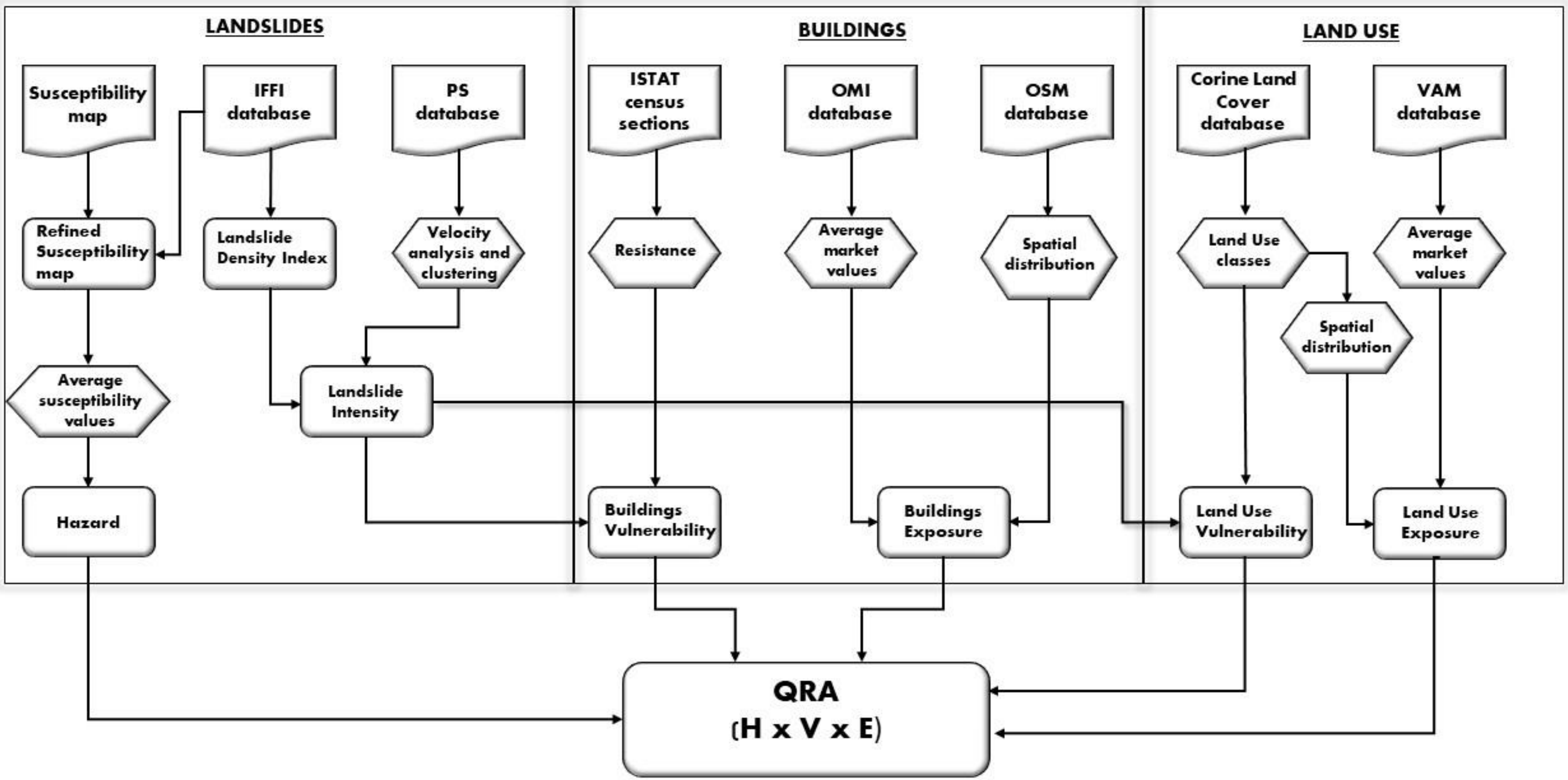
Arno basin case study



Arno River basin (9100 km^2)

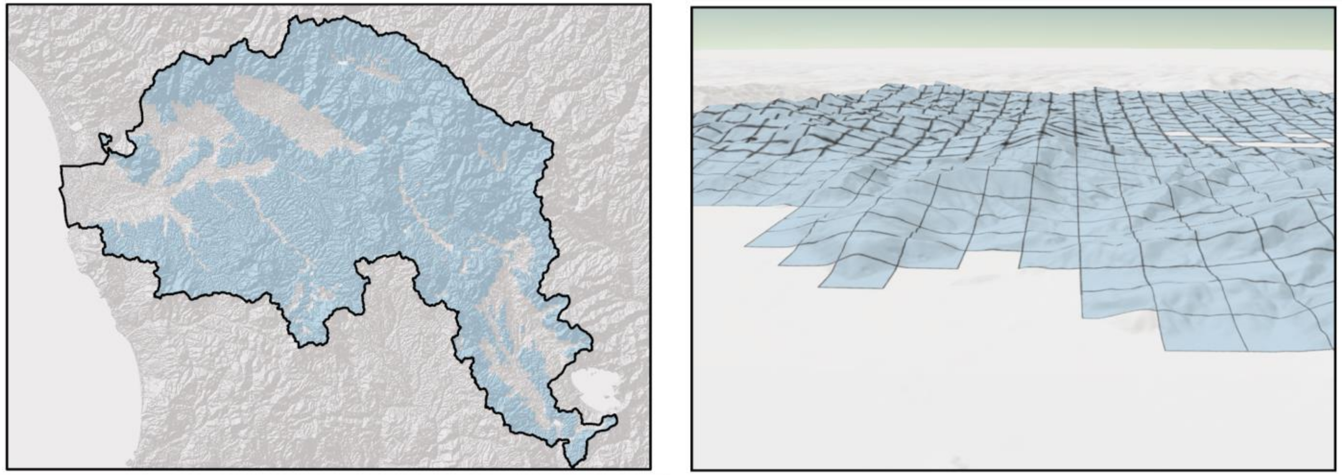
Input data	Parameter
DTM (10m)	**Grid analysis**
Italian landslide inventory (IFFI)	**Hazard and Intenisty**
Landslide susceptibility map of Italy	**Hazard**
Satellite InSAR data	**Intensity**
ISTAT census sections	Building structural resistance – **Building Vulnerability**
Real estate market observatory (OMI)	Building values (€) – **Building Exposure**
Open Street Map	Building footprint – **Building Exposure**
CORINE Land Cover	Land use spatial distribution – **Land use Vulnerability and Exposure**
Mean Agricultural Values (VAM)	Land use values (€) – **Land use Exposure**

