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Assessment of shallow-landslide risk mitigation measures based on land use planning through probabilistic modelling

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Abstract

On October 25, 2011 an extreme rainfall event affected a wide area along the coasts of Cinque Terre (eastern Liguria, northern Italy). Particularly, in the Vernazza catchment, the event triggered hundreds of shallow landslides and a debris flood that caused three casualties. Investigation of slope stability after the event was carried out aiming at defining the most effective mitigation measures which may be adopted in future land use planning. To this objective a susceptibility model was produced and a series of scenarios were simulated using probabilistic methods. The susceptibility model has provided information about landslide conditioning factors on which to act for reducing landslide occurrence and therefore the associated risk. The simulations have taken into consideration the following alternative types of mitigation measures: (1) restoration of abandoned terraces, (2) reforestation of abandoned terraces, (3) use of local structural measures over stretches of potentially unstable hillsides and (4) avoidance of any intervention. The advantages and the disadvantages of proposed mitigation measures for shallow landslide risk are discussed considering the results of the simulations and taking into account their complex interaction with environmental, historical, cultural and socio-economic aspects. The results show that the most effective mitigation strategy for reducing landslide risk at short-term consists of applying structural measures over potentially unstable slopes. However, a long-term program promoting the development of agricultural or forestall practices on terraced slopes is necessary. In fact, the simulations indicate if no measures are applied to avoid the degradation of the terraced areas, landslide areal frequency would inevitably increase.

Keywords: shallow landslide, debris flood, probabilistic modelling, risk management, terraced slopes, Cinque Terre

1. Introduction

On October 25, 2011 a rainfall-triggered debris flood (cf. Hungr et al. 2001) that killed three people and generated economic losses estimated at 130 million Euros affected the village of Vernazza (Cinque Terre National Park, NW Italy) (Fig. 1). A large part of the sediments carried by the debris flood came from 364 shallow landslides generated in the Vernazza catchment (5.8 km^2) during the rainfall event (Cevasco et al. 2012).

This paper focuses on the assessment of the efficacy of different measures based on land planning that may be adopted to reduce shallow landslides areal frequency and related risk. The choice of appropriate landslide mitigation measures in the study area, which belongs to a National Park recognized as a “World Heritage Site” by UNESCO, is a very sensitive issue. As a matter of fact, land management strategies should take into account not only the issues related to natural hazards, but also their complex interaction with environmental, historical, cultural and socio-economic aspects.

Shallow landslides are strongly conditioned by land use and hillslope morphology (e.g. Remondo et al. 2003; Dai et al. 2004; Lee and Talib 2005; Begueria 2006; Carrara et al. 2008; Cervi et al., 2010; Piacentini et al. 2012). It has been noted by several authors that mountainous forested areas typically appear to be less susceptible to shallow landslides than unforested mountain slopes (e.g. Greenway 1987; Tasser et al. 2003). Human occupation of mountainous areas is generally accompanied by deforestation and undercutting of natural slopes by activities such as road, footpath and terrace construction. These modifications on land use and hillslope morphology generally lead to an increase of landslide frequency (Rogers and Selby 1980; Gerrard and Gardner 2002; Glade 2003; Bruschi et al 2013). Thus, in densely populated mountainous regions shallow mass movements often constitute a process of land degradation involving risk implications.

The most common and spatially extended anthropogenic modification of natural slopes worldwide is the terracing of hillsides. The terrace is a popular engineered agricultural landform used in mountainous regions to raise crop output and to reduce erosion by controlling surface runoff (Terranova 1989; Rackham and Moody 1992; Parrotta and Agnoletti, 2012). However, although terraces may have positive effects and may constitute an important cultural landscape heritage, shallow landslides are recurrent phenomena along terraced slopes, especially where abandonment of farming has resulted in the lack of maintenance of the terrace system (e.g. Tamura 1996; Lasanta et al. 2001; Terranova et al. 2002; Crosta et al. 2003; Canuti et al. 2004; Cao et al. 2007; Brancucci and Masetti 2008; Kitutu et al. 2011; García-Ruiz and Lana-Renault 2012).

People from Liguria (NW Italy) have modified during centuries the landscape of their coastal region building terraces on more than the 20% of the territory to create suitable terrain for farming (Brancucci and Paliaga 2008; Brandolini et al. 2008). In Liguria, the terraces have suffered an extensive abandonment since the 1960's causing changes to land use and, therefore, landslide activity (Canuti et al. 2004). Nowadays, terrace degradation continues causing increasing landslide hazard, loss of biodiversity and productive land and disappearance of a rich cultural heritage (Terranova et al. 2006; Agnoletti 2007; Arnaez et al. 2011). This is also the case of Cinque Terre National Park where abandoned and non-maintained terraces have become hazardous features because of their instability during the intensive rainfall events that regularly occur in the Liguria region. For instance, a significant part of the material mobilized by the Vernazza debris flood came from crumbling terraces affected by landslides. In this respect, it should be emphasised that the Cinque Terre were recognized as a "World Heritage Site" because of its terraced scenery. For this reason, cost-effective solutions should be found which could balance the reduction of landslide risk with the protection of this environmental and socio-cultural heritage of the region.

After the 2011 extreme meteorological event occurred in eastern Liguria (ARPAL-CFMI-PC 2011) different activities were developed by local administrations to define the most suitable measures to mitigate slope instability and flooding (Brandolini et al.

2012). This study investigates the relationships between different types of land use which may be planned in the Vernazza catchment and the areal frequency of shallow landslides. With this objective, a susceptibility model was produced and a series of scenarios were simulated. The susceptibility model provided information about landslide conditioning factors that can be modified so as to reduce shallow landslide processes and risk. The simulations showed the effects of four alternatives for landslide risk management: (1) restoration of the abandoned terraces, (2) reforestation of abandoned terraces, (3) application of local structural measures over potentially unstable hillsides and (4) do nothing.

2. Study area

The Vernazza catchment is a small basin located along the coast of the Cinque Terre (easternmost Liguria, north-western Italy), on the Tyrrhenian side of the northern Apennines (Fig. 1). The shoreline of "Cinque Terre", extending NW-SE for 11 km, is mostly characterized by a steep rocky coast. The Cinque Terre area is bounded, to NE, by a chain of mountains exceeding, in many cases, the altitude of 600 m asl and culminating with the top of Mt Malpertuso (815 m). This ridge, that is parallel and very close to the coastline (2-3 km), represents the divide between Cinque Terre and Vara valley. From this main ridge, several secondary divides perpendicular to the coastline branch seaward, defining small catchments; the Vernazza catchment, with an extent of about 5.8 km^2, is the widest among them.

Along the coast of Cinque Terre four small villages (Monterosso, Vernazza, Manarola and Riomaggiore) are located in the final stretches of deep cut valleys while only one (Corniglia) is located on a former marine terrace at an elevation of 100 m. Due to its scenic, environmental, historical and cultural value, the entire area was recognized since 1997 as a World Heritage Site by UNESCO, and included since 1999 in the Cinque Terre National Park.

Climate is typically Mediterranean, characterized by hot and dry summers and mild winters. The mean annual precipitation is about 950–1050 mm along the coast of Cinque Terre, but significantly increases a few kilometres inland, reaching 1600-1700 mm in Vara valley. At Levanto, located along the coast 7 km NW of Vernazza, maximum of rainfall occurs in October (mean value 156 mm per month). Inland the maximum rainfall (222 mm) occurs in December (Vara valley - Padivarma rain gauge, 10 km from the coast).

From a geological point of view the Cinque Terre area belongs to the Northern Apennines, characterized by sedimentary tectonic units. In particular, units belonging to the Tuscan and Sub-Ligurian Domains outcrop in the Vernazza catchment (Fig. 2). Regarding the Tuscan Domain, a flysch made up of sandstones and clayey siltstones (Macigno Fm., upper Oligocene), belonging to the Tuscan Nappe outcrops. In the framework of Sub-ligurian Domain, claystones with limestones and silty sandstones turbidites (Canetolo Shales and Limestones, Paleogene), marly limestones with thin claystone interbeds (Groppo del Vescovo Limestones, early-middle Eocene), fine sandstones turbidites (Ponte Bratica Sandstones, upper Oligocene), belonging to the Canetolo Unit, and silty marl and siltstone (T. Pignone Marls, Oligocene), belonging to Marra Unit, outcrop (Abbate 1969; Regione Liguria 2006a). The aforementioned units are part of a wide overturned antiform fold the axis of which strikes 150N (Giammarino and Giglia 1990). The main morphological and topographic features (coastline, watersheds, streams, etc.) are influenced, to a large extent, by brittle tectonic fault and fracture systems striking NW-SE, NE-SW and, secondly, N-S and E-W.

From a geomorphological point of view, the drainage pattern at Cinque Terre is characterized by short streams with ephemeral hydrological regimes and steep profiles from which considerable erosive and transport capacity derives. Slopes of the Vernazza catchment are normally very steep and more than 50% of the terrain gradient ranges between 30° and 40°. Both hydrological and morphological characteristics of this area cause low thicknesses, up to 1 m, of eluvial-colluvial cover. Whilst the Cinque Terre coast is mainly characterized by several large and complex landslides (De Stefanis et al. 1978; Terranova 1987; Federici et al. 2001; Cevasco 2007), in the Vernazza catchment shallow instability in the soil cover prevails.

