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# Cost-based analysis of mitigation measures for shallow-landslide risk reduction strategies

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**Abstract**

Landslide risk assessments are usually permeated by a certain degree of subjectivity. In order to reduce it, we have developed an original methodology which enables risk assessments to be carried out in fully quantitative terms, integrating both physical and economic science techniques. This risk assessment combines geomorphological studies, probabilistic modelling and cost-benefit analyses (CBA). We applied the methodology to an area of north-west Italy that was affected in 2011 by a dramatic rainfall-induced landslide event, and where a risk management program is necessary for avoiding future losses. We analyzed the cost-effectiveness of several landslide mitigation measures applying the proposed procedure. The results demonstrate that measures previously considered as suitable for mitigating shallow landslides were inappropriate from the economic viewpoint. The applied techniques also served to optimize economically the most appropriate mitigation measure. Moreover, our methodology allowed to calculate the maximum affordable investment on a cost-effective mitigation measure; this result will be a reference for designing innovative solutions to mitigate landslides in the study area.

**Keywords:**

Shallow landslide; risk assessment; mitigation; cost-benefit analysis; Liguria; Italy

## 1. Introduction

Decisions for managing landslide risk are often made just taking into account the available budget; analysis of the economic suitability or even optimization of the application of the proposed mitigation measures are generally not considered. Thus, the application of costly and oversized structural measures for stabilizing slopes are frequent when funding is available; and landslide risk mitigation does not usually happen when the budget is scarce (cf. Winter and Bromhead, 2012). These situations can be avoided by implementing quantitative landslide risk assessments. However, the latter involve difficult tasks and decisions that should take into account a wide range of issues, including hazard analysis, potential loss estimation and design of mitigation measures (Crozier and Glade, 2005; Gutiérrez et al., 2010; Van Asch et al., 2014). To date, this complex evaluation has commonly been carried out using semi-quantitative approaches; applying qualitative or quantitative procedures in different stages of the assessment according to the available data (e.g. Lateltin et al. 2005). However, nowadays there is an increasing need to perform quantitative risk analysis (Corominas et al., 2014) and, in some cases, the conditions are favourable to develop risk assessments totally based on measurable parameters (see e.g. Galve et al., 2012a, b).

Among other options, cost-based approaches can be reliable methodologies for developing landslide risk assessment in fully quantitative terms. These techniques can be applied at local and regional scale. The completion of this type of analysis at those scales depends on (1) the production of a sound landslide hazard map and (2) the estimation of costs generated by landslides and those economic losses saved due to the implementation of specific mitigation measures. Currently, procedures for performing comprehensive landslide susceptibility and/or hazard maps (i.e. hazard zoning) are widespread and well developed (e.g. Brenning, 2005; Chung, 2006; Lee et al., 2007; Rossi et al., 2010; Felicísimo et al., 2013; Piacentini et al., 2012; Lari et al., 2014; Piacentini et al., 2015), primarily because they require information currently accessible or easy to produce (DEMs, land use maps, geological information and landslide inventories). However, the usual absence of available information on costs produced by landslide occurrence prevents the calculation of risk in economic terms. This explains the scarce number of articles that describe quantitative approaches aimed at landslide risk estimation (e.g. Remondo et al., 2005; Zêzere et al., 2008; Jaiswal et al., 2010). The same problem also concerns the making available of reliable market prices for mitigation solutions. There is a wealth of literature on landslide mitigation measures and their technical suitability (e.g. Cornforth, 2005; Glade et al., 2005; Huebl and Fiebiger, 2005; Highland and Bobrowsky, 2008; Andreu et al., 2008; Bromhead et al., 2012; Mavrouli et al., 2014; Bowman, 2015) but it is difficult to obtain information in detail about their implementation costs. This is a common obstacle to analyze the cost-effectiveness of a proposed measure. For this reason, papers describing cost-benefit analysis (CBA) of landslide mitigation alternatives are rare. This deficit of knowledge on cost-based studies may prevent stakeholders from having an overview of optimum solutions for managing landslide risk. The development of quantitative risk assessment methods, capable of managing landslide problems in different settings, represents a crucial need for landslide risk managers. Among the modest number of papers dealing with cost-based landslide risk assessment the following can be highlighted. Fuchs and McAlpin (2005) analyzed the economic benefits of avalanche defence structures and discussed the protection that the public sector should provide. Holub and Fuchs (2008) used the results of a cost-benefit analysis to demonstrate that local structural measures should be considered as additional or alternative solutions to conventional structures for mitigating torrent-related phenomena (flash floods or debris flow). Agliardi et al. (2009) describe how to integrate rock fall numerical modelling and CBA to evaluate the cost efficiency of two protection scenarios. Lee and Chi (2011) combined geotechnical calculations with a cursory economical evaluation to assess the cost-benefit ratio of a proposed structural solution for stabilize a slope. Chen et al. (2010) and Narasimhan et al. (2015) provide two similar cost-based analyses of strategies to mitigate damages produced by flow-like phenomena. These authors based their assessment on the cost-benefit ratios obtained by implementing a specific mitigation strategy. Ballesteros-Canovas et al. (2013) present a comparable methodology for assessing the best option to reduce flood risk. The cited publications mainly deal with snow avalanches, rock falls and torrent-related hazards that may hit populated areas and describe methodologies aimed at analyzing the cost efficiency of static scenarios (i.e. the proposed protection scenario do not change to achieve the maximum efficiency). The present study attempts to fill a gap on landslide risk assessment and management by describing a methodology based on quantitative techniques to establish appropriate measures for mitigating shallow landslide risk along roads. Moreover, the techniques presented are designed to provide optimized mitigation solutions analyzing dynamic scenarios (i.e. the proposed mitigation solutions can be resized to achieve the maximum efficiency). We applied the procedure to an area of north-west Italy (Vernazza catchment, Cinque Terre National Park), that was affected by an impressive landslide-event on October 2011. The proposed methodology is completely based on measurable parameters and reduces the subjectivity that usually permeates risk assessments. It combines both physical and economic issues that make the study a multidisciplinary and a complex analysis. This complexity produces a significant level of uncertainty, but we also adopted a strategy to narrow it down. The case study shows: (1) how quantitative assessments can change local preconceptions about the best way to manage landslides; and (2) the importance of conducting this type of studies for avoiding to divert resources which could be better used. This research has also shown how the methods previously applied by Galve et al. (2012a, b) for analyzing the economic viability of a structural solution to mitigate sinkholes in a roadway may be adaptable to other geomorphic hazards in different environmental contexts.