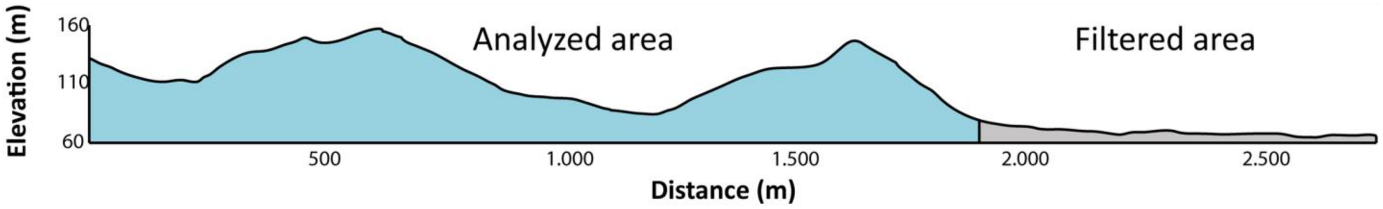
Arno basin case study – Methodology

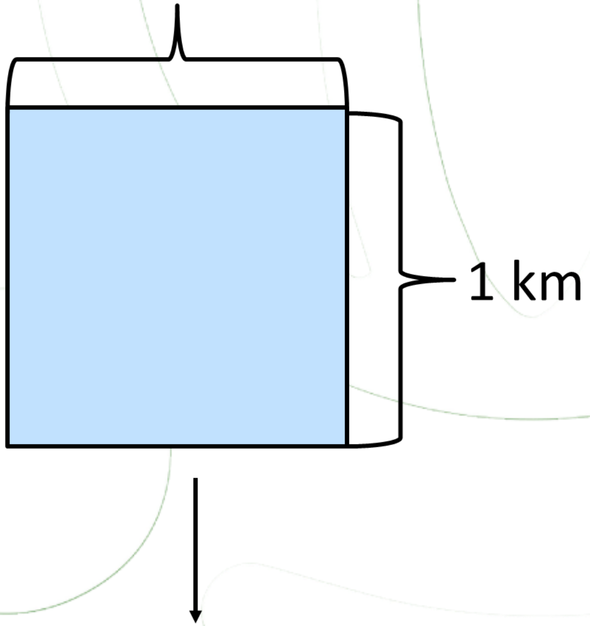


Arno basin case study – Mapping unit

- Regular grid with 1 km^2 spatial resolution
- Flat areas removed





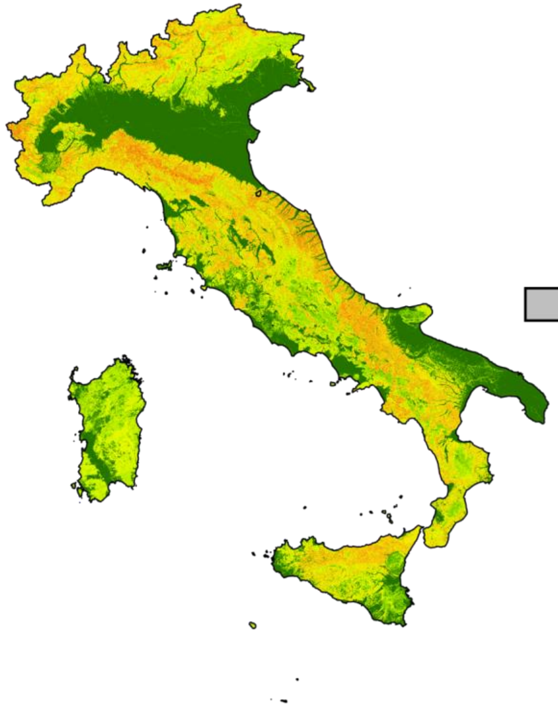


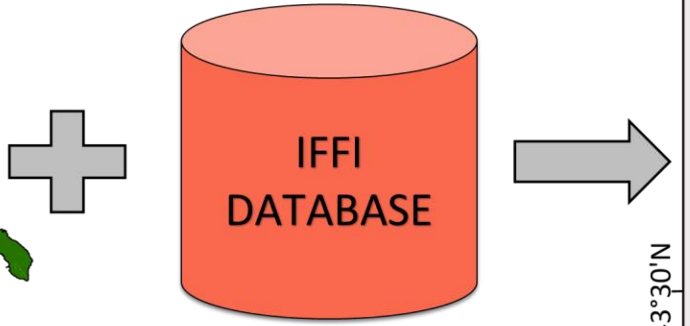
Risk = H x V(I) x E

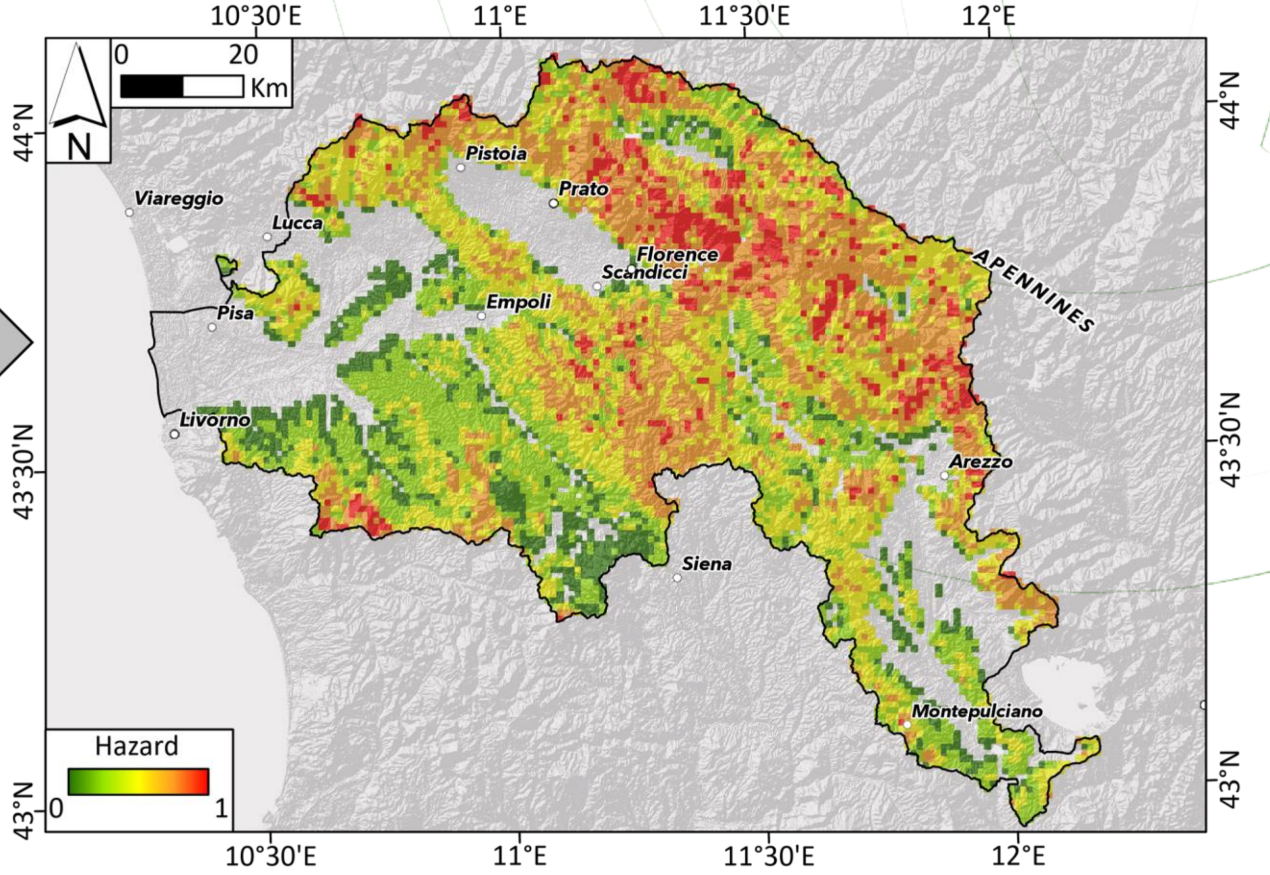
H = Hazard
V = Vulnerability
I = Intensity
E = Exposure

Arno basin case study – Hazard

Hazard was approximated to Susceptibility.





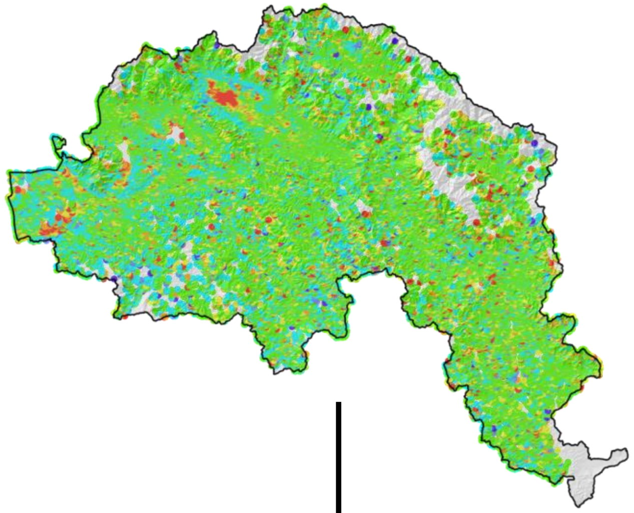


Map from Trigila et al. (2013)

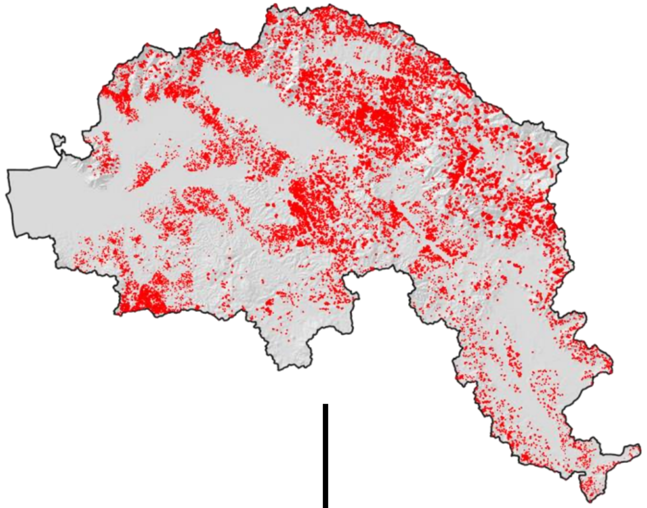
Arno basin case study – Vulnerability – Landslide Intensity

Vulnerability = f (Landslide Intensity, Response of exposed element)

- where **Landslide Intensity** = f (Landslide Area, Landslide Velocity)



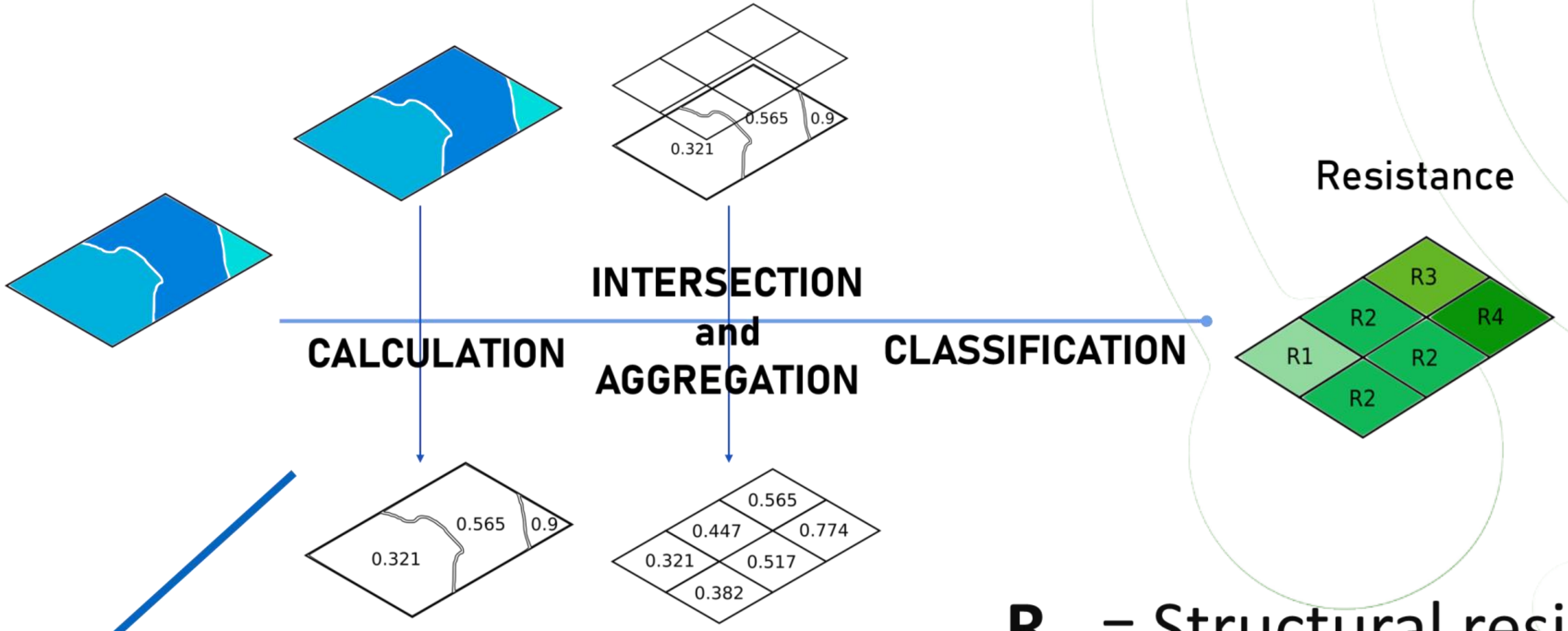
Ground deformation velocity



Landslide area

	Vel < 4mm/yr	4mm/yr < Vel < 16mm/yr	Vel > 16mm/yt	No Vel
A0	I0	I1	I2	I0
A1	I1	I2	I3	I1
A2	I2	I3	I4	I2
A3	I3	I4	I4	I3