During the past centuries the slopes at Cinque Terre were almost completely transformed by terracing for agricultural purposes. Colluvial deposits were retained by dry stone walls for an estimated total length of about 6000 km. The height of the dry stone walls ranges between 1.5 and 2.5 m depending both on the steepness of the slope and the width of the terraces. Moreover, several drainage works were carried out for running water control and supply. These changes have deeply modified the previous top-soil cover stratigraphic and hydrological features. The lack of maintenance of the dry stone walls, following the progressive exodus of farmers started at the end of 1800's, caused disruption and loss of terraced areas. In abandoned areas, vegetation cover mainly consists of Mediterranean scrub and pines tend progressively to overgrow.

Despite the fact that approximately half of slopes within the Vernazza catchment were originally terraced for vineyards and oliveyards, they are currently cultivated only for 8% (Cevasco et al. 2013a; 2013b; Fig.1). On terraces that have been abandoned for a long time, plenty of vegetation cover has grown up (33%), while on the recently abandoned terraces vegetation is sparse, consisting mainly of shrubs (7%). The upper part of the Vernazza valley is characterized by forest and scrub lands (52%).

3. The October 25, 2011, rainfall event and landsliding in the Vernazza catchment

On October 25, 2011 after a long dry period, an intense rainfall event hit a wide area elongated SW-NE between eastern Ligurian coast and northern Tuscany. The rainstorm caused floods, landslides, 13 casualties, and severe structural and economic damage. The intensive rainfall event lasted less than 24 hours (Fig. 3). The Magra basin was the most affected by the rainfall with average cumulative rainfall of 190 mm/24 h and peaks locally ranging between 300 mm and about 500 mm (ARPAL-CFMI-PC 2012). At Borghetto Vara (Vara valley, about 10 km from the coast) both the cumulative rainfall and rainfall intensity reached their maximum, with respectively 539 mm/24h; 150 mm/h, 330 mm/3h and 470 mm/6h between 0900 and 1500 UTC (Fig. 4). During the event a very high intensity rainfall peak of 18 mm/5min was also recorded at Borghetto. Lower but significant rainfall values were recorded along the coast: at Monterosso a cumulative rainfall of 382 mm and rainfall intensities reaching 90 mm/h, 195 mm/3h and 350 mm/6h were recorded between 0900 and 1500 UTC. At Levanto a peak rainfall intensity of 111 mm/h was recorded between 1000 and 1100 UTC (Fig. 4). These values show that both along the coast and inland in just one day the cumulative rainfall was more than double the mean value of the rainiest months. The return period of the recorded peak values was estimated higher than 100 years (ARPAL-CFMI-PC 2011).

No quantitative rainfall data are available for the Vernazza catchment. Nevertheless, eyewitnesses information collected at Vernazza suggests that both cumulative rainfall and the rainfall intensity were higher than the values recorded at Monterosso. Rainfall was lower moving further along the coast to the SE; at Corniolo, located at 238 m between Manarola and Riomaggiore, the total cumulative rainfall was 111 mm with maximum hourly intensity of 36.4 mm/h.

In the Vernazza catchment the heavy rainfall of October 25, 2011 caused widespread erosion and triggered hundreds of shallow landslides from which a catastrophic debris flood was formed (Figs. 5 and 6). Shallow landslides mainly consisted of earth and debris slides, often evolving into flows (Cruden & Varnes, 1996; Hungr et al., 2001). Most shallow landslides were of the order of hundreds of square metres in area, with some of a thousand square metres. These comprised the failure of eluvial and colluvial soils of up to 1.5 m depth on woodland and of artificially reworked deposits up to 2.5 m on terraced slopes (Cevasco et al. 2013b; 2013c). In most cases the failure surface was the contact surface between debris cover and bedrock. Sediment transport along steep channels and erosive energy of streams were increased by earth and debris supply from shallow landslides, causing a debris flood (according to the definition by Hungr et al. 2001) or hyperconcentrated flow (as defined in Costa 1984 and Hutchinson 1988) in the lower part of the valley. The final tract of the Vernazza stream, diverted in 1870's by a 150m-long tunnel, was obstructed by debris. This caused the flooding of the Vernazza centre where mud and debris deposits reached an average thickness of about 4 m.

In the whole Vernazza municipality, the effects of landsliding and flooding were disastrous, both in terms of economic damage (evaluated about 130 million Euros) and human loss (three casualties). In particular, some buildings, bridges and covered tracts of the Vernazza stream were destroyed; all the roads connecting to Vernazza village and the Genova - La Spezia railway were interrupted; severe damages were suffered also by tourist trails.

4. Quantitative assessment of land use planning measures for shallow landslide mitigation purposes

A landslide spatial probability (susceptibility) model was the reference to assess the impact of several land planning measures for shallow landslide mitigation purposes. This susceptibility model was produced using a landslide event inventory compiled after the rainfall event of October 25, 2011(Cevasco et al. 2013a) by means of the following steps: (1) multiple preliminary models were generated comparing quantitatively the distribution of the landslides and the spatial pattern of different sets of conditioning factors. (2) The prediction power of these factors and their combinations was estimated applying the 2-fold cross validation technique. (3) The combination with the highest predictive capability was used to produce the landslide susceptibility model of the Vernazza catchment. New susceptibility models were produced by implementing several land use changes in the latter model. The difference between the spatial probabilities estimated in this model and the new ones indicated the impact of the implemented land use changes (i.e. land planning measures) on landslide areal frequency. Additionally, this difference computed only with data of the slopes oriented towards roads and residential areas provided a relative measure about the influence of the land use change on landslide risk. This methodology and its outputs are illustrated in detail below.

4.1. Landslide and conditioning factors data base

A detailed landslide-event inventory was constructed by means of a detailed field survey and the interpretation of stereoscopic aerial photographs and orthorectified images. These images, provided by the Liguria Regional Administration, were taken by the Air Service of Remote Sensing and Monitoring of Civil Protection of Friuli Venezia Giulia Regional Administration on 11 November 2011 and they have a ground resolution of 3 cm to 50 cm (depending on altitude). The inventoried landslides correspond to one temporal population.

A total of 364 landslides were mapped in an area of 5.8 km^2. Their location and characteristics were stored in a spatial database constructed and implemented on a GIS (ArcGIS 9®). Data of a suitable set of causal factors having a relationship with slope failures was also added to the same spatial database. Multiple thematic maps of potential conditioning factors were derived using this information. These thematic maps contain information about geology, land use, topography and terrain morphology. Their characteristics and data source are briefly included in Table 1. Landslide inventory and thematic maps were transformed into raster format with a pixel size of 5 x 5 m in order to apply the methodology used to produce the susceptibility model.

4.2. Susceptibility modelling

The spatial probability of landslides in the study area was estimated according to the following procedure. Landslide source areas were modelled rather than the entire landslide body because the detachment in shallow slides/flows, such as those studied in this work, normally starts there. The number of analyzed landslides was reduced to 344 due to spatial resolution limitations when the landslide source areas were selected. Consequently, the model was produced for landslides with a minimum area determined by the pixel size, the position of the landslide with respect to the raster grid and the algorithm used to transform the vector data to raster data. Thus, it was estimated that the susceptibility model is referred to landslides with an area greater than 15 m^2. The following step in the procedure was to produce multiple spatial relative probability models applying the Favourability Functions (FF) mathematical framework (Chung and Fabbri 1993). There are several existing mathematical functions that can be used as FF as discussed by Fabbri et al. (2004 and references therein). The Likelihood Ratio (LR) function applied to categorical variables was used in this study (Chung 2006). The LR highlights the difference between the portion of the study area containing landslides and the remainder. The greater the difference between the values of a conditioning factor in the landslide areas and in the remainder areas, the greater the capacity is of that conditioning factor for identifying landslide-prone zones.

The models were produced by overlaying of the causal factor raster maps. This operation generates new raster maps formed by Unique Conditions Units (UCUs) with a LR value associated. This LR value was calculated multiplying the LR values for each factor at every pixel. Subsequently, the UCUs were reclassified into equal-area classes and ranked according to its LR value producing spatial relative probability models. The prediction capability of these models was assessed applying a 2-fold cross validation technique. The landslide inventory was split into two approximately equal parts. These parts were used as train and test sets for constructing prediction-rate curves (Chung et al.

1995). The shape, the proportion of predicted landslides within 20% of the highest susceptibility area and the Area Under the Prediction-Rate Curve (AUPRC) were used as the main criteria to evaluate quantitatively the predictive capability of the models (see e.g. Lee et al., 2007 and Galve et al., 2009).

The results obtained in the Vernazza catchment are presented in Fig. 7 and Table 2. The latter includes the variable combinations, the AUPRC and the percentage of landslides predicted with the 20% highest susceptibility area calculated for each model (*PRED20* in Table 2). Fig. 7 shows the most significant PRCs. The variables with prediction capability, out of the twelve previously selected (Table 1), were *elevation*, *geology* and *land use*. The combination of those three variables, in spite of its simplicity, provides a reasonably satisfactory forecast regarding the spatial distribution of landslides. This combination generates a model that predicts 59% of the landslides with the 20% highest susceptibility area. According to the analysis, the terraced zones between 77 and 297 m asl −where the clays and limestones of Canetolo Fm. and sandstone flysch of the Ponte Bratica Fm. coincide with terraced hillslopes− are the most susceptible areas in the Vernazza catchment. However, it may be argued that the combination of the terraced terrain with all the geological formations can produce instability zones. The mechanism of landslides on terraced areas was described by Crosta et al. (2003) who identified the formation of perched groundwater tables and the build-up of positive pore pressures in layers above permeability barriers as responsible for shallow failures. In the Vernazza case study, the contact between soils and the underlying bedrock has to be considered as the main permeability barrier (Cevasco et al. 2013b).