## 2. Materials and methods

The proposed methodology links several logical steps and is derived from both physical and economic science techniques (Fig. 1). The following procedure was implemented: (1) production and validation of a landslide hazard model; (2) estimation of how the implementation of mitigation solutions can influence the areal frequency of landslides; (3) compilation of data on economic losses caused by landslide and calculation of the implementation costs of planned measures to mitigate them; (4) carrying out of a cost-benefit analysis (CBA) in order to identify the most cost-effective measure and how optimize it from the economic point of view; and finally, (5) analysis of the sensitivity of the CBA results to the variation of the input parameters.

The full description of the methods used to generate the hazard model (1) and to calculate the impact of mitigation measures on landslide areal frequency (2) is reported in Galve et al. (2015). For this reason, in this paper, only a brief outline of (1) and (2) is described, while a more detailed description of the methodology which dealing with the economic analysis (3; 4; 5) is presented.

### 2.1 Case study

The Vernazza catchment covers approximately 5.7 km$^2$ and is located in the easternmost part of Liguria (NW Italy) (Fig. 2). This area was declared as a World Heritage Site by UNESCO in 1997 and it is included in the Cinque Terre National Park. Cinque Terre is an outstanding example of a man-made landscape comprising centuries-old agricultural terraces retained by dry stone walls (Terranova et al., 2006; Brandolini, in press).

The Vernazza basin is characterized by very steep slopes with a terrain gradient ranging mainly between 30° and 40°. It has very short streams with ephemeral hydrological regime that, during heavy rainfall, can have considerable erosive and transport capacity. Similar to many other basins of eastern Liguria, the main village (Vernazza) is located in the terminal segment of a deep cut valley, where the Vernazza channel drains into the sea.

The bedrock lithology of the Vernazza catchment is mainly comprises sandstones and clayey siltstones flysch (Macigno Fm.) and claystones with limestones and silty sandstones turbidites (Canetolo Shales and Limestones). These formations are part of a wide overturned antiform fold (Regione Liguria, 2006). The bedrock is prevalently mantled by low thickness (1–2 m) soil slope covers that have been largely reworked for terracing. About 50% of the slopes were transformed by terracing for olive grove and vineyard cultivations. Currently, following the progressive exodus of farmers since the end of XIX Century, only 8% of the slopes are still cultivated. The remaining 50% of the slopes are located in the upper part of the catchment and are covered by forest and shrub lands.

The climate of the Cinque Terre coast is Mediterranean, with hot and dry summers and mild winters. The mean annual precipitation is about 1,000 mm and the rainiest month is October, with a mean value of 156 mm. Notwithstanding these average climate conditions, the region has been characterized in the last 25 years by even more frequent high intensity rainfall causing widespread geo-hydrological effects and associate severe damage (Cevasco et al., 2008; Brandolini et al., 2012; Silvestro et al., 2012; Cevasco et al. 2015; Del Monte et al., 2015).

Due to geological, geomorphological and land-use settings, the slopes of the Vernazza basin are susceptible to rainfall-induced shallow landslides of flow type. Following the intense urbanization, the valley floor is at high flood risk as dramatically the 2011 event confirmed.

#### 2.1.1 The October 25, 2011 landslide event

On October 25, 2011 the Vernazza catchment was affected by a very intense rainfall event. A cumulative rainfall of 382 mm and rainfall intensities reaching 90 mm/h, 195 mm/3 h and 350 mm/6 h were recorded in the nearest Monterosso rain gauge. The return period of the recorded peak values was estimated higher than 100 years (ARPAL-CFMI-PC, 2011). Historical archival research revealed that the final tract of the Vernazza valley was affected by a similar event in 1857 and 1859 (Rollando, 2003).