Arno basin case study – Vulnerability – Building structural resistance



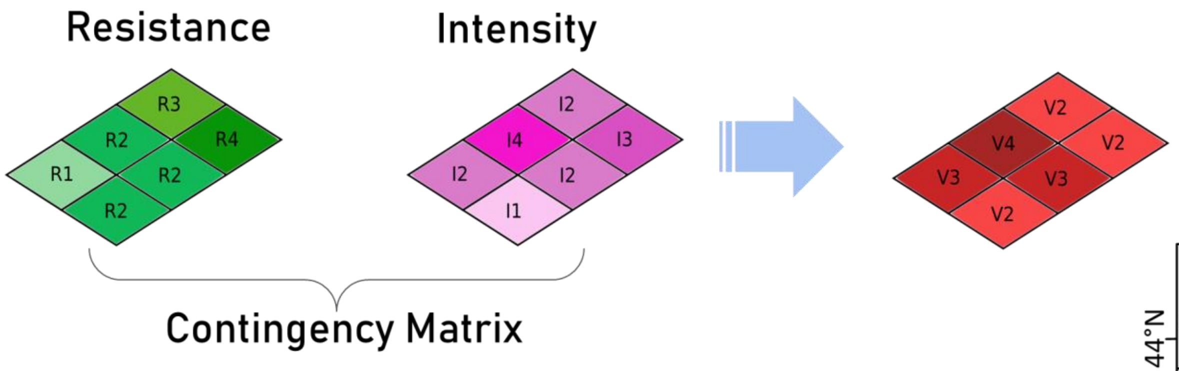
$$R_{str} = (\varepsilon_{sty} \cdot \varepsilon_{sht} \cdot \varepsilon_{smn})^{1/3}$$

Modified from Li et al., 2010

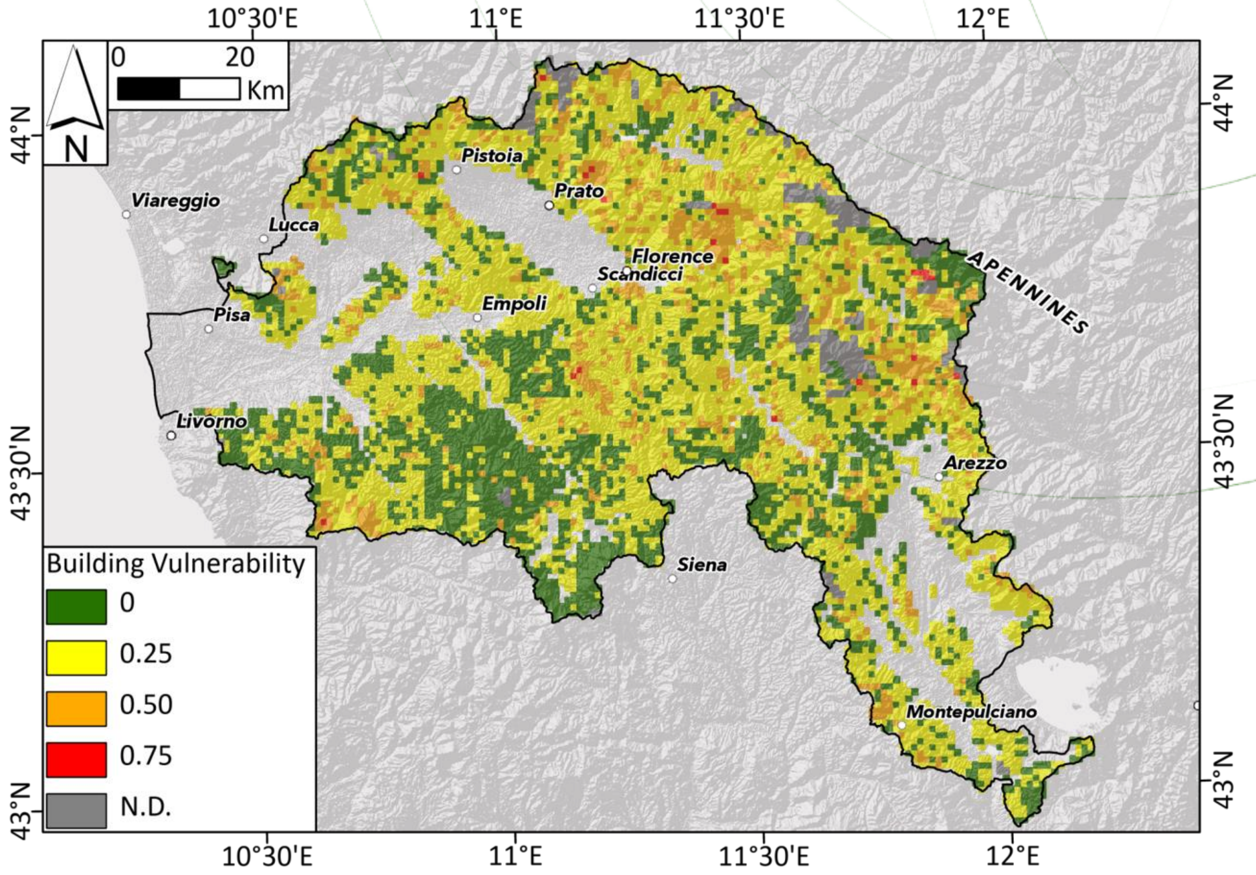
R_{str}= Structural resistance

ξ_{sty}= type of material construction
ξ_{sht}= number of floors
ξ_{smn}= maintenance state

Arno basin case study – Building Vulnerability



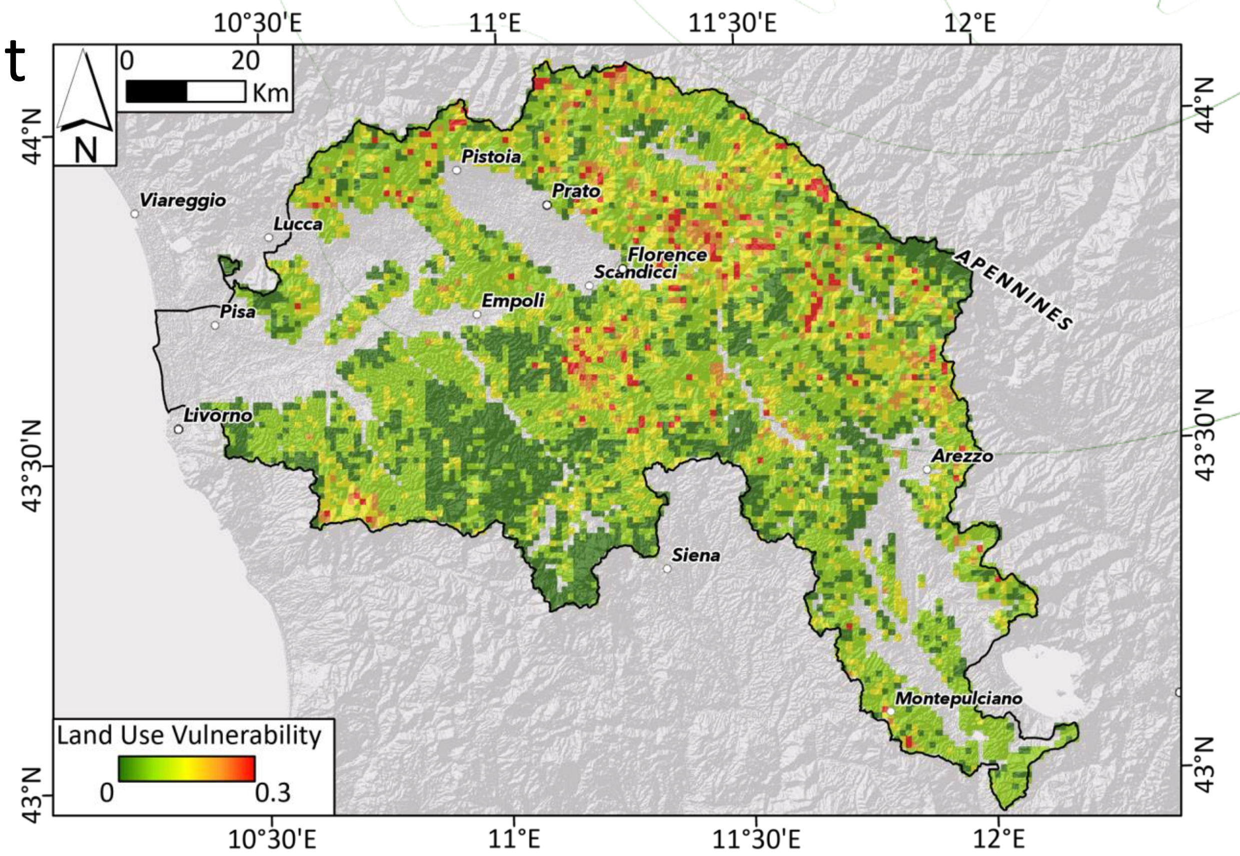
	I0	I1	I2	I3	I4
R4	0	0.25	0.25	0.50	0.75
R3	0	0.25	0.50	0.75	1
R2	0	0.50	0.75	0.75	1
R1	0	0.50	0.75	1	1
R0	0	0.75	1	1	1
N.D.	N.D.	N.D.	N.D.	N.D.	N.D.