The high significance of the variable *land use* in the models, such as it has been observed in many other shallow landslide case studies (e.g. Remondo et al. 2003; Lee and Talib 2005; Begueria 2006; Bruschi et al., 2013), corroborates that land planning is very important to mitigate these processes. Although the slope gradient variable has generally been shown elsewhere to have a good spatial correlation with the distribution of landslides (e.g. Remondo et al. 2003; Begueria 2006; Van Westen et al. 2008), surprisingly it did not show prediction capability in this case study. The cross-validation shows that the slope variable does not discriminate (AUPRC=0.5; Table 2) between landslide-prone and stable areas within the studied basin. This effect can be explained because most of the Vernazza catchment presents steep hillslopes. In addition, during the field survey it was observed that many landslides were generated in concave slopes. For this reason, it was thought that this factor would have a high prediction power, but the validation of the models did not support such hypothesis.

The combination of variables with the highest prediction power determined in the first phase of the analysis was used in the subsequent computation of the spatial probability (susceptibility) model. This raster model shows the probability (*P*) of every pixel to be the source area of a shallow slide/flow-type mass movement for a landslide event as the October 25, 2011 one. The following expression (Chung 2006) was used to derive the value of *P*:

$$P = 1 - \left[1 - p_{sc}\right]^{\frac{n_s}{n_c}}$$

where

p_{sc} = proportion of expected new landslides in the susceptibility class. This parameter was computed on the basis of the step decreasing monotonic function fitted to the areal frequency of the landslides in each susceptibility class (Fig. 8).

$n_s =$ number of landslides (>15 m^2) occurred in the October 25, 2011 event.

$n_c =$ number of pixels of the susceptibility class.

Taking into consideration that the estimated probabilities are referred to a specific extreme rainfall event, the susceptibility model (Fig. 9) was used for obtaining interesting information on landslide occurrence. For example, Fig. 10 shows the estimated spatial probabilities for each land use class. It can be observed that terraced land displays spatial probabilities approximately one order of magnitude higher than non-terraced land. Terraced oliveyards and abandoned terraces show higher susceptibility values than terraced vineyards, but the differences are not relevant. Terraces colonised by natural vegetation or devoted to meadows are less landslide-prone than the other terraced land, but significantly more unstable than the natural slopes covered by forest.

The comparison between damage data and the calculated spatial probability provided a measure on how well model predictions fit the damages produced by the event. The following values were calculated taking into account that 90% of the landslides observed in the study area had a length of less than 65 m. Thus, the model shows that almost six landslides could be triggered at less than 65 m from the buildings located in the Vernazza catchment. On October 25, 2011, six buildings were impacted by landslide debris. The susceptibility model indicates that the debris of 65 landslides was likely to reach the roads. During the rainfall event, the mobilized material of 79 landslides blocked the roads at different locations within the Vernazza cathment. The susceptibility model indicates that 43% of the hillslopes of the Vernazza catchment (those transformed by human activities) could be affected by 88% of the landslides that could occur in the study area as it happened during the October 25, 2011 event. By contrast, the natural forest, covering 45% of the total area, would be affected by only 9% of the expected landslides.

4.3. Simulation of landslide occurrence as response to land use change

The results of land use change simulations can provide decision makers with criteria to support the application of landslide mitigation measures based on spatial planning. Firstly, it was decided to simulate a plausible and suitable land use change in the study area: the restoring of the abandoned terraces by the emplacement of vineyards. This choice was prompted by the fact that the terraced vineyards are the dominat feature of the landscape in Vernazza municipality and one of the key elements of cultural significance in this World Heritage site. At present, the terraced area occupied by vineyards (0.34 km^2) is similar to the non-cultivated terraced area (0.44 km^2). Therefore, it was possible to compare the landslide susceptibility of the two land-use classes. The computed LR in vineyards is 15% lower than in abandoned terraces. This seems to indicate that the restoration of the non-cultivated terraces could reduce the landslide areal frequency in these zones.

The effect on landslide occurrence of the simulated land use change was assessed comparing the spatial probabilities estimated by the reference model and the model generated applying the chosen land use change. The proportional increase or decrease in the probability of landslide occurrence between the reference and the simulated model would quantitatively indicate the effect of restoring abandoned terraces by the emplacement of vineyards (or other mitigation measures based on land planning).

The simulated model was estimated recalculating the reference model. This was performed by substituting the non-cultivated terrace pixels by vineyard pixels in the land use raster map and by carrying on again the raster map overlay. Thus, a simulated raster map formed by UCUs was generated. It was confirmed that these UCUs or factor combinations were the same in the simulated and in the reference model. These models only differed with regard to the spatial distribution and the area of the UCUs. Thus, the simulation model was a mere redistribution of the spatial probability values. As the spatial probability value associated with each UCU was known, the recalculation of the spatial probability model was direct. The results of the explained operation are described below.

The land use change simulations indicated that the restoration of the abandoned terraces by emplacement of vineyards may reduce the landslide areal frequency by only 1.5 % taking into consideration the entire study area and the landslides that may affect buildings and roads. Therefore, contrary to the expectations, the proposed mitigation measure does not seem to provide an effective impact against landslide processes. In the light of these results, three possible risk management alternatives were also considered: (1) reforestation of abandoned terraces, (2) use of local structural measures on potentially unstable hillsides and (3) avoid any measure trying to stop the general trend of abandonment of the terraces. In the case of the latter, the total abandonment of the terraces was simulated to show the most extreme scenario. By applying the first option (reforestation), the number of landslides that are likely to affect buildings and roads may be reduced by up to 24% and 11%, respectively. With regard to the entire catchment, the reduction of the spatial probability of shallow landslides may be around 10%. Thus, this measure would lead to a reduction in landslide incidence, particularly with respect to the impact on buildings.

The option of local structural measures was tested with the support of the reference susceptibility model. The model was used for selecting the most potentially unstable hillslopes. The alternative was assessed assuming that structural measures (e.g. reinforcement of dry walls, protection structures for the roads) are implemented in the potentially unstable slopes with maximum effectiveness. Thus, it was estimated that the protection of 23% of the road stretches and intervention on 29% of the slopes oriented towards buildings might reduce the exposure of these elements to shallow landslides by 66% (Fig. 11). The areal frequency of shallow landslides, taking into account the entire study area, may be reduced by up to 14% using this solution.

Finally, it was estimated that the areal frequency of shallow landslides might increase by up to 2.5% in Vernazza catchment if measures to safeguard the terrace landscape are not implemented. Buildings and roads could be exposed to an increase in impacts from landslides by 5% and 3% respectively if all terraces are abandoned. Therefore, a possible future debris flood, associated with a shallow-landslide event, might be more severe than the one occurred on October 25, 2011 if the progressive abandonment of terraces is not halted. The suitability of the tested measures will be discussed in the following section.

5. Discussion

The most relevant output of the cross validation of the susceptibility models is that the best model was generated by using only three conditioning factors (*elevation*, *geology*, *land use*). Moreover, the evaluation of the prediction power of the variables suggests that the previous field observations about causal factors were biased. In fact, contrary to expectations, variables such as slope or curvature have not had enough prediction capability to improve the models produced by combining the three factors mentioned above. Although the susceptibility model was produced by combining only three categorical variables and the spatial probability computation involves some loss in spatial resolution (see Fig. 8), the model fits reasonably well the spatial distribution of the damage generated by landslides on October 25, 2011. However, the different distribution of rainfall within the catchment is likely to have conditioned the spatial distribution of mass movements. Thus, new inventories of rainfall-induced landslides are needed to better verify the forecast skill of the model. Until this is possible, the derived susceptibility model, could be the best tool for assessing quantitatively measures for landslide risk management based on spatial planning.

Land-use changes simulations provided useful information about possible mitigation measures of landslide areal frequency. Simulation results suggested that: (1) the restoring of the abandoned terraces does not seem to be effective against landslide processes; (2) a reduction of landslide risk can be achieved by reforesting abandoned terraces; (3) the application of local structural works on potentially unstable slopes seems to be able to provide a significant reduction of landslide risk with regard to roads and buildings, but it is not so effective at a basin scale; and (4) do nothing waiting for the natural reforestation of terraced areas is the most ineffective measure because it may increase slope instability in the near future.

Nevertheless, the outputs of the simulations must be taken with caution. For example, the state of conservation of the dry stone walls was not taken into account by the simulations. Therefore the reduction of landslide areal frequency by restoring abandoned terraces might has been underestimated. The analyzed landslides affected both abandoned and cultivated terraced areas characterized by dry stone masonry in a poor state of conservation. The similar landslide areal frequency observed for abandoned and cultivated terraces (see Fig. 10) can be, at least partially, attributed to the previous aspect. The landslide response of a restored and maintained terrace system is unknown in the absence of a more detailed analysis regarding the dry stone walls maintenance. By contrast, the effect on landslide areal frequency may be overestimated by the simulations in the case of the reforestation and structural works alternatives due to the following reasons: (1) a transition period is necessary to get positive effects on slope processes by reforesting (Carl and Richter 1989); within this period, which can reach some decades depending on vegetation type, erosional processes and shallow landslides can be triggered by rainfall (Cammeraat et al. 2005); (2) maximum effectiveness of the mitigation measures was assumed although this does not happen in practice.