On the basis of a landslide inventory, carried out by detailed field surveys and analysis of high-resolution aerial photographs, more than 500 shallow landslides triggered by the 25 October 2011 storm were identified in the whole Vernazza catchment (Cevasco et al., 2012; 2013a). A total of 364 landslides were mapped; 174 landslides were not representable to scale. The landslides affected an area of 8.5 ha, corresponding to about 1.5% of the basin area (Cevasco et al., 2014). The average density of landslides was 63 landslides/km$^2$. Landslide phenomena that occurred on October 25, 2011 initiated as debris slides (Cruden and Varnes, 1996) and in most of cases evolved into debris avalanches or, sometimes, into debris flows. According to Hungr et al. (2014), debris avalanches are very rapid shallow flows of partially or fully saturated debris on a steep slope, without confinement in an established channel; instead debris flows are very rapid to extremely rapid flow of saturated non-plastic debris in a steep channel. Landslide areal extent ranges between hundreds of square metres up to thousands square metres. The failure surface corresponded, in most cases, to the contact between regolith and bedrock (Cevasco et al., 2013b). The highest density of failures (landslide source area) was observed on slopes with inclinations between 35° and 40° whereas phenomena affected mainly abandoned or poorly maintained terraces in the middle and lower catchment.

A disastrous debris flood occurred at the valley floor, affecting the Vernazza village and causing three fatalities. Debris heights up to 5–6 m were deposited in the historical centre of the Vernazza village. The deposition volume on the Vernazza valley floor was estimated about 60,000 m$^3$ (Cevasco and Brandolini, 2015). The solid charge of the flood was increased because of the material mobilized by landslides: (1) mainly soil and debris from colluvial deposits; (2) anthropically reworked sediments; (3) stones from terrace walls; and (4) materials from embankments of the roads and from the infill of a car park located in a valley outside the village.

Damage caused by landsliding and flooding was very severe in the area covered by the Cinque Terre National Park (see Table 1). The road network within the whole Vernazza catchment, the Genova – La Spezia railway, the tourist trails, the agricultural terracing, buildings, bridges, water supply and sewerage systems were affected (Brandolini and Cevasco, 2015). The road network was damaged by 77 shallow landslides which caused interruption of vehicle circulation (Fig. 3) and, moreover, road segments were completely destroyed (2 cases) or covered by deposits of debris flows. This impact on the road network, together with the interruption of the railway line, caused the complete isolation of Vernazza, which was accessible only by the sea for some days.

**2.2. Input data**

The data used for establishing optimum solutions to mitigate the damage produced by future landslides affecting the roads of the described study area include: (i) a digital elevation model (DEM) with a 5 m of resolution and parameters derived from it such as slope angle, aspect angle, slope concavity, and elevation; (ii) geological and land use maps; (iii) a landslide-event inventory including the location of the source and run out areas of 364 shallow landslides (Fig. 4), their characteristics and data of a suitable set of causal factors having a relationship with slope failures; and (iv) location of elements at risk (roads in our case study, Fig. 4). This information was digitized and included in a Geographical Information System (GIS) as different data layers. The inventory and cartographic data about causal factors were transformed into raster format with a pixel size of 5 x 5 m. Furthermore, data were compiled describing the temporal frequency of the studied landslide-event, the cost caused by landslides on roads (see section 2.5) and unit prices of mitigation measures.

**2.3. Modelling landslide hazard**

Risk estimations need a forecast of future landslide (areal and temporal) frequency to calculate potential losses due to these phenomena. Hence, we produced a hazard map that integrates the most probable spatial distribution of future landslides and the best estimate on their temporal frequency. This map indicates the annual probability to slide of each pixel in the study area. The first step for producing that hazard map was to classify the pixels of the study area according to its propension to slide producing a susceptibility map. Among the most widespread techniques for modelling landslide susceptibility we applied the Likelihood Ratio method (Chung, 2006) for producing multiple susceptibility models using each causal factor separately and different combinations of them. Subsequently, the predictive power of these models was evaluated by applying a 2-fold cross validation technique. The combination of causal factors that show the highest predictive capability were used to produce the definitive landslide susceptibility model. The hazard map was produced by dividing the values of areal frequency calculated in the susceptibility model by the return period of the triggering event; in our case, an extreme rainfall. We defined a best estimate for that return period in 100 years according to the estimates of ARPAL-CFMI-PC (2011).

## 2.4. Modelling landslide hazard reduction caused by mitigation measure implementation

A reduction in landslide frequency can lead to significant cost savings. Evaluation of potential cost savings was achieved through comparing costs incurred for the current land use with those incurred in response to four different land use scenarios (Galve et al., 2015). The four land use scenarios are:

1. *Total abandonment of terraces*. Following the current trend.

2. *Restoration of abandoned terraces*. The restoring of the abandoned and poorly maintained terraces with the re-emplacement of the typical cultivations of Cinque Terre (vineyards and olive grove) should be the most consistent choice with the aims of preservation and enhancement of cultural heritage in the study area.

3. *Reforestation*. Reforestation of terraced areas could be a cheap and easy means of mitigating shallow landslide risk.

4. *Local structural works on problematic slopes*. The measures proposed were structural bioengineering solutions to stabilize the most susceptible slopes oriented towards the roads, respecting the traditional terraced landscape.

The percentage of change between the values of landslide frequency in the reference and in the simulated models measures the potential reduction (or increase) of landslide hazard due to the implementation of a mitigation solution. This percentage can be translated into economic terms because the reduction of the hazard could lead to a reduction of the potential losses according to the exposure of the elements at risk. This translation needs a study on the economic losses caused by landslides which is explained in the following section.