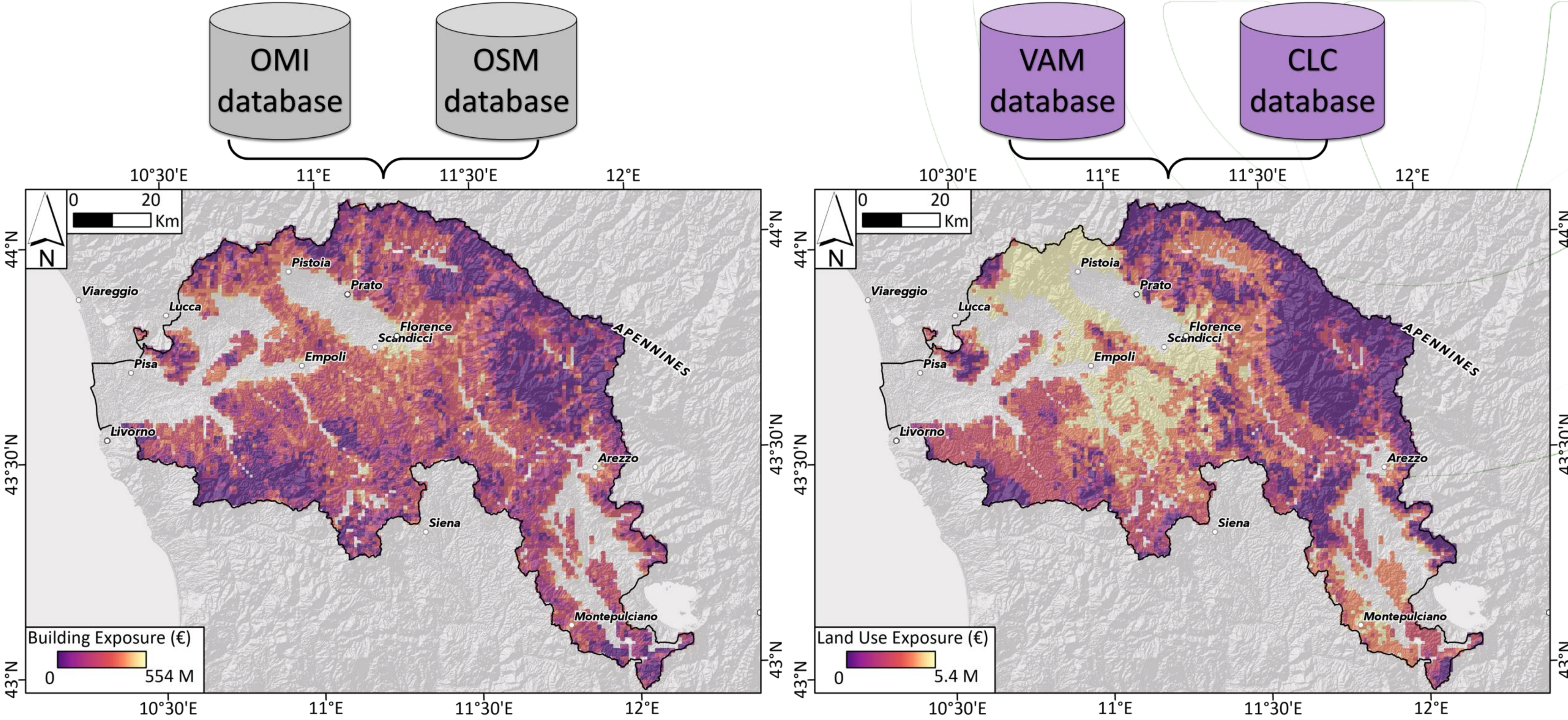
Arno basin case study – Land Use Vulnerability

- Reclassification CORINE Land Cover into 6 classes
- Definition of a vulnerability value for each class
- Vulnerability of land use within mapping unit

	I0	I1	I2	I3	I4
Agricultural Areas	**0**	**0.05**	**0.15**	**0.2**	**0.25**
Permanent Crops	**0**	**0.05**	**0.1**	**0.2**	**0.3**
Grasslands	**0**	**0.05**	**0.1**	**0.15**	**0.2**
Woods	**0**	**0.05**	**0.1**	**0.2**	**0.3**
Shrubs	**0**	**0**	**0**	**0.05**	**0.1**
Water	**0**	**0**	**0**	**0.05**	**0.1**