By knowing the assumptions, limitations and results of the applied methodology, several additional issues need to be considered for assessing the most suitable landslide risk mitigation measure.

- Terraces restoration is very likely to attract public and private funding. This intervention could promote socio-economic activities thus favouring the return of new generations to agricultural activities. On one hand, this option can result in a better soil defence in the long term (Scaramellini and Varotto 2008; Parrotta and Agnoletti 2012; Stanchi et al. 2012). Nevertheless, the reconstruction of terraces is very expensive and can provide results only at medium and long terms. The lack of skilled workers able to reconstruct dry stone walls is another important problem to be faced.

- Reforestation is a cheap and easy to handle solution for reduce landslide processes, but this measure will lead to the loss of the cultural heritage of the terraced landscape and its biodiversity with impact on socio-economic development (Terranova 1984; Antrop 2003; Terranova et al. 2006; Agnoletti 2007; Arnaez et al. 2011).
- Local structural works on problematic slopes, if carried out through soil bioengineering techniques (Schiechtl and Stem 1996; Singh 2010) are suitable to safeguard the landscape. However, this measure does not solve the issue of land management at basin scale.
- Finally, choosing to avoid any intervention on the current slope dynamics, even if could be the cheapest option, could result in risk increasing and loss of the terraced landscape heritage.

6. Conclusions

After the extreme event which affected the Cinque Terre area (eastern Liguria) on October 25, 2011, an investigation was carried out to assess the stability conditions of the Vernazza catchment hillslopes producing a landslide inventory and a susceptibility model. This model was used to quantitatively assess land planning measures that may reduce landslide areal frequency and related risk. The certainty and reliability of the results and the applicability of the investigated measures have been discussed. As a result, we conclude that the most suitable spatial planning solution for reducing landslide processes in the Vernazza catchment appears to be the integration of two measures. On the one hand, applying structural works in the short term to stabilize the most landslide-prone slopes oriented towards roads and residential areas. These potentially unstable slopes may be recognized by using the produced susceptibility model. This model may also be transformed into a hazard model and used to optimize the design of the slope stabilization structures through cost-benefit and risk acceptability analysis (see, for example, Galve et al. 2012 for the methodology applied to structural mitigation measures for sinkholes). On the other hand, it is recommended that a long-term program of restoration and/or reforestation of abandoned terrace slopes and the maintenance of the active ones is adopted. The simulations carried out indicate that if no measures are applied to avoid the degradation of terraces (both active and abandoned), landslide areal frequency could increase and therefore the risk associated with future debris floods. Reforestation is an economical and reliable intervention to mitigate landslides but it does not meet landscape valorisation requirements of the Cinque Terre National Park. These requirements would be met by a terrace restoration programme, but this measure is very expensive and does not seem to improve terraced slope stability according to simulation results.

This research has thrown up that further work (i.e. structural solutions design and structure stability, cost-benefit and risk acceptability analyses) needs to be done to establish the most suitable solution for the Vernazza catchment hillsides stabilization at slope (i.e. structural works) and basin scale (i.e. terrace restoration vs. reforestation).

Acknowledgements

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Tables

Table 1 Variables used in this research

ID	**VARIABLE**	**Source**	**Data source scale**
E	Elevation	Topographic map of Liguria region	1:5,000
A	Aspect	Digital Elevation Model	pixel of 5x5 m
S	Slope	Digital Elevation Model	pixel of 5x5 m
C	Curvature	Digital Elevation Model	pixel of 5x5 m
P	Plan Curvature	Digital Elevation Model	pixel of 5x5 m
T	Profile Curvature	Digital Elevation Model	pixel of 5x5 m
V	Distance to drainage network	Topographic map of Liguria region	1:5,000
O	Distance to ridges	Topographic map of Liguria region	1:5,000
W	Wetness Index	Digital Elevation Model	pixel of 5x5 m
F	Distance to faults	Regione Liguria, 2006a	1:25,000
L	Land use	Cevasco et al., 2013a	1:5,000
G	Geology	Regione Liguria, 2006a	1:25,000

Table 2 Results of the cross-validation of the models

RANKING	**MODEL CODE**	Elevation	Aspect	Slope	Dist. to streams	Curvature	Plan curvature	Profile curvature	Dist. to ridges	Wetness index	Dist. to faults	Land use	Geology	Num. variables	**AUPRC**	**PRED20***
1	ELG	●										●	●	3	**0.77**	59 %
2	EVLG	●			●							●	●	4	**0.76**	59 %
3	SVLG			●	●							●	●	4	**0.75**	55 %
4	ESLG	●		●								●	●	4	**0.75**	55 %
5	SVPLG			●	●		●					●	●	5	**0.75**	55 %
6	EPLG	●					●					●	●	4	**0.75**	54 %
7	ECPLG	●				●	●					●	●	5	**0.75**	54 %
8	EVPLG	●			●		●					●	●	5	**0.75**	54 %
9	LG											●	●	2	**0.75**	38 %
10	EL	●											●	2	**0.74**	55 %
11	SVOLG			●	●				●			●	●	5	**0.74**	47 %
12	SVWLG			●	●					●		●	●	5	**0.74**	45 %
13	SVCLG			●	●	●						●	●	5	**0.74**	44 %
14	L											●		1	**0.73**	55 %
15	EG	●											●	2	**0.73**	50 %
16	[All]	●	●	●	●	●	●	●	●	●	●	●	●	12	**0.73**	48 %
17	ASVLG		●	●	●							●	●	5	**0.73**	47 %
18	SVTLG			●	●			●				●	●	5	**0.73**	42 %
19	ETLG	●						●				●	●	4	**0.72**	42 %
20	G												●	1	**0.72**	35 %
21	E	●												1	**0.70**	41 %
22	SVFLG			●	●						●	●	●	5	**0.70**	40 %
23	S			●										1	**0.50**	9 %

*PRED20: Percentage of landslides predicted with the 20% highest susceptibility area.

Figure captions

Fig. 1 Top: Location of the study area. The red dashed line indicates the boundaries of Cinque Terre; the grey area corresponds to the Vernazza catchment; blue dots indicate rain gauges (Le: Levanto; Mo: Monterosso; Co: Corniolo; Bo: Borghetto Vara). Bottom: Land use map of the Vernazza catchment (after Cevasco et al., 2013a, modified). Legend: 1) meadow; 2) scrub land; 3) forest; 4) terraced oliveyards; 5) terraced vineyards; 6) recently abandoned terraces; 7) forested abandoned terraces; 8) urban area. Base map after Regione Liguria (2006b).

Fig. 2 Geological map of the Vernazza catchment (after Regione Liguria, 2006a, modified). Legend: 1) Ponte Bratica Sandstones; 2) Groppo del Vescovo Limestones; 3) Canetolo Shales and Limestones; 4) T. Pignone Marls; 5) Macigno Fm. 6) Macigno Fm. - fine-grained sandstone lithofacies; 7) Macigno Fm. – pelitic and silty lithofacies; 8) Macigno Fm. – silty-marly lithofacies; 9) reverse faults and overthrusts; 10) direct faults.

Fig. 3 12h cumulative rainfall estimated at 1800 UTC in Ligura region during the event of October 25, 2011 (after A.R.P.A.L.-C.F.M.I.-P.C. 2012 , modified)

Fig. 4 Hietograms (blue bar) and cumulative rainfall (red line) for Borghetto, Levanto S. Gottardo, Monterosso and Corniolo meteorological stations (data from Regione Liguria – ARPAL 2011).

Fig. 5 Map of shallow landslides and erosional processes induced by rainfall on October 25, 2011 (after Cevasco et al. 2013a). Legend: 1) flow; 2) slide; 3) widespread outwash;

4) rill/gully erosion; 5) debris flood deposit; 6) down-cutting talweg ; 7) watershed boundary

Fig. 6 Examples of effects induced by rainfall of October 25, 2011 in the Vernazza catchment. a) shallow landslides, mainly of flow type, affecting an abandoned terraced slope close to Vernazza village; b) a complex shallow landslide affecting a partially abandoned terraced slope in the middle sector of the catchment; c) erosional processes that destroyed an embankment for parking area built on a tributary of the Vernazza stream; d) the alluvial fan generated by the debris flood at the marina of Vernazza (photo by Vernazza Municipality Administration).

Fig. 7 Prediction-rate curves (PRCs) for the more significant models. PRCs are cumulative frequency curves that indicate the proportion of landslides in the test set that occurs within a certain proportion of the area with the highest susceptibility (Chung et al. 1995). The larger the area between the PRC and the diagonal (grey line), the greater the prediction capability of the model.