**2.5. Estimation of economic losses produced by landslides**

The estimation of the economic losses caused by landslides can be carried out using different approaches. Moreover, this estimation may consider only direct or direct plus indirect cost (cf. Schuster, 1996). Direct cost refers to the cost of the materials and work units used to clean, repair or reconstruct a building or infrastructure impacted by a landslide. Those losses on the productivity of the area affected directly or indirectly by landsliding are the indirect costs.

The most straightforward approach to estimate direct costs is by means of inventories of the consequences of landslides on buildings and infrastructures. If this inventory covers a long time span, the costs related to past events must be transformed to present-day prices by using historical inflation rates. However, damage inventories are not very common and are usually produced after a landslide-event triggered by a major climatic or tectonic phenomenon. In regions where the active landsliding causes few problems and/or is not perceived as a major hazard, these inventories are scarce or they do not exist. In this case, three solutions may be taken to overcome the lack of information: (1) using published data about similar landslide damages (see data provided by Zezere et al., 2008, Crovelli and Coe, 2009; Nayak, 2010; Jaiswal et al., 2010; Vranken et al., 2013; OCDPC n°83 del 27 maggio 2013; Mateos et al., 2013;

Klose et al., 2015; Pizziolo et al., 2015; Table 2), (2) calculating the average costs for recovering a damaged structure simulating a hypothetical situation (e.g. Giacomelli, 2005; Bonachea, 2006; Galve et al., 2012a) or (3) carrying out a vulnerability analysis of the exposed structures (e.g. Mavrouli and Corominas, 2010; Sterlacchini et al., 2014 and references therein) and multiplying the resulting vulnerability with their cost.

Indirect costs are very diverse, and can include the temporal loss in the serviceability of a road, the health care costs of injured people, depreciation of land values, costs of legal actions, etc. Indirect losses associated to the temporal loss in the serviceability of a road can be calculated using well-established models in the cases in which a specific event or roadblock is analyzed or simulated on a truck or strategic transportation infrastructures where data about traffic flow and types of vehicles is available (e.g. Giacomelli, 2005; Galve et al., 2012a and b; Mateos et al., 2013; Winter et al., 2014). Other types of indirect costs usually are not considered nor calculated in many risk analyses because they are very difficult, often impossible, to estimate accurately, as mostly are not registered in market prices. However, indirect costs are usually higher than direct costs (see e.g. Perrin and Jhaveri, 2004; Galve et al., 2012a, b). For this reason, it is advisable, where possible, to estimate these costs; the acceptance of a mitigation measure could be conditioned by the incorporation of this information in the assessment. A sensitivity analysis considering virtual indirect costs equal to direct costs is also advisable in the case that there is not enough data to estimate the former. Indirect losses are commonly greater than direct losses, but it is difficult to establish by how much. Therefore, a pragmatic estimate of minimum costs can be achieved by taking indirect costs as being equal to direct costs.

The cost-based assessments only take into account economic losses. Personal losses, i.e. injuries and casualties due to landslides, are not considered, although their economic consequences may be contemplated (see e.g. Corominas et al., 2005). Personal or social losses can be transformed into monetary figures using the debatable concept of the Value of Statistical Life (VSL). Porter (2002) discussed this concept and reports that VSL can vary from 1 to 10 million US$. We prefer to perform a cost-based analysis without assigning a controversial economic value to human lives.

We based our damage loss estimation on data provided by local administrations. These data were reported on specific technical forms, predisposed by the Regional Government Administration and Civil Protection National Department, aimed to the comprehensive evaluation of the economical damage caused by landsliding and flooding for refund requests. The technical forms reported the following information: i) location of the area affected by the damage (1:5,000 scale map and photographs); ii) description of the type of damage; iii) planned recovery intervention; iiv) estimated cost of recovery interventions. The damages described in each technical form were assigned to a mapped landslide or to the debris flood. This allowed us to select the damages produced by landslides in the road network. Since this study implies the analysis of the interaction between shallow landslides and road network, the inventory map (Cevasco et al., 2013a) was carried out at a detailed scale (1:5,000 scale).

Through the comparison of the data derived from technical forms and the inventory map, the economic cost of recovery interventions was associated with the different types of phenomena and their extent, distinguishing damage caused by not channelled shallow landslides (NCSL, including debris slides and debris avalanches) and channelled processes (CP, including debris flows and erosional processes along streams). At last, only the damages related to NCSL affecting roads were selected and considered for the analysis.

### 2.6. Cost-benefit analysis of mitigation measures

Cost-benefit analysis (CBA) is the main tool for assessing the cost-based acceptance of a mitigation measure. CBA compares landslide mitigation solutions by calculating financial indices such as the Net Present Value (NPV) or the Internal Rate of Return (IRR). These indices identify the cost-effectiveness of a measure taking into account its lifespan and the time value of the money. The latter is considered through the application of an interest rate called the Discount Rate and is used to bring future cost values into the present. In the NPV case, decisions about the application of a determined measure or strategy can be made on the basis of whether a positive or negative value is obtained. On the other hand, IRR indicates the profitability of an investment and must be greater than a predefined discount rate. Additionally, CBA is not only used for knowing if a determined mitigation measure is cost-effective, but also can be applied for optimizing a solution to mitigate risk from the economic point of view.