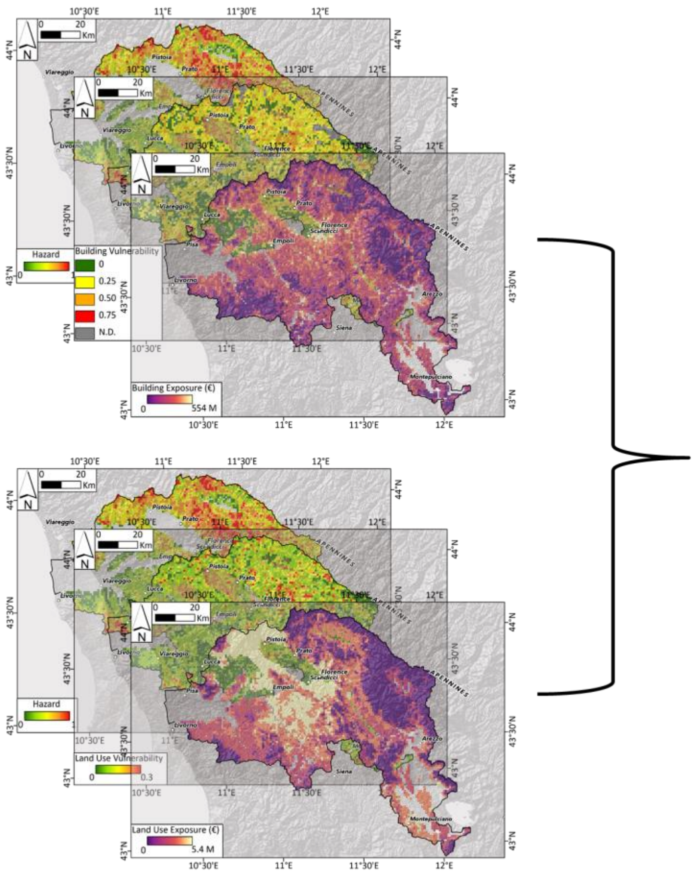


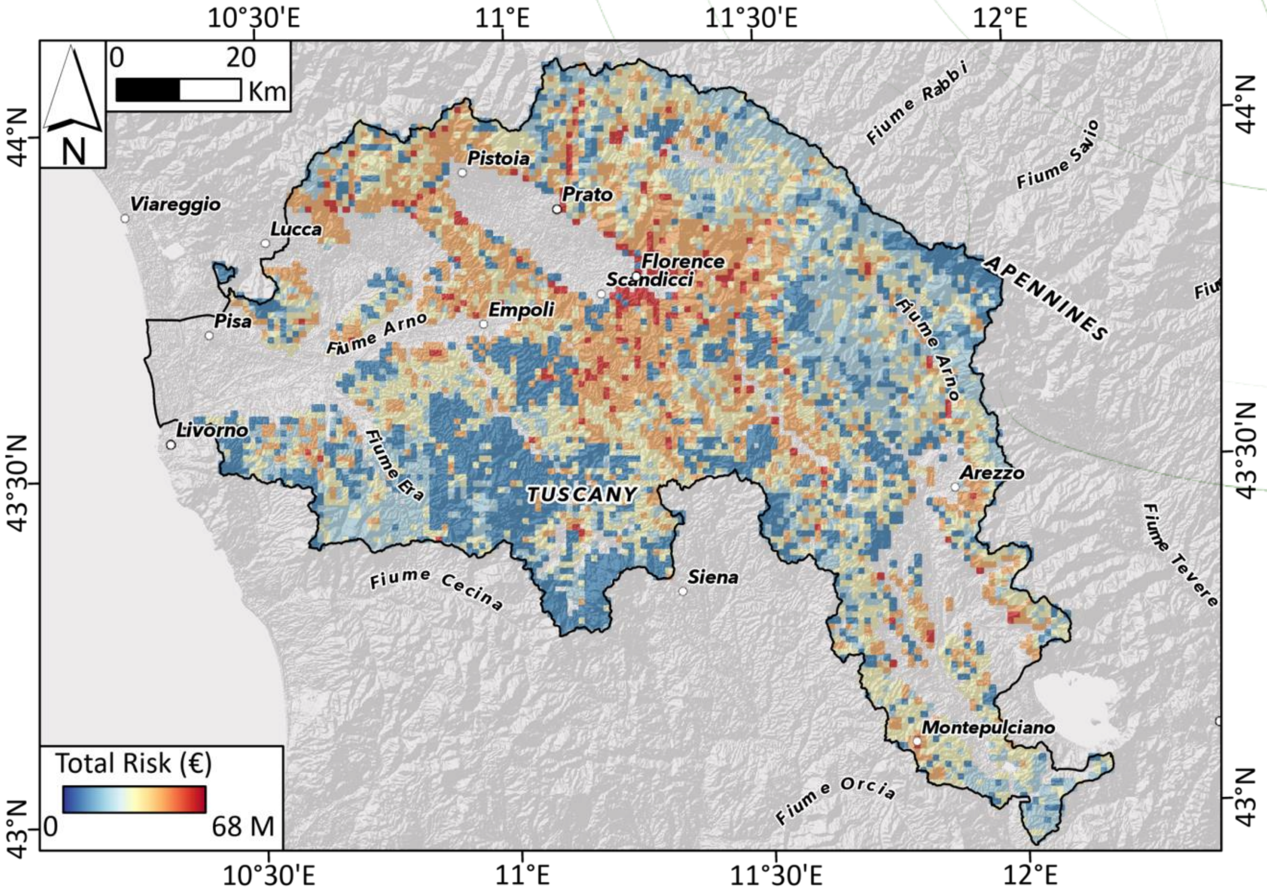
Arno basin case study – Exposure



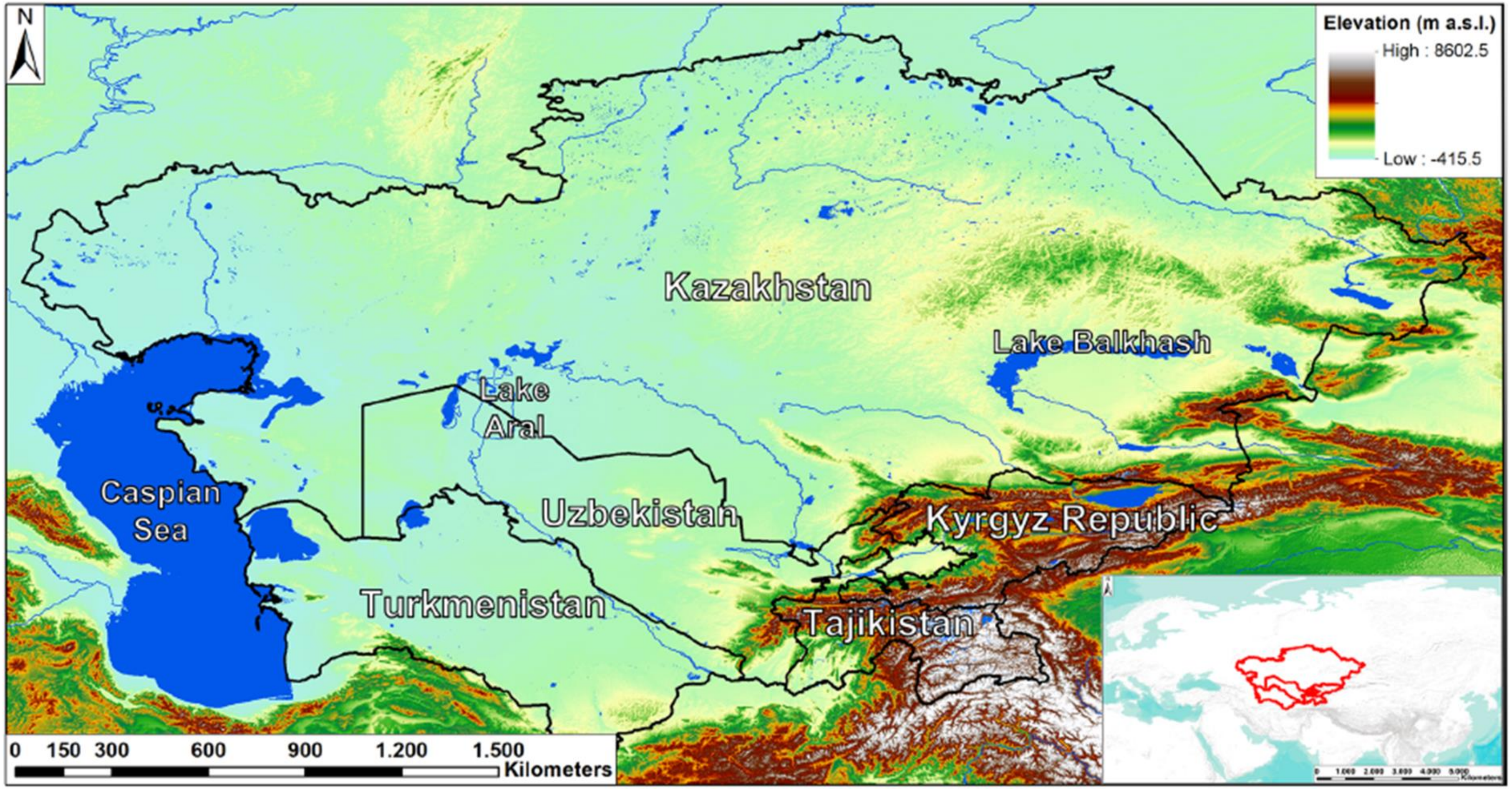
Arno basin case study – Risk

- **Risk** (element) = Hazard x Vulnerability (element) x Exposure (element)
- **Total Risk** (€) = Building Risk (€) + Land use Risk (€)





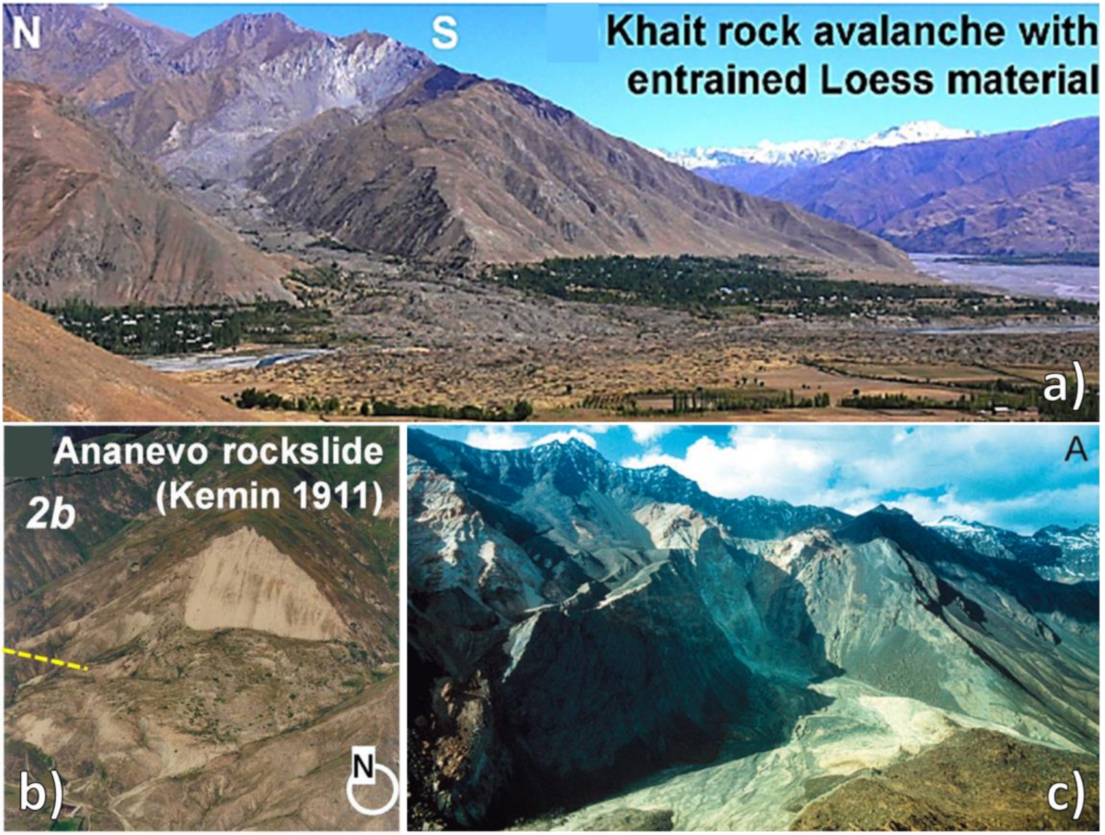
Central Asia - Case study

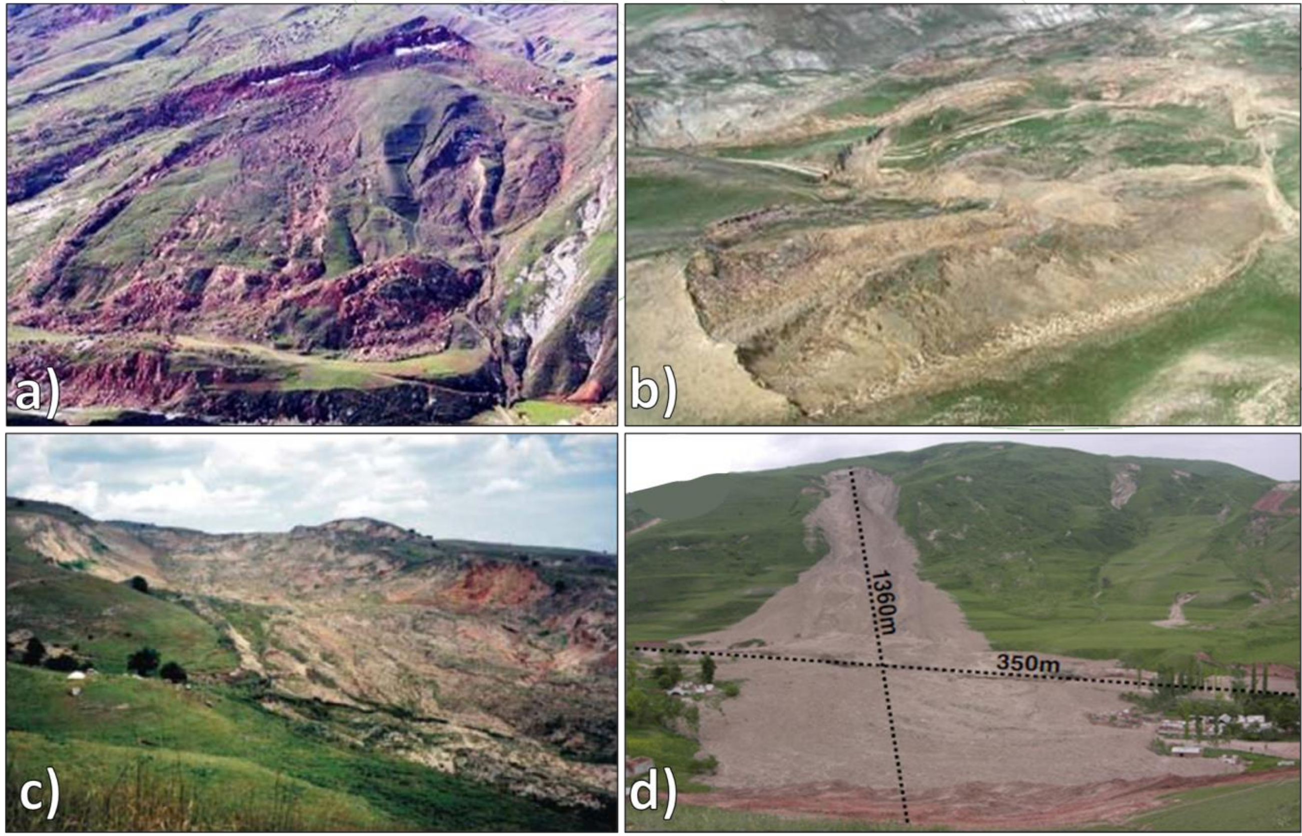


Caleca et al. (2023)