Fig. 8 Histogram plot (blue columns) representing the proportion of landslides in each susceptibility class from the highest to the lowest susceptibility classes. Red line indicate the estimated empirical areal frequency of landslides based on a fitted step (or discontinuous) decreasing monotonic function. The limits of the stretches of this monotonic function were defined according to the slope changes observed in the success-rate curve (SRC) (orange line). The SRC is a cumulative frequency curve that indicates the proportion of the landslide population that occurs within a certain proportion of the area with the highest susceptibility (Chung and Fabbri 1999). The use of a monotonic function involves some loss in spatial resolution because this transformation reduces the number of susceptibility classes but it is necessary to overcome the land use change simulations. Similar approaches that use monotonic functions has been applied to produce probabilistic models by Fabbri et al. (2004), Zêzere et al. (2004), Chung (2006) and Galve et al. (2011).

Fig. 9 Susceptibility map produced for the Vernazza catchment. The landslide source areas used for producing the map have been indicated with black points. Susceptibility values indicate the spatial probability of the pixels to be a landslide source area for a landslide event equal to the one occurred on October 25, 2011.

Fig. 10 Box-plot of the spatial probabilities estimated for each land use class. See text for further explanation.

Fig. 11 Stretches of roads selected to be protected (in red) and location of hill slopes chosen to apply structural measures to avoid damages on buildings caused by landslides (in yellow). Vernazza catchment is indicated with a dotted purple line.

Figure 1

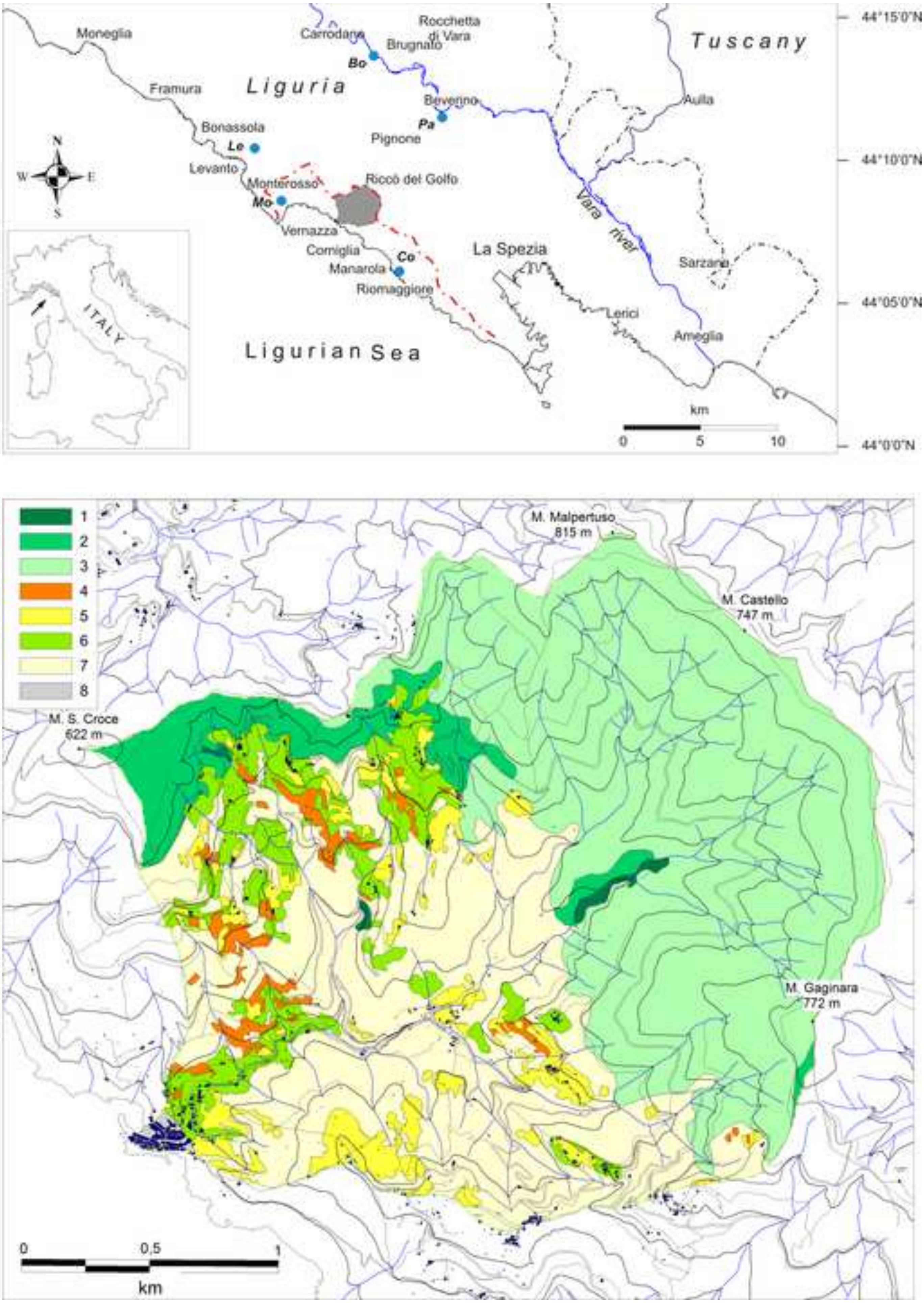

Moneglia
Carrodano
Rocchetta di Vara
Brugnato
Bo
Tuscany
Framura
Liguria
Beverino
Aulla
Pa
Bonassola
Pignone
Le
N
W
E
S
Levanto
Monterosso
Riccò del Golfo
Mo
Vernazza
Corniglia
Co
La Spezia
Vara river
Sarzana
Manarola
Riomaggiore
Lerici
ITALY
Ameglia
Ligurian Sea
km
0
5
10
44°15'0"N
44°10'0"N
44°05'0"N
44°0'0"N
1
2
3
4
5
6
7
8
M. Malpertuso 815 m
M. Castello 747 m
M. S. Croce 622 m
M. Gaginara 772 m
0
0,5
1
km

Figure 2

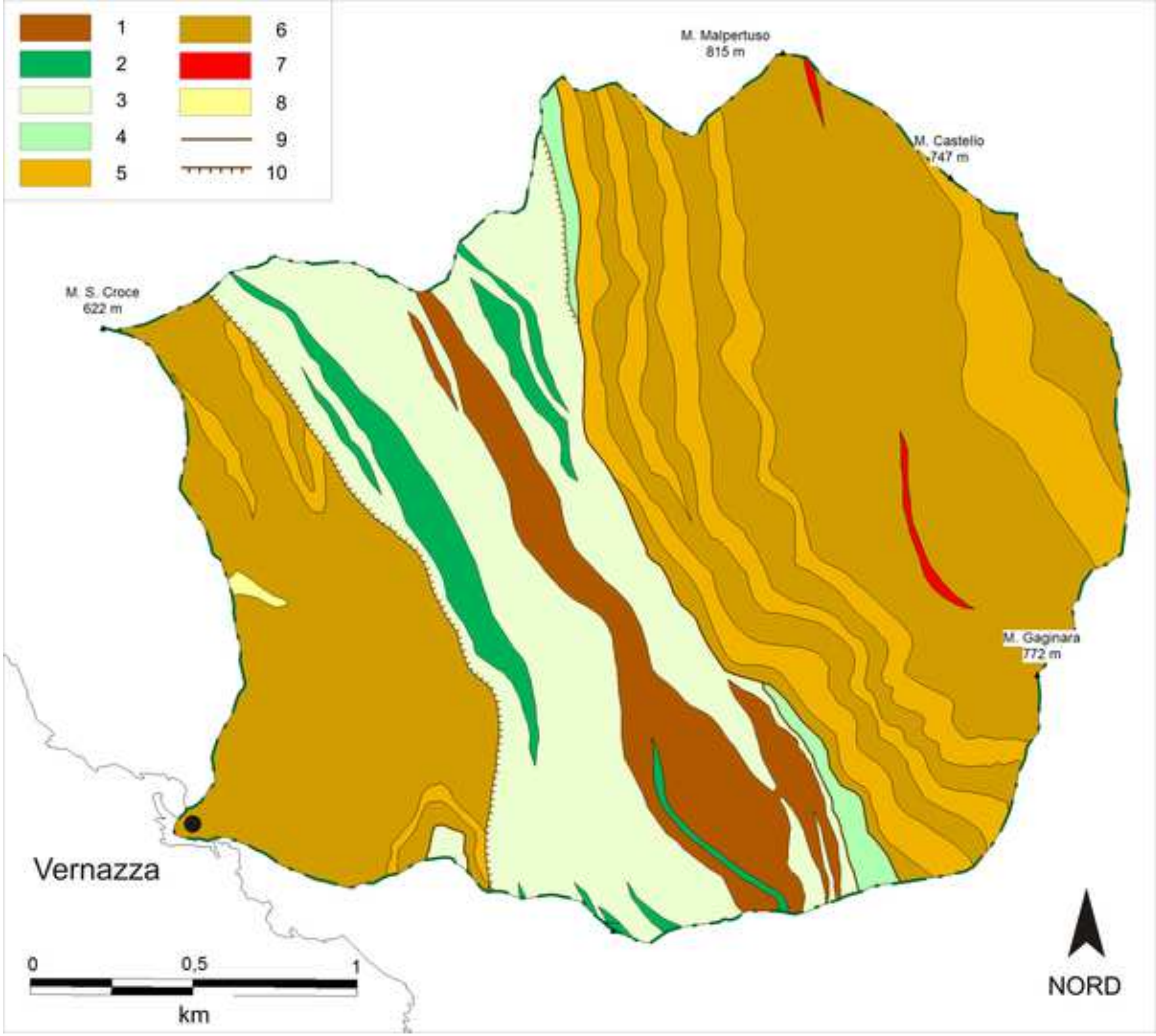

1
2
3
4
5
6
7
8
9
10
M. Malpertuso
815 m
M. Castello
747 m
M. S. Croce
622 m
M. Gaginara
772 m
Vernazza
0
0,5
1
km
NORD