In general, the analysis follows the classical with- and without- approach; CBA compares the landslide-related damages (generated over a specific time and transformed in monetary terms) in a "without mitigation" situation and multiple "with mitigation" scenarios. In our case, CBA was used to compare the damages estimated by using the landslide hazard model ("without mitigation" situation) and three simulated hazard models ("with mitigation" scenarios). These simulated models take account of the mitigation measures proposed to reduce landslide hazard in the road network. The zones where these corrective measures are applied reduce their propensity to be affected by landslides. Obviously, this reduction on landslide susceptibility produces a diminution of the associated economic losses, in other words, the amount of money not spent for recovering road stretches affected by landslides is considered as a benefit. On the other hand, the mitigation measures have an associated cost and we analyzed the equilibrium between these costs (i.e. investment for carrying out the proposed mitigation measures); the benefit derived from these changes in losses savings; and the residual risk that the changes cannot be avoided. Examples of calculations for a simple CBA are shown in Table 3.

We also use CBA to study the optimum design for each analyzed mitigation measure by calculating the maximum of the following function:

$$Z(p)=\sum_{t=1}^{n}\frac{B_t(p)-D_t(p)}{(1+i)^t}-C(p) \qquad (1)$$

where $Z(p)$ is the NPV obtained through the application of a particular design of a mitigation measure with a life span equal to $t$; $B_t(p)$ and $D_t(p)$ are the economic losses avoided and not avoided thanks to this measure in a time $t$, respectively; $C(p)$ is the initial investment on the mitigation measure; and $i$ is a predefined discount rate. We consider $t$ = 50 years because civil engineering structures are usually designed for service periods well above that life span and it is a reasonable planning horizon for CBAs that deal with public works. All these variables, with the exception of the discount rate, are functions of the so-called design parameter $p$ that corresponds to a characteristic of the mitigation measure directly related to its capacity for reducing future damages. For example, the parameter $p$ could refer to the height of a dam related to its capacity for controlling floods, the length of road segments protected by a fence for stopping falling rocks, or the resistance of a geogrid to avoid the collapse of an embankment through a sinkhole-prone area. Thus, Eq. (1) describes the variability of the NPV as a function of the changes on the design parameter and defines its economic optimum value and cost-effective range. In our case study, the parameter $p$ indicates the percentage of the area where the mitigation measure is applied. To optimize the investment (i.e. to achieve the maximum reduction on landslide frequency by investing the minimum amount of money), we simulate the application of a measure in the pixels of the map with the highest hazard value and continuing with the remainder pixels in order of decreasing hazard. As we apply the measure to further pixels (i.e. the percentage of the area covered by the mitigation measure is incremented), we observe the increase in the investment, the reduction of the residual risk and the increase in the NPV value. The investment reaches its optimum when the NPV value passes from negative to positive values.

The estimations derived from hazard modelling and damage loss estimation are combined to estimate the terms $B(p)$ and $D(p)$ using the Eq (2) and (3).

$$B(p) = H_a(p) * L \qquad (2)$$

$$D(p) = H_r(p) * L \qquad (3)$$

where $H_a(p)$ is the hazard avoided by the mitigation solution by applying a determined value of the design parameter $p$ in the considered location; $H_r(p)$ is the residual hazard not avoided by the measure; and $L$ is the average potential loss if the hazardous event takes place (Eq. 4). The “potential loss” ($L$) concept encompass in one parameter the terms vulnerability ($V$) and exposure ($E$) (value/cost of the exposed element).

$$L = V * E \qquad (4)$$

In other words, $B(p)$ indicates the reduction of the damages through the application of the mitigation measure and $D(p)$ corresponds to the remained residual risk. The well-know expression proposed by Varnes (1984) to compute risk (Eq. 5) is included in these two functions. Risk ($R$), in the Varnes’ terms, corresponds to the sum of $B(p)$ and $D(p)$ (see Eqs. 5, 6, 7, 8).

$$R = H * V * E \qquad (5)$$

$$R = H * L \qquad (6)$$

$$H = H_a(p) + H_r(p) \qquad (7)$$

$$R = [H_a(p) + H_r(p)] * L = H_a(p) * L + H_r(p) * L = B(p) + D(p) \qquad (8)$$

The parameter $C(p)$ is the cost of the mitigation measure (i.e. investment on mitigation). This is influenced by the design parameter $p$. For example, in the case of a dam, the greater the height ($p$ parameter related with its capacity to control floods), the greater the construction cost.

The definition of the discount rate ($i$) is always controversial because there is not a widely accepted criterion to define its value. This is an important issue because it may condition the acceptability of a mitigation measure. The suggested discount rates in the specialized literature vary from 2% recommended by the Congressional Budget Office of USA (Rose et al., 2007) to a maximum of 12% suggested by the Overseas Development Administration (ODA, 1988). A discount rate of 5% is an accepted value for long-term projects funded by public money (Nordhaus, 2004). Instead of applying a constant value as discount rate, we preferred to use the alternative presented by Lentz (2006) that models the value of discount rate through time (see Lentz, 2006, for more details and discussion on this formula).

Intensity can be integrated in the methodology through intensity-frequency analyses (also called magnitude-frequency analysis in studies of other natural hazards). This intensity-frequency analysis seeks to relate temporal probability of landslides with their intensity and, therefore, this may be related to their potential losses. A priori large landslides (with high intensity) may cause extensive damage (high costs). An example of how to integrate the intensity in this procedure is described by Galve et al. (2012a).