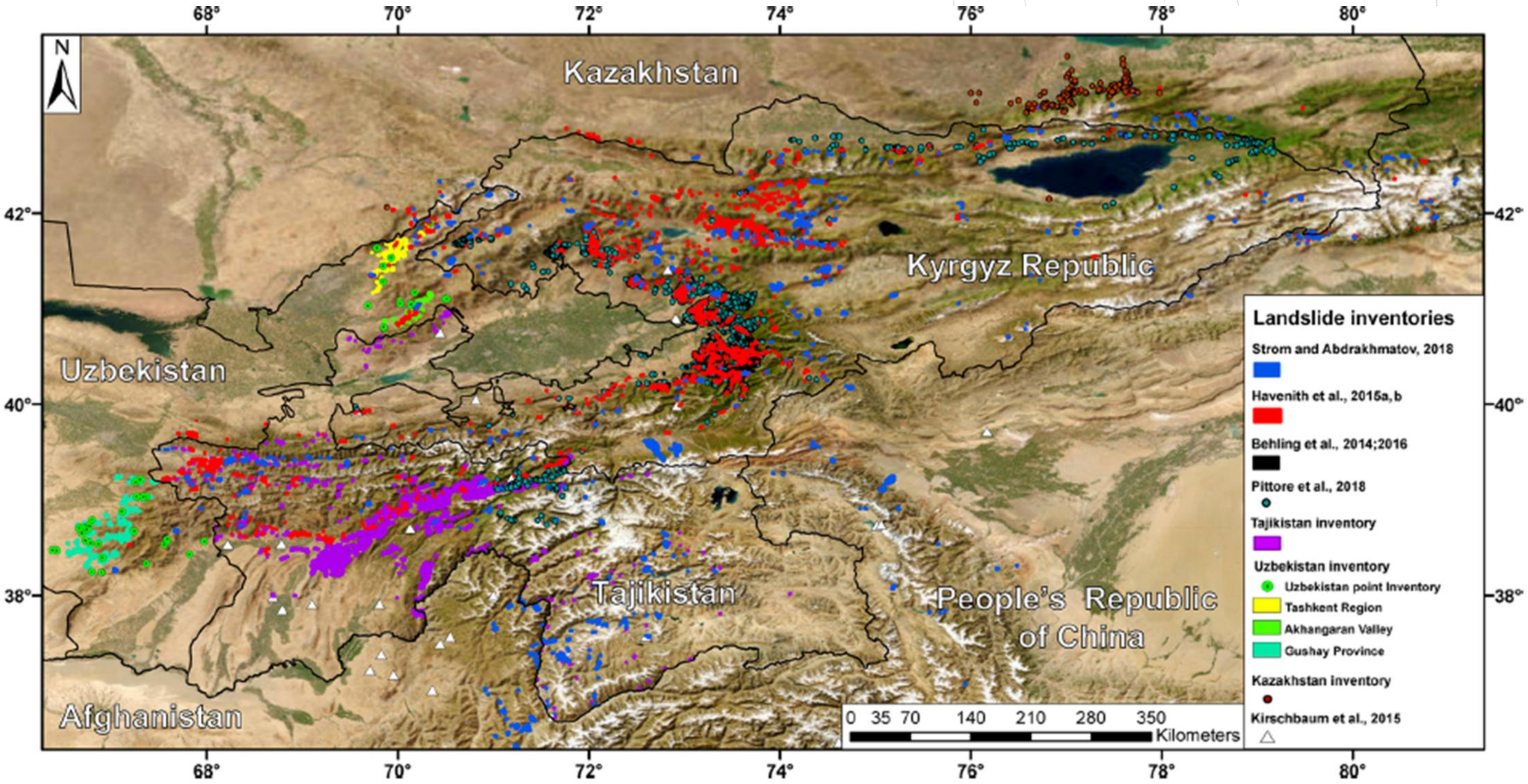
Central Asia - Case study

- In CA landslide phenomena are triggered by natural events such as earthquakes, floods, rainfall and snowmelt
- In the past few decades, the number and intensity of landslides have grown owing to climate change and the increase of the anthropic pressure (uncontrolled land and water use, rising of the water tables due to the increase of irrigation, deforestation, mining and excavation activities).





Central Asia - Landslide inventories

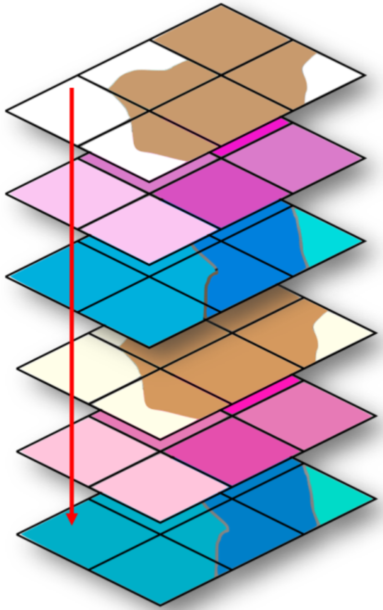


Central Asia - Landslide susceptibility

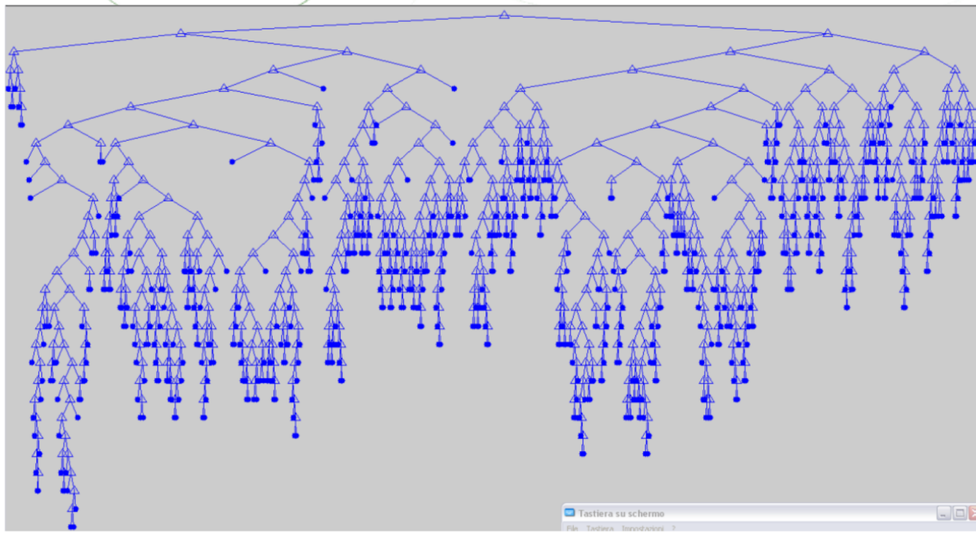
Random forest model

Strong Points:

- Both categorical and numerical variables can be used
- No assumption about the statistical distribution of the data
- It accounts for interactions and nonlinearities between variables
- Avoid overfitting
- It allows exploring a large number of explanatory variables at the same time
- It’s unambiguous and objective



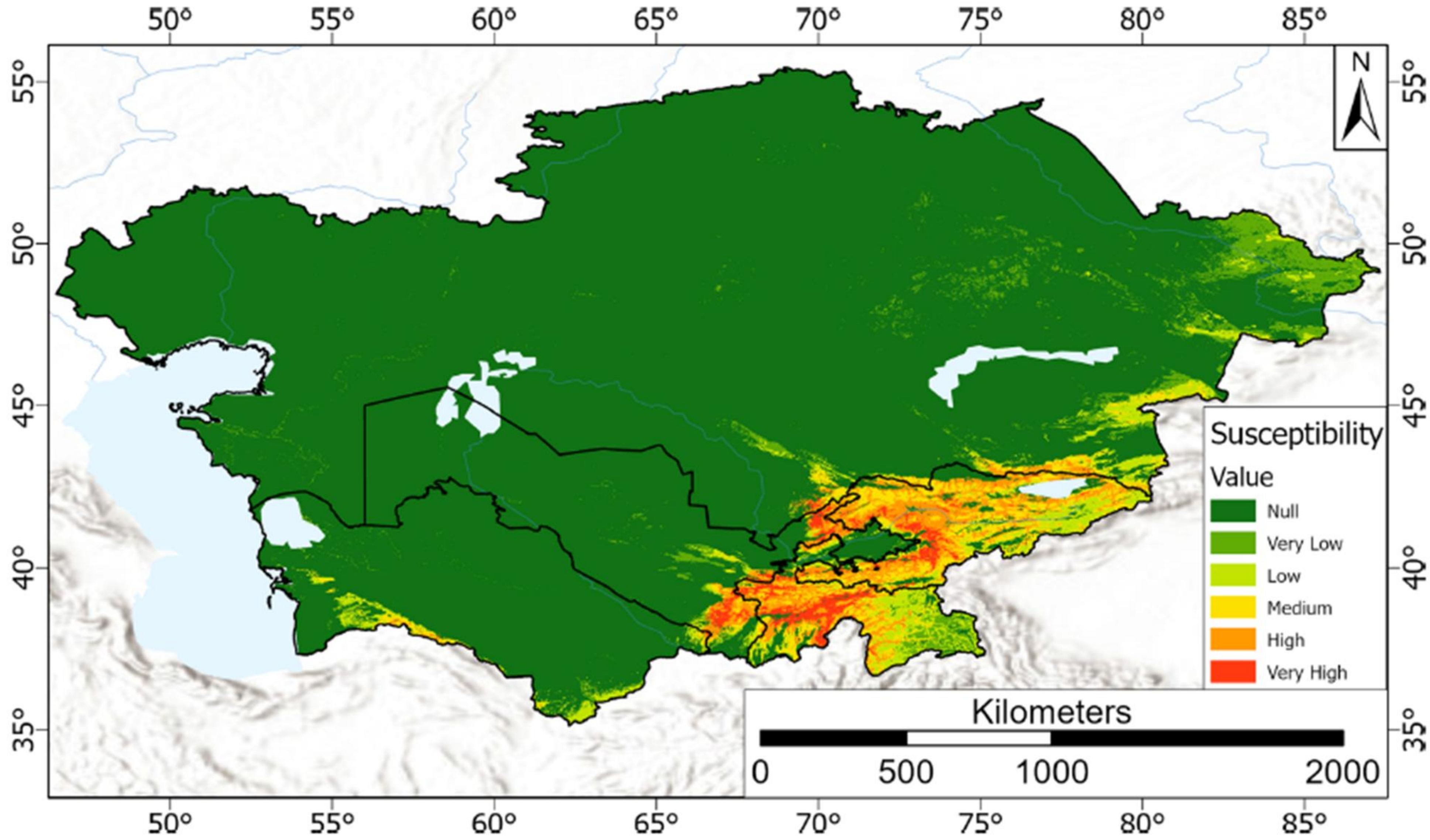
- pixel- based approach
- pixel size: 70 m
- about 2.2 * 10^9 pixels analyzed