Figure 3

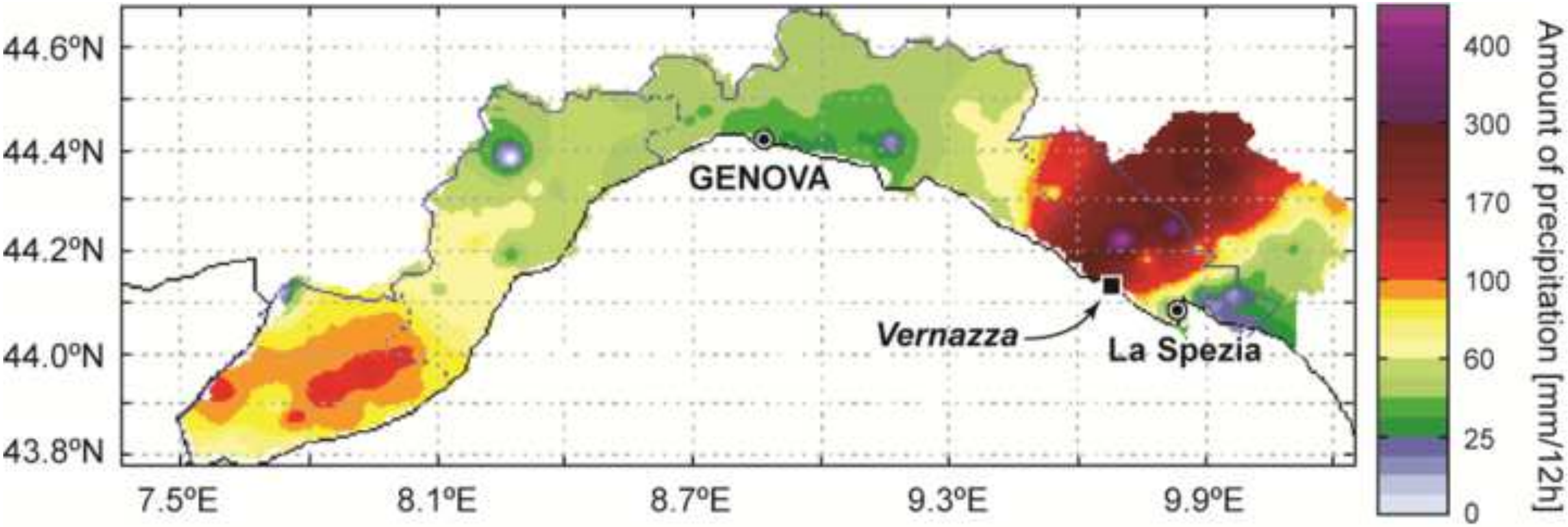
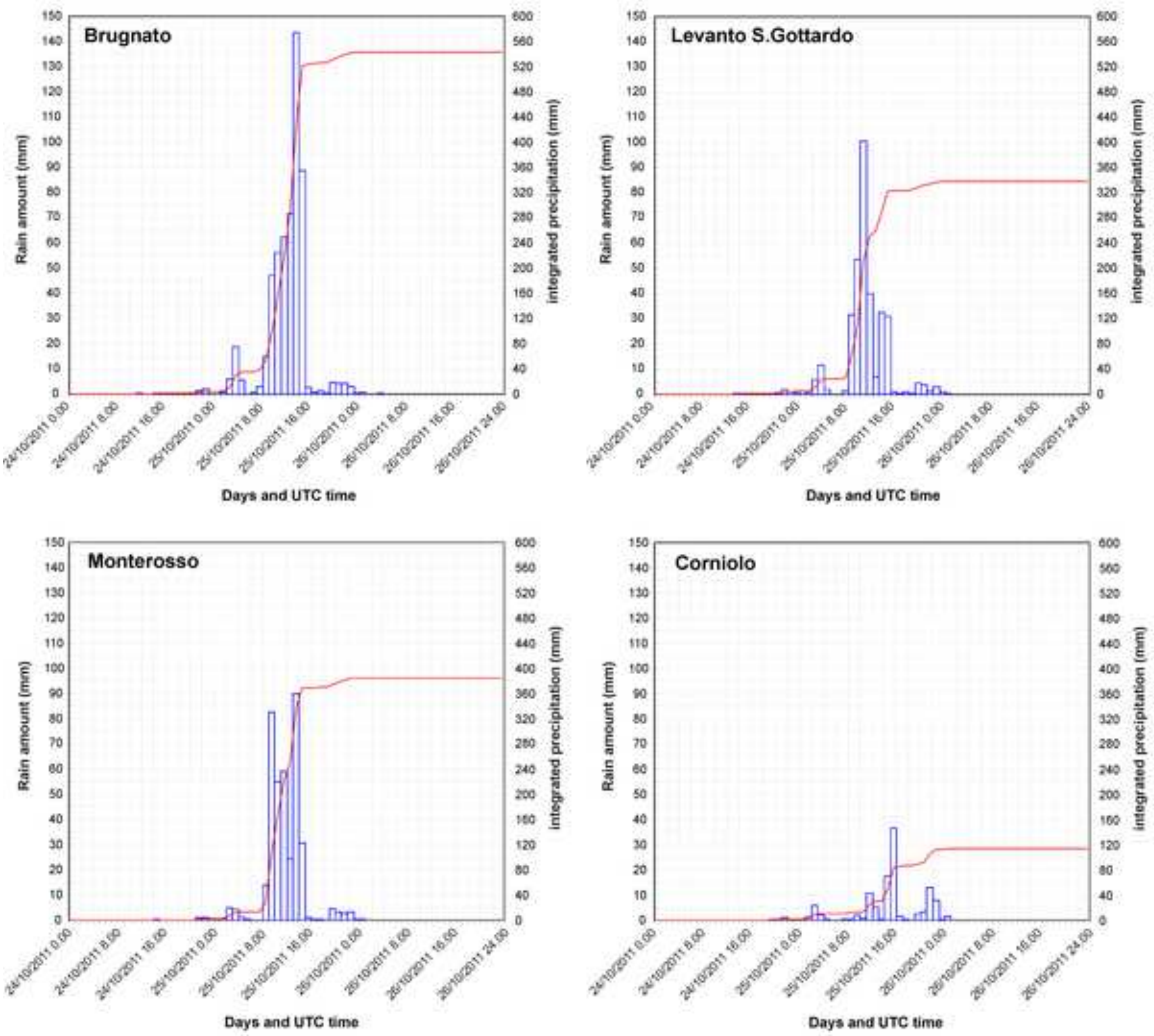

44.6ºN
44.4ºN
44.2ºN
44.0ºN
43.8ºN
7.5ºE
8.1ºE
8.7ºE
9.3ºE
9.9ºE
GENOVA
Vernazza
La Spezia
400
300
170
100
60
25
0
Amount of precipitation [mm/12h]

Figure 4



Brugnato
Levanto S.Gottardo
Monterosso
Corniolo
Rain amount (mm)
integrated precipitation (mm)
Days and UTC time
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
0
40
80
120
160
200
240
280
320
360
400
440
480
520
560
600
24/10/2011 0.00
24/10/2011 8.00
24/10/2011 16.00
25/10/2011 0.00
25/10/2011 8.00
25/10/2011 16.00
26/10/2011 0.00
26/10/2011 8.00
26/10/2011 16.00
26/10/2011 24.00