#### 2.6.1 Sensitivity analysis

Finally, we carried out a sensitivity analysis studying the impact of the most uncertain parameters on the CBA results. The values used in a CBA usually show a high degree of uncertainty and some of them may condition the applicability of a mitigation measure. This analysis can throw up many questions which may be usefully explored in the decision-making process for determining the most suitable measure. Situations not dealt with in the CBA considering best estimates can be taken into account through the sensitivity analysis. These values are within a reasonable range defined in our case by using expert judgement. The parameters examined for the Vernazza catchment were the following:

1. *Heavy rainfall event return period*. Three additional possible scenarios were studied regarding the return period of the landslide-event triggering factor: a recurrence interval of 50, 150 and 200 years for the extreme precipitation event. The first option (50 years) is conservative because it is hypothesized that in the future the hazard will be higher than currently. On the other hand, a 150 yrs recurrence interval was selected taking as reference the last similar event

registered in the study area (Rollando, 2003). Finally, an optimistic scenario with a return period of 200 yrs was also tested to know the profitability of the measures in the less hazardous case.

2. *Average cost of damages due to shallow landslides*. The uncertainty over the average direct losses caused by landslides in Vernazza is very low. However, the CBA only considers direct costs and ignores indirect costs. We do not have data for estimating indirect costs, but we speculated that these costs were almost in the same order than direct costs. Thus, we assessed the impact on the NPV if the average losses due to shallow landslide were to be doubled. This is reasonable because in most of the cases the indirect costs are greater than direct costs (Table 2), and we only equal these values. The scenario considering total costs may be believed conservative, but it is closer to reality. On the other hand, it may change the perception about the suitability of a measure under certain conditions. In our case, a clearly cost-effective measure considering direct and (figured) indirect costs were also taken into account as a suitable alternative against landslide processes. Additionally, we consider a lower average landslide cost calculating the overestimation of the economic losses provided by municipal and provincial administrations. The average unit cost, derived from the analysis of seven projects of terracing reconstruction planned after 2011 event, was calculated in about 500 Euros/$m^3$ (Fig. 5.F). This cost is 30% higher than the unit cost calculated by the regional price list (380 Euros/$m^3$). This increase in the cost estimations should be attributed to more complex and onerous intervention conditions. Thus, we also carried out the calculations using an average landslide cost 30% lower than the best estimate.

3. *Landslide probability*. Changes on landslide frequency were also tested to study the influence of this parameter on the results of the CBA. An increase and decrease of landslide occurrence of 15% was simulated.

4. *Efficiency of the proposed mitigation measures*. The previous analyses carried out by Galve et al. (2015) assumed a maximum effectiveness of the proposed structural works for reducing the occurrence of shallow landslides. In other words, where the structural measure is applied the probability of landslides is reduced to zero although this does not happen in practice. On the other hand, the same authors stated that the effect of terrace restoration on slope stability might have been underestimated. For these two reasons, we have considered the following situation: (1) a 70% of effectiveness of reforesting and the proposed slope stabilization techniques and (2) increasing the efficacy of the restored terraces one order of magnitude.

5. *Discount rate*. The selection of an appropriate discount rate is always questionable. We used the modelled discount rate according to Lentz's proposal (Lentz, 2006) as best estimate. Nevertheless, it is acceptable to apply a wide range of values from 2 to 12% as discount rates. We have used as reference for the case study the Italy long-term interest rates which vary between 2% and 13% during the last 20 years (European Central Bank, 2015). The average Italian interest rate in the latter time span was 5.5%; a similar value recommended by Nordhaus (2004) as discount rate for long-term projects. Thus, the NPV of the different alternatives using discount rates ranging between 2% and 13% was calculated.

# 3. Results

## 3.1. Impact of mitigation measures on landslide areal frequency

Galve et al. (2015) provided detailed descriptions of landslide frequency reduction as a result of mitigation measures. A summary of the main results of this analysis is provided below.

1. Abandoned terraces are critical elements in the Vernazza catchment as they are very susceptible to collapse when heavy/intense rainfalls occur. Cultivated terraces, although more stable, show instability problems due to the lack of maintenance. Analysis of the estimated spatial probability of landslide occurrence for different land uses shows that terraced land displays values approximately one order of magnitude higher than non-terraced land. Terraces abandoned for a long time (> 50 years) and re-colonised by natural vegetation show lower landslide probabilities than do cultivated or recently abandoned terraces. However, if there is no intervention on these elements a more hazardous situation than the present could result.
2. The restoration of abandoned terraces seems to be not very effective in reducing landslide areal frequency. This measure only can reduce the frequency of landslide by up to 1.5%.
3. The frequency of landslides that may affect roads can be reduced by up to 24% by reforesting abandoned terraces.
4. Apparently, the most suitable solution for reducing landslide damage in the study area is to design local structural works on unstable slopes. It was estimated that the protection of 23% of the roads stretches could reduce the number of landslides that affect this infrastructure by 66%.