Central Asia - Landslide susceptibility

- MERIT DEM and DEM-derived products. This includes aspect, slope gradient, total curvature, profile curvature, planar curvature, flow accumulation, topographic wetness index (TWI), stream power index (SPI), and topographic position index (TPI).
- Lithology. This is derived from the geological map of the former Soviet Union made by the USGS (Persits et al., 1997).
- Soil-type map. This is taken from the Digital Soil Map of the World (DSMW) database (Copernicus land use;https://land.copernicus.eu/, last access: 27 July 2022).
- Distance from faults. It is the minimum distance, in meters, between each landslide and the nearest fault. The fault database is derived from the AFEAD catalogue (Styron and Pagani, 2020) and was modified after Poggi et al. (2023a).
- Distance from roads. It is the minimum distance, in meters, between each landslide and the nearest road. The road database is derived from Scaini et al. (2023).
- Distance from rivers. It is the minimum distance, in meters, between each landslide and the nearest river. The river network database is derived from Coccia et al. (2023).
- Distance from hypocenters. It is the minimum distance, in meters, between each landslide and the nearest earthquake hypocenter with a magnitude greater than 6.5 (following the methodology adopted by Havenith et al., 2015a). The hypocenter database was provided by Poggi et al. (2023a).
- Peak ground acceleration (PGA). Four kinds of PGA maps according to different return times (475 and 1000 years) and different materials (soil layers and bedrock) to which it refers were created (Poggi et al., 2023b).
- Rainfall distribution maps . Derived from ERA5 database

Central Asia - Landslide susceptibility



Central Asia -Exposure

- Elements at risks: population , buildings and transportation systems

Population exposure

Source: high-resolution global-scale dataset + national census data
Output : total number of inhabitants in each cell (100 m resolution)

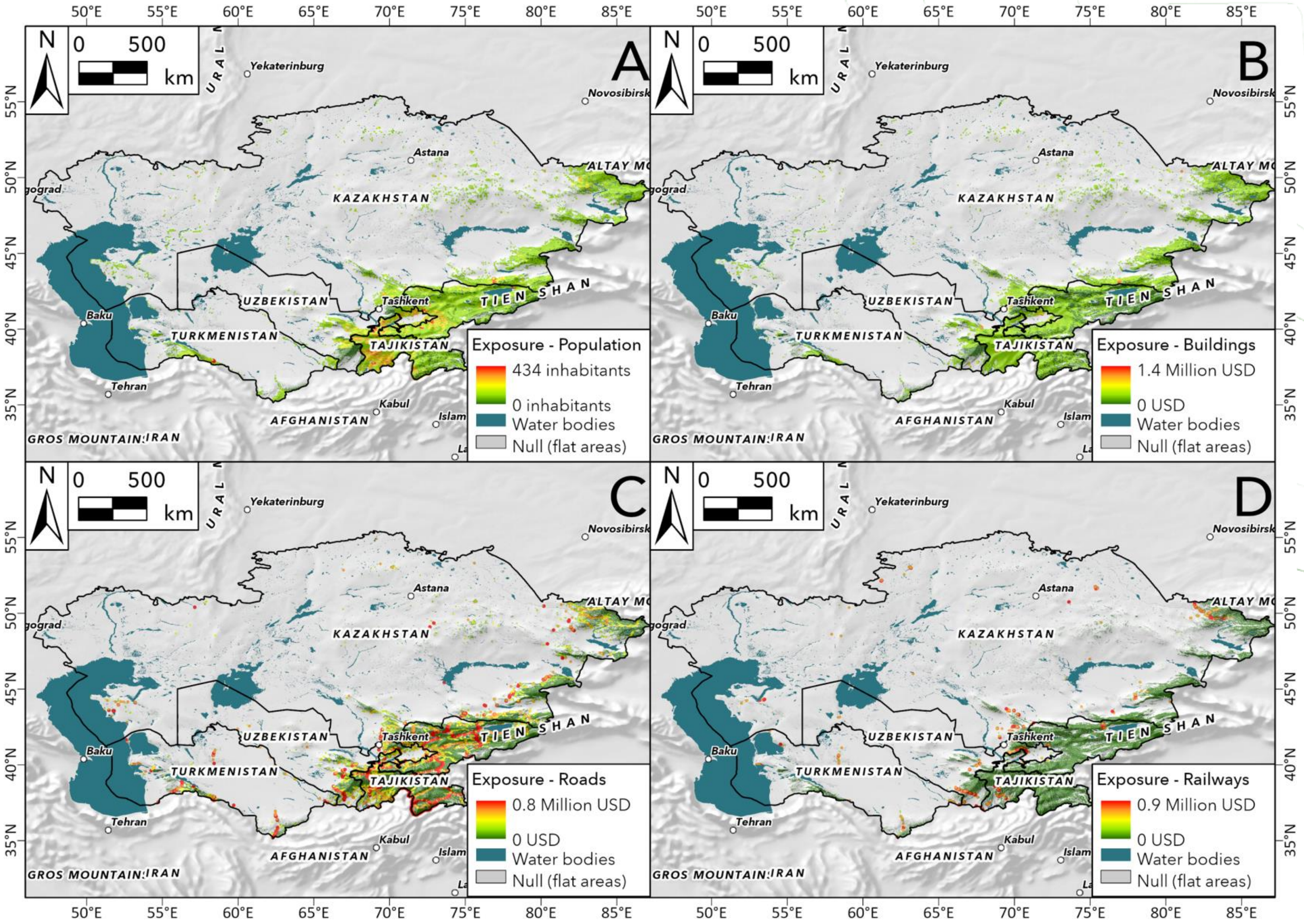
Building exposure

Source: literature
Type of buildings: residential and commercial
Output : economic value of both residential and commercial buildings at 200 m resolution

Trasportation exposure

Source: Open Street Map data + reconstruction costs
Type of transportation: roads and railways
Output : total reconstruction cost is defined for each linear infrastructure sub-type by multiplying its length and reconstruction cost (USD/m) within each cell at 200m resolution

Central Asia -Exposure



Central Asia -QRA

Hazard= Susceptibility

Vulnerability = 1

Spatial resolution = 200-m grid

Population risk

$$R_p = H \times P$$

R_p is the number of lives potentially at risk,

H is hazard

P is the mean number of inhabitants within each cell of the grid analysis.