Figure 5

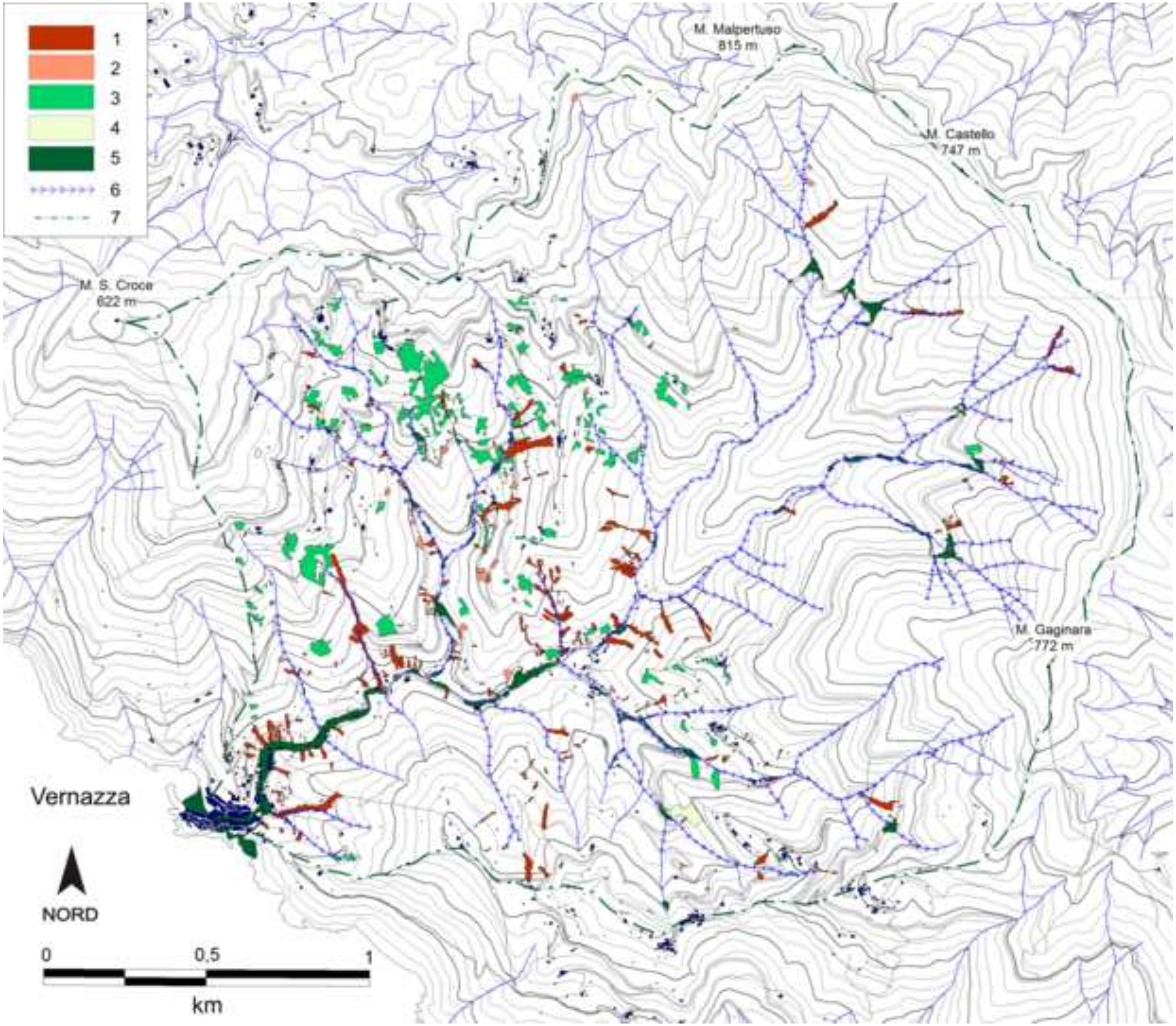
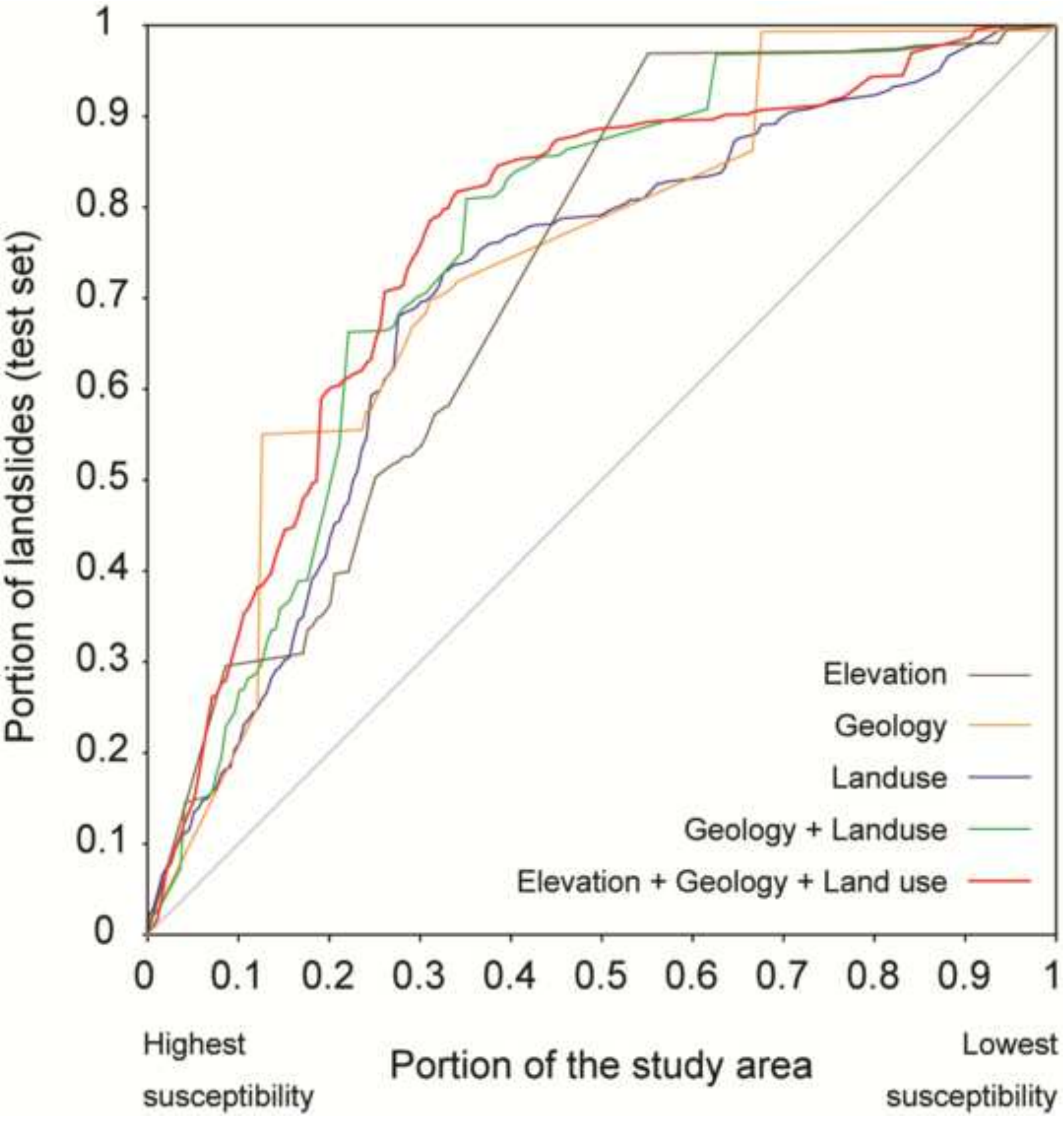

1
2
3
4
5
6
7
M. Malpertuso
815 m
M. Castello
747 m
M. S. Croce
622 m
M. Gaginara
772 m
Vernazza
NORD
0
0,5
1
km

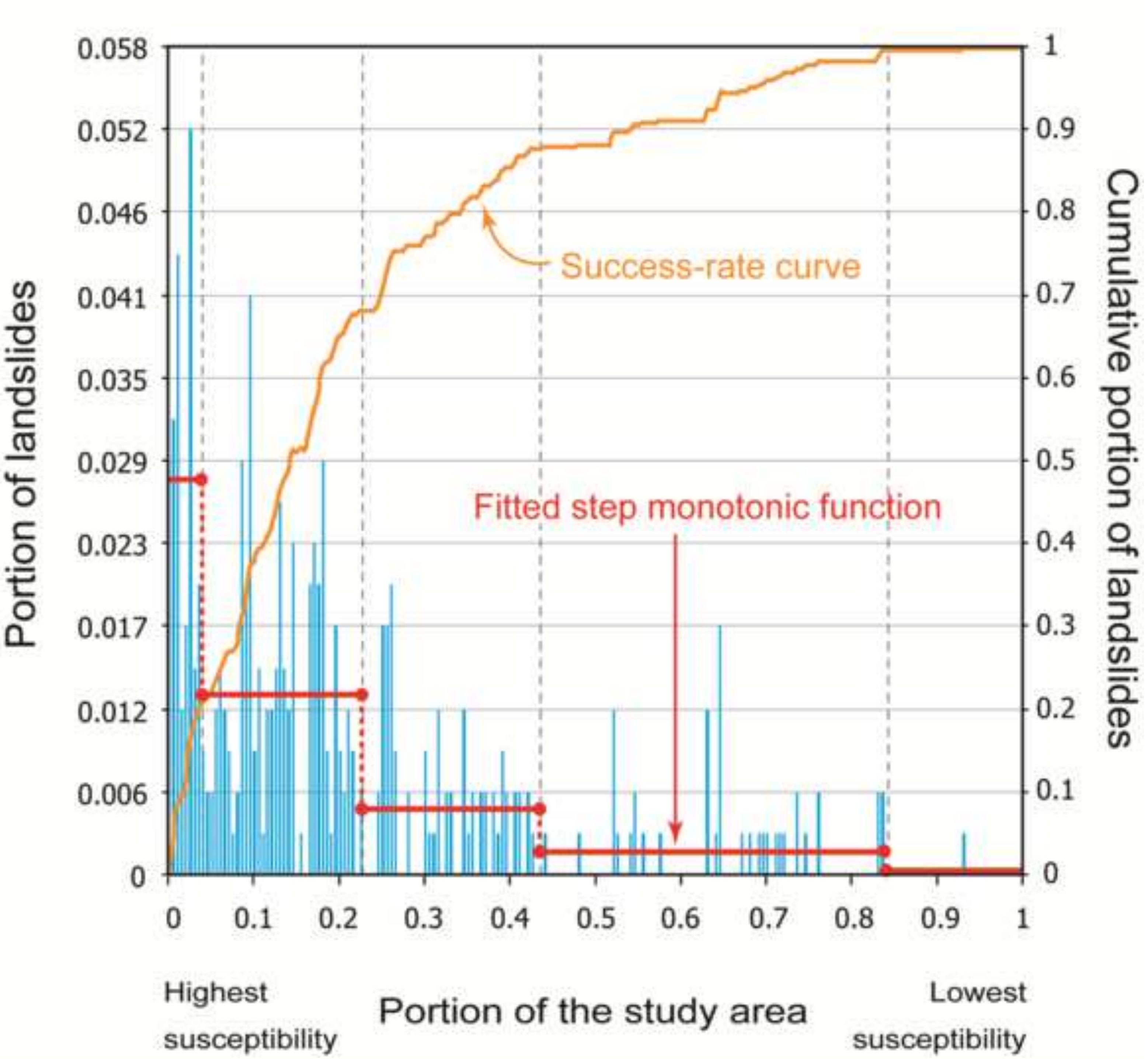
Figure 6

Figure 7



Portion of landslides (test set)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Highest susceptibility
Portion of the study area
Lowest susceptibility
Elevation
Geology
Landuse
Geology + Landuse
Elevation + Geology + Land use