## 3.2. Economic losses produced by landslides

The cost derived from landsliding in the Vernazza catchment are of the same order of magnitude as the reported economic losses caused by shallow landslides in developed countries (190–600 KEuro/landslide; Crovelli and Coe, 2009; Mateos et al., 2013; Klose et al. 2014; Pizziolo et al., 2015) (Table 2). The total economic damage caused by the 25 October 2011 event in the study area was estimated in 66.7 MEuros, without considering damage to private economic activities (Fig. 5.A). About 52% of the calculated total economic damage was caused by the debris flood that affected the Vernazza village, in the valley floor. It includes damage to the railway, village streets and parking, bridges, buildings, water supply and sewage systems, debris removal and disposal, hydraulic and maritime works. The remnant 48% of damage was caused by NCSL and CP (see subsection 2.5 for definitions) affecting the road network, slope terracing and buildings located in the catchment hillsides. Fig. 5.B shows that 73% (23.6 MEuros) of the calculated in the catchment hillsides due to NCSL and CP affected the road network (55% and 18% respectively); 22% (about 7 MEuros) affected slope terracing and buildings and the remaining 5% (1.6 MEuros) affected sewerage system and road network, including also less numerous damage caused by rock falls and rock slides on the road network.

Relations landslide type / average extent (Fig. 5C) and landslide type / economic cost (Fig. 5 D) were analyzed for NCSL. The landslide that affected roads had an average extent of about 660 $m^2$ for debris avalanches and about 220 $m^2$ for debris slides (Fig. 5.C). Although debris slides affected smaller areas than debris avalanches, the average cost of interventions for NCSL affecting roads (Fig. 5. D) was higher for the former (about 300,000 Euros) than for the latter (about 200,000 Euros). This is due to landslide geometry; the width is greater in the debris slides than in the debris avalanches and consequently the length of road destroyed from the former during an event is longer. In regard to NCSL affecting slope terracing and/or buildings, costs of interventions are higher for debris avalanches (about 330,000 Euros) than for debris slides (about 140,000 Euros). In figure 5.E the relation between of the economic cost damage along roads and shallow landslide extent are shown. Significant differences in the trend of the economic costs of damage / landslide extent ratio, depending on the landslide type, were identified. The higher economic cost of damage / landslide extent ratio was found for debris slides. However, strong correlations were not found between landslide size and damage cost and we decided not to integrate these data in the CBA. Our analysis was finally performed using the average damage cost produced by one landslide (debris slide/avalanche) in the study area (250,000 Euro). Using this value we have produced the risk model of the study area (Fig. 6).

### 3.3. Cost-effectiveness of the proposed mitigation measures

The results of the CBA can be summarized as follows:

1. The estimated unit cost for restoring terraces varies between 0.6 and 1 MEuro/ha and by taking into account the expected shallow landslide risk reduction along roads derived from this measure (1.5%), CBA indicates that a spend of no more than 4,000 Euro/ha can be justified. Therefore, in this case, the restoration of abandoned terraces is very far from being a cost-effective measure for combating slope instability. Although the reduction of landslide areal frequency by restoring abandoned terraces might have been

underestimated, the cost of the needed works for rebuilt the terrace system makes this option not profitable.

2. Reforesting the abandoned terraces seems to be the most appropriate solution for reducing landslide hazard efficiently from the economic point of view; even though a transition period is needed to start having positive effects on slope stability. We integrated the phase between planting and establishment of the vegetation in the calculations simulating an exponential growth of the forest reaching a maximum ground stabilization state at 50 years. We directly correlated the forest growth to the reduction on the landslide areal frequency (see Fig. 7). The estimated unit cost for reforesting was 6,000 Euro/ha and CBA indicates that this measure is cost-effective even if it cost up to 13,000 Euro/ha taking into account the mentioned transition period (Fig. 7). The investment for reducing by 11% debris slides/avalanches affecting the roads by means of reforesting 12.7 ha occupied by abandoned terraces is 76,000 Euro. It is estimated that this measure will reduce by up to 44% the future landslides in the reforested area (Fig. 8). This investment is expected to be paid off in a time period of 30 years. A NPV of 90,000 Euro is estimated for a time span of 50 years. The Internal Rate of Return (IRR) has been calculated at 6.4%. The cost-effectiveness of this measure is based on its low cost and ease of application.

3. We evaluated two possible configurations for the structural measures: (1) a combined structure formed by a dry stone wall reinforced with a live crib wall and (2) vegetated rock gabions (Fig. 9). The first option meets the cultural heritage requirements of the area maintaining the original materials and scenery

of the terraced landscape. The second option respects the landscape aesthetics, but introduces different building rules and materials. The combination of wood crib walls with dry stone walls may cost between 0.8 and 1.3 MEuro/ha. The cost of the replacement of dry stone walls by vegetated rock gabions was estimated in 0.2-0.3 MEuro/ha.

CBA shows that the maximum investment affordable in cost-effective terms for the corrective works is ~3 MEuro implementing an engineering solution over the most landslide-prone 57 ha (57%) of the slopes oriented towards roads (~52,000 Euro/ha) (Fig. 10). Thus, the combination of wood crib walls with dry stone walls or the green gabions do not achieve the cost-effectiveness requirements; the application of these bioengineering solutions is clearly unprofitable. In contrast to earlier ideas (see Galve et al., 2015), actions using structural measures on the most unstable slopes of the Vernazza catchment are not suitable for reducing landslide risk.