Total risk

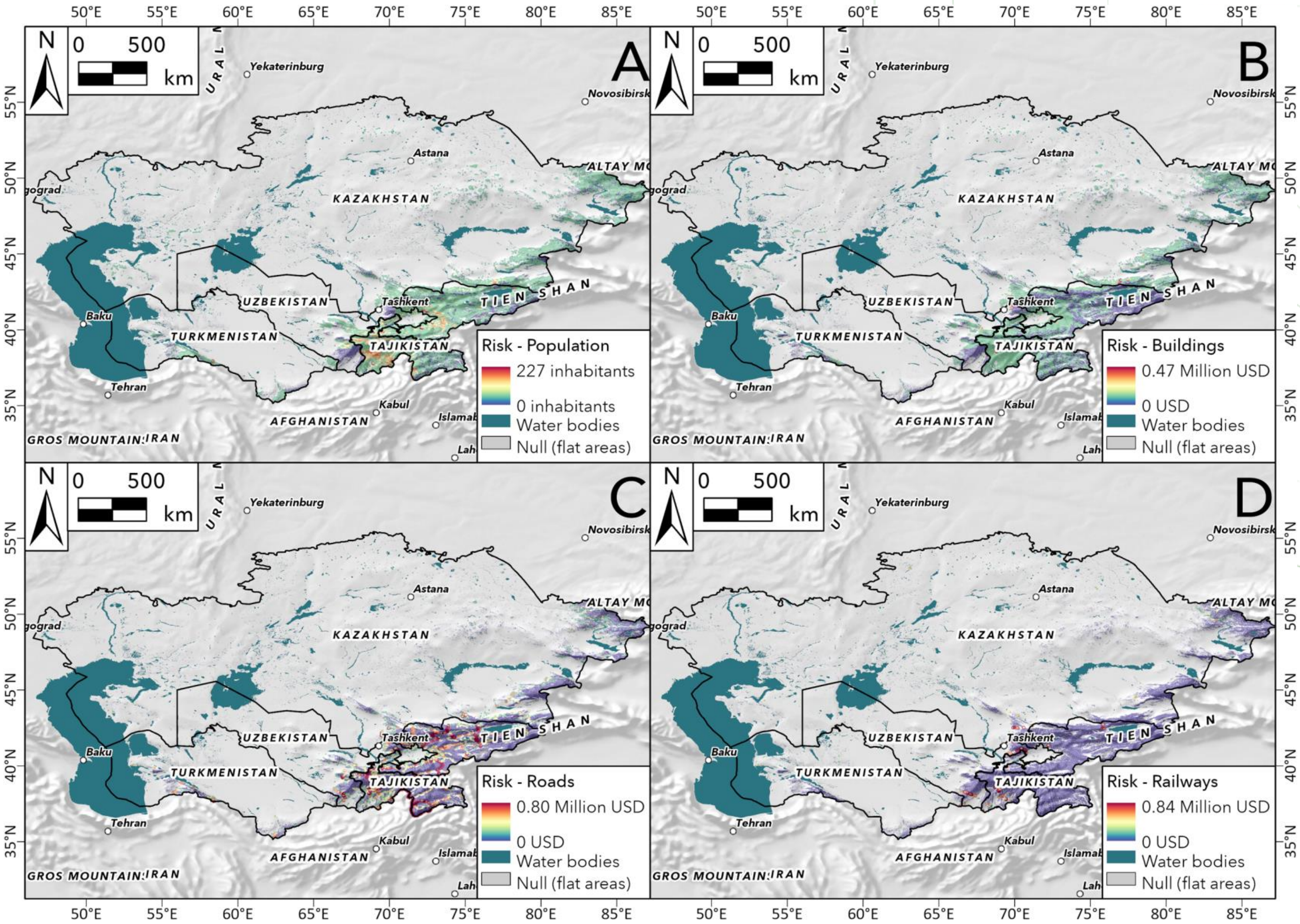
$$R_{tot} = R_b + R_{ro} + R_{ra}$$

R_b risk of building

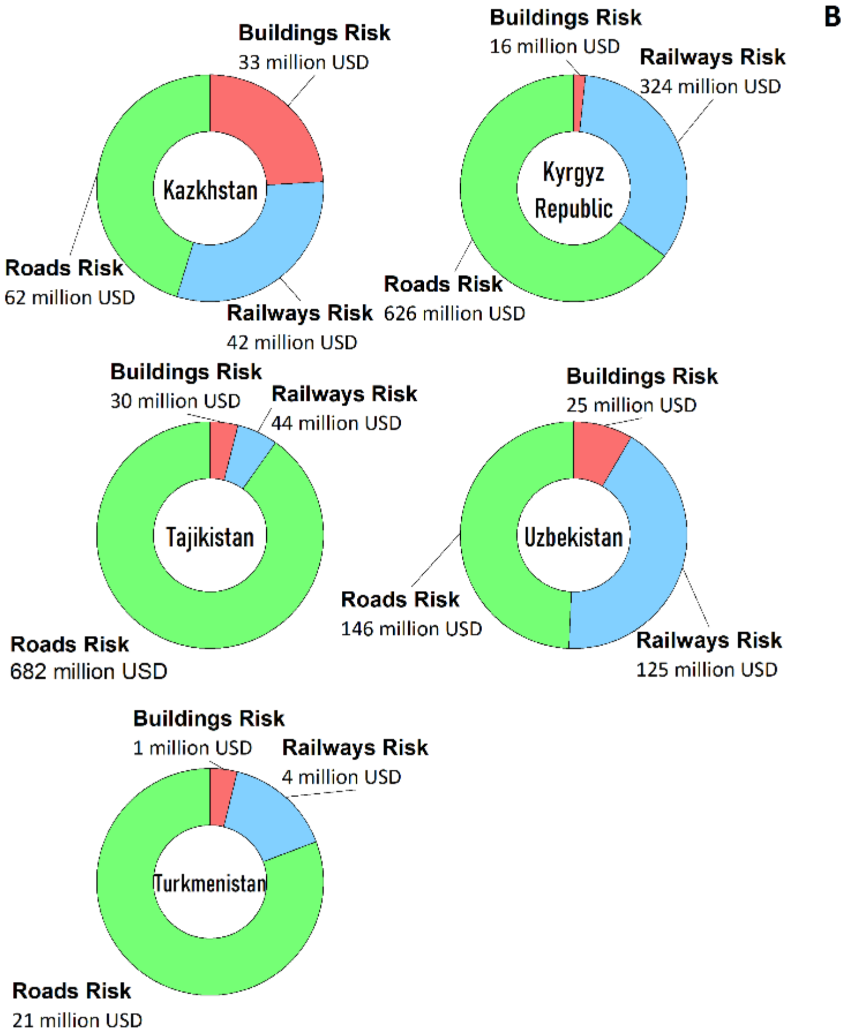
R_{ro} risk of roads

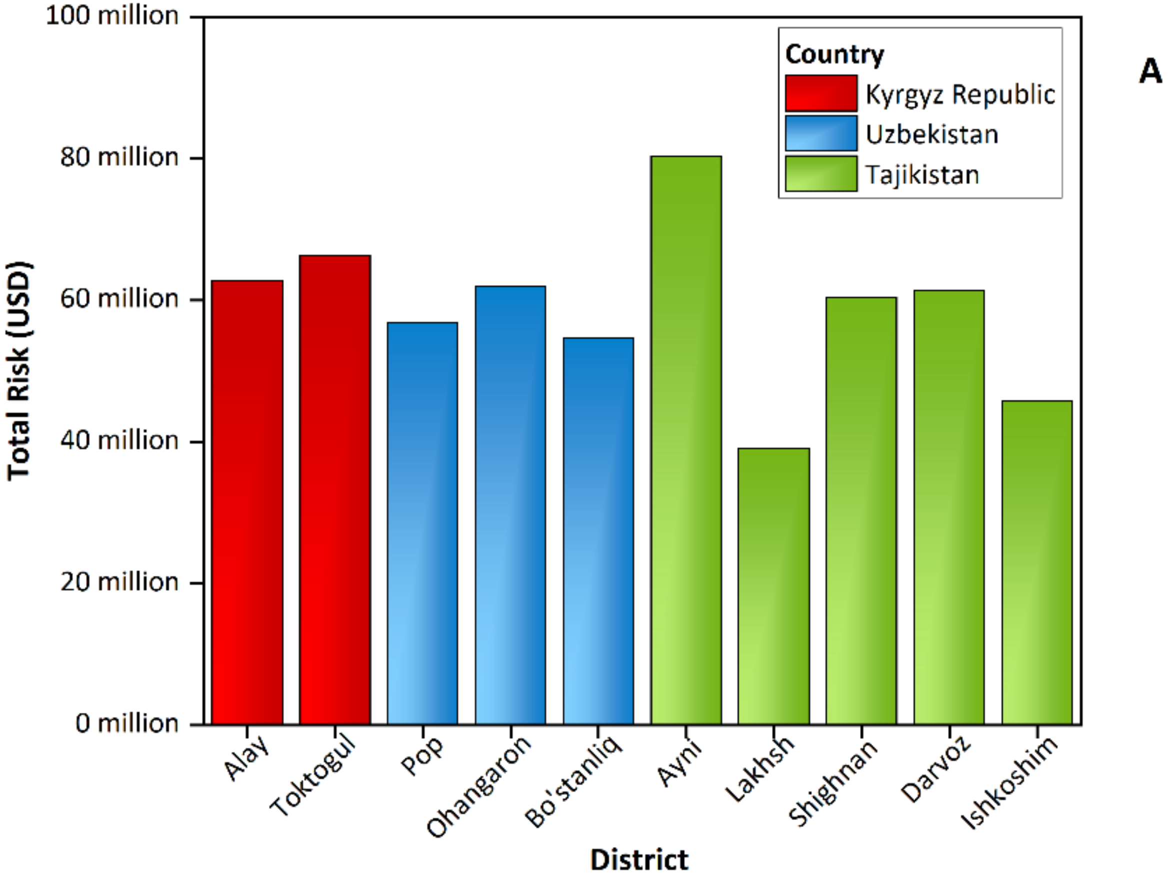
R_{ra} risk of railways

Central Asia -QRA



Central Asia -QRA





Next challenges

From susceptibility to hazard:

TIME BECOMES A FACTOR:

- Additional analyses
- More input data needed, with better quality
- Setting precise objectives

TRIGGERING FACTORS

- *Rainfall*

Establishing critical rainfall conditions for landslides of target magnitude

Probabilistic analysis to assess temporal probability of exceedance

CLIMATE CHANGE involved!

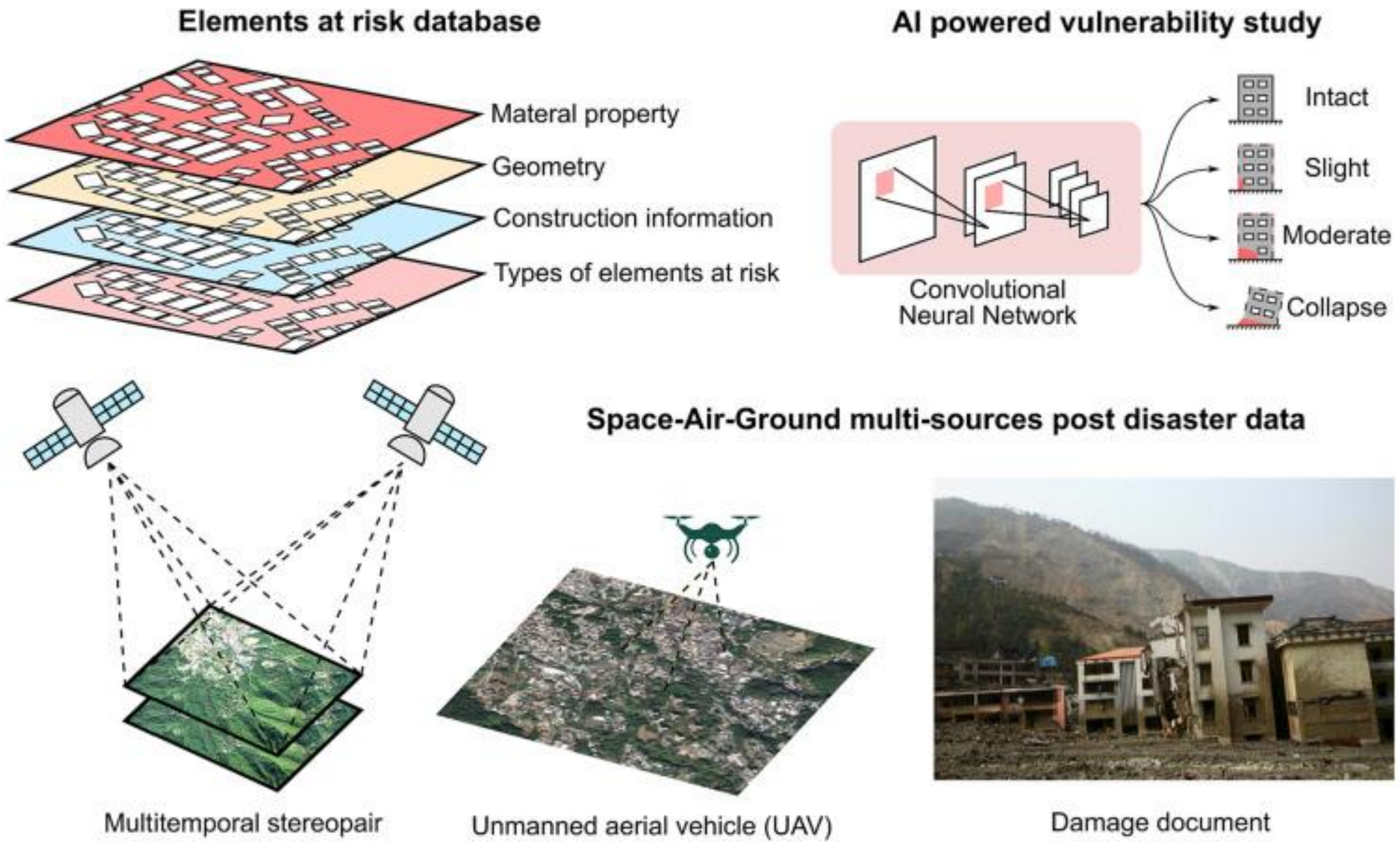
- *Earthquakes*

Establishing critical earthquake magnitude for landslides of target magnitude

Probabilistic analysis to assess temporal probability of exceedance

Next challenges

RIsk analyses:



- Enhanced Elements at risk and post disaster database
- Precise building damage evaluation
- Multi-vulnerability assessment due to frequently occurring cascading hazards

THANKS!

IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System
(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-Mission 4 “Education and Research” - Component 2: “From research to business” - Investment 3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”

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