Figure 8



0.058
0.052
0.046
0.041
0.035
0.029
0.023
0.017
0.012
0.006
0
Portion of landslides
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Cumulative portion of landslides
Success-rate curve
Fitted step monotonic function
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Highest susceptibility
Portion of the study area
Lowest susceptibility

Figure 9

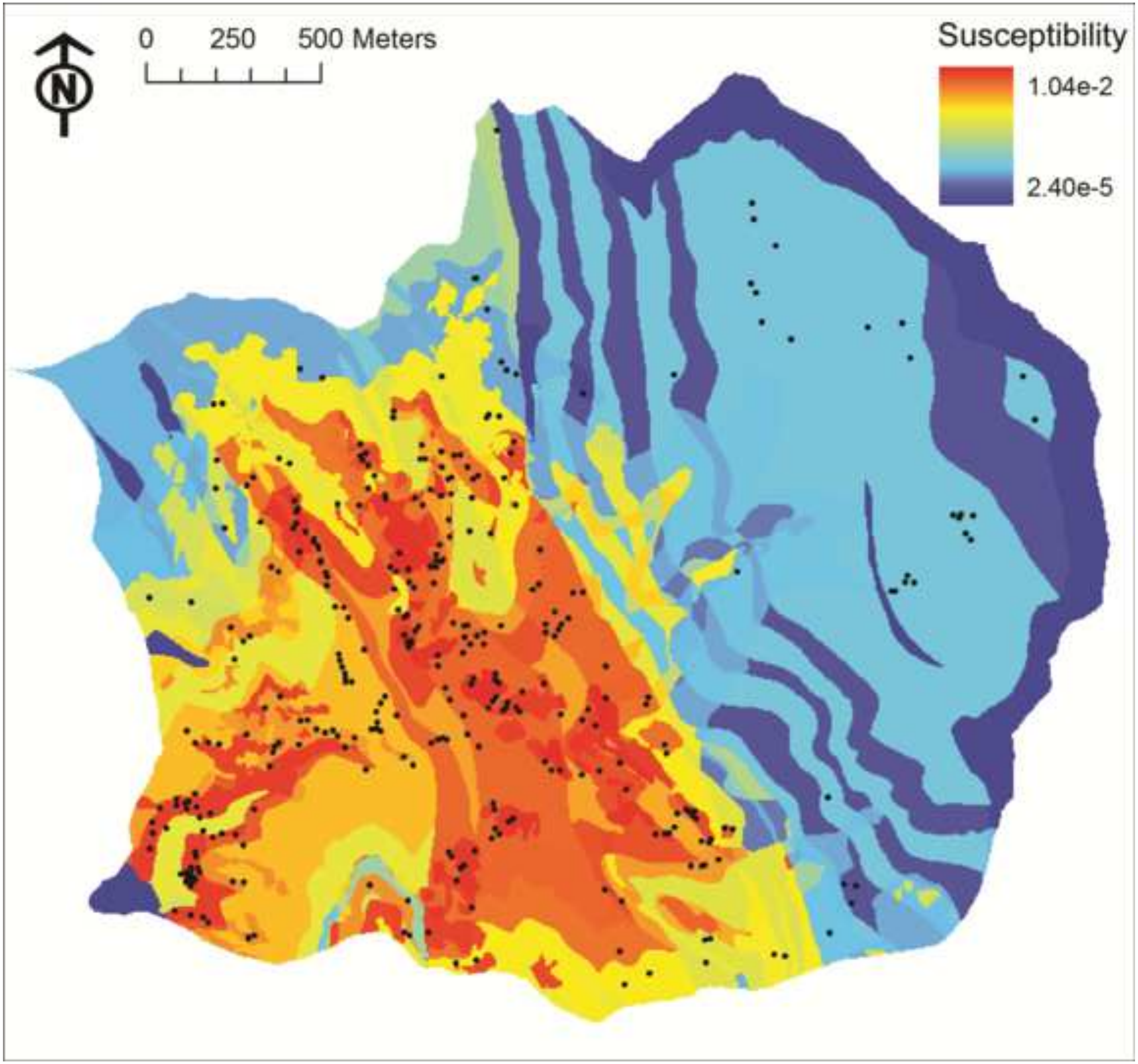
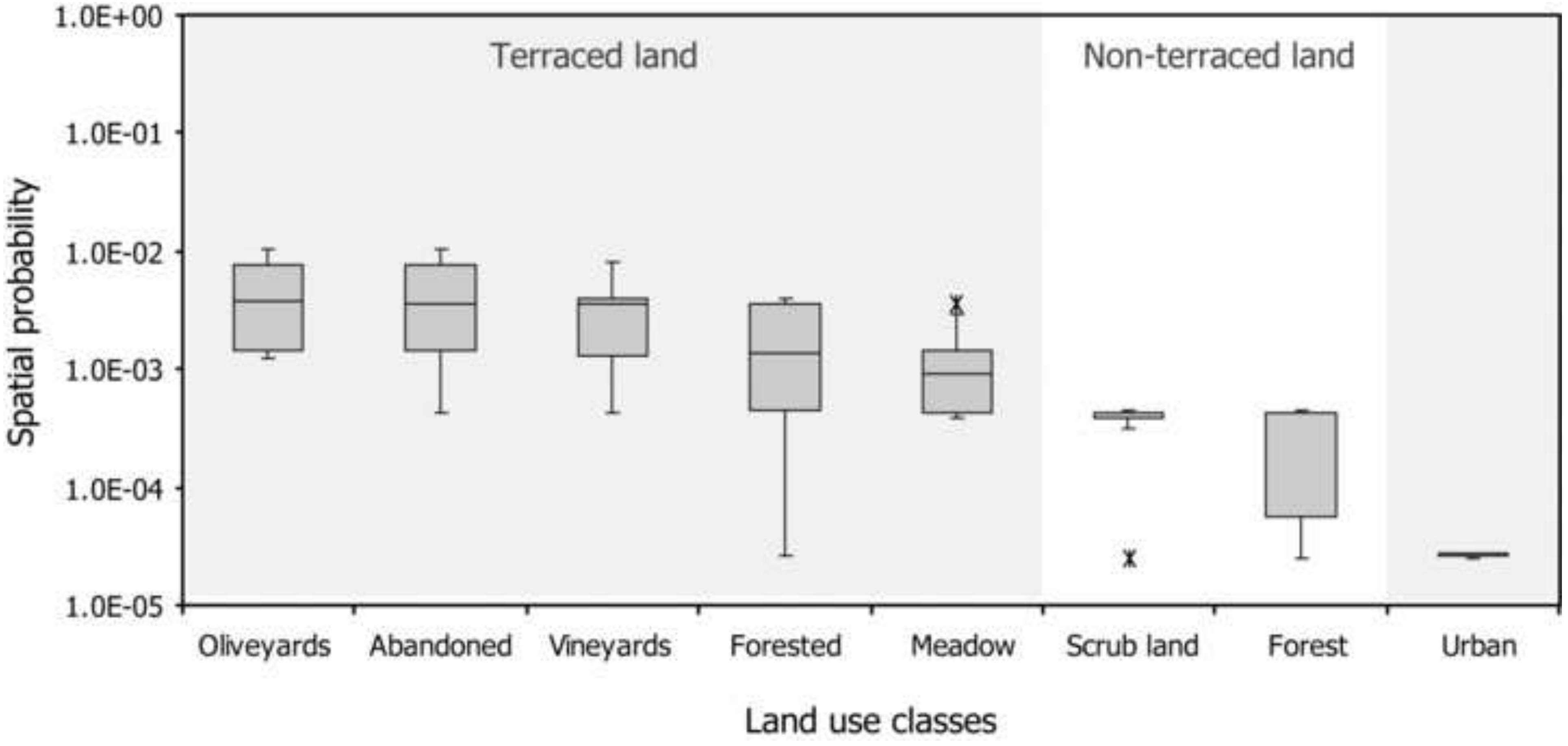


Figure 10



1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
Spatial probability
Terraced land
Non-terraced land
Oliveyards
Abandoned
Vineyards
Forested
Meadow
Scrub land
Forest
Urban
Land use classes

Figure 11