#### 3.3.1 Sensitivity analysis of CBA

According to the results of the sensitivity analysis, the restoration of abandoned terraces is a measure economically ineffective for reducing landslide risk in all the considered cases. Even when NPV is calculated considering: i) a return period of 50 years; ii) an average cost of damages per landslide of 500,000 Euro ; iii) an increase in landslide probability of 15%; iv) one order of magnitude increment of efficacy on landslide reduction of the measure; and v) a discount rate of 2%, the result is negative. On the other hand, sensitivity analysis points out that the cost-effectiveness of reforesting is tied only to one constraint.

Reforesting is not profitable if a discount rate of 13% is considered but this is a very extreme condition (Fig. 11). Regarding the use of local structural works on unstable slopes, the proposed measures are too expensive for being cost-effective solutions. Even in the case of green gabions and considering the most favourable situations (e.g. return period = 50 yrs; landslide costs = 500,000 Euro), these measures must have an efficiency of almost 100% for being cost-effective. Moreover, in this case, this solution would be implemented only in the 5% most potentially unstable slopes (Fig. 12) with a total cost no more than ~1.5 MEuro (~250,000 Euro/ha). Therefore, this is another piece of evidence indicating that the engineering solutions seem to be economically unsuitable for mitigating shallow landslides in the study area because the simulated situations under which these measures are cost-effective are unlikely.

## 4. Discussion and conclusions

The performed analysis has shown that the most cost-effective measure to stabilize the slopes in the study area is reforesting. This is not a surprising result because reforesting is frequently the initial response in managing shallow landslide processes, also decreasing both runoff and sediment loss (Trimble, 1990; Kosmas et al., 2000; Grove and Rackam, 2001; Nunes et al., 2010), particularly in humid areas where the establishment of vegetation is rapid. Reforesting is not a panacea as exemplified by Winter and Corby (2012) because this measure effectively contributes to stability only on a decadal scale. However, our study supports the suitability of this solution also taking into account the transition period between planting and establishment of the vegetation. The analysis also defined the areas to be reforested and the maximum affordable investment; this is a step towards improving landslide risk assessment. It is worth noting that nature itself reforested (and stabilized) most of the abandoned terraced slopes in the Vernazza catchment, particularly during the last sixty years. This reduced noticeably the instability of the slopes. We can estimate, using our hazard model, that currently this reduction at basin scale is ~35%. This nature-guided process favoured by the humid climate of the study area prevented a major disaster in Vernazza.

Nonetheless, our main result may provide drawbacks from the land management point of view. In fact, whilst reforesting abandoned terraces can clearly reduce risk, this alternative may cause loss of the cultural heritage and biodiversity related to the terraced landscape. On the other hand, the CBA results show that terrace restoration is unmistakably an unprofitable measure against landslides. However, it is worth noting that these results do not include the losses produced by the debris flood or the benefits of terrace restoration on the economy of Vernazza and its territory. It is clear that the debris flood was fed by materials from terraces and their stabilization could be cost-effective taking into account the damages produced by the flood. Moreover, the degradation of the terraced landscape of the Vernazza catchment could lead to the withdrawal of Cinque Terre National Park from the List of World Heritage Sites; this undoubtedly would lead to a negative impact on the local economy mainly based on tourism. Therefore, there is still much work to do in terms of (1) analyzing the effects of landslides on other elements at risk, (2) integrating the debris flood in the risk analysis and (3) including mitigation measures into a more comprehensive economic study. Moreover, the analysis has another limitation because it has considered a landslide event with 100 year-return period and not other single landslides that can occur within this 100 years period. This may underestimate landslide risk in the study area.

Terraces are efficient soil conservation structures to raise crop output, reduce erosion and intercept runoff water (Parrotta and Agnoletti 2012, Stanchi et al., 2012). However, these structures may become unstable under extreme conditions (i.e. intense rainfall events or earthquakes) and if their maintenance is rejected. Galve et al. (2015) pointed out that, currently, terraced terrain is the most unstable zone in the Vernazza catchment. In fact, the calculated spatial probability of landslides on terraced slopes displays values approximately one order of magnitude higher than that on non-terraced slopes. In long-abandoned terraced areas with terraces that have been re-colonised by natural vegetation a lower landslide probability was found than for cultivated or recently abandoned terraces. These results are consistent with previous studies developed in different poorly maintained terraced landscapes distributed worldwide where terraced slopes are usually described as the most landslide-prone areas (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; García-Ruiz and Lana-Renault 2011; Kitutu et al. 2011). These results seem to indicate that the maintenance of the terrace system should be a priority for avoiding losses caused by landslides. As the Vernazza case demonstrates, the abandonment of terraces produces a hazardous situation, but their restoration is expensive. On the other hand, the economic analysis performed in this study demonstrates that landslide hazard reduction cannot be used as the unique criterion for supporting the recovery of the terrace system in Vernazza. This action should be also supported using other arguments such as cultural, historical and environmental issues.

An interesting finding of the application of the proposed approach has been that our conclusions differ in some aspects from those previously published by Galve et al. (2015). In fact, the mitigation measure initially proposed as the most suitable in the study area for reducing the landslide risk (structural measures) has proven to be inefficient from the economic point of view. The application of structural engineering solutions over a large area is required to mitigate efficiently shallow landslides and that implies great costs. CBA demonstrates that in the case study the only acceptable mitigation measures are those that can be implemented extensively at low cost. This result is in accordance with the observations of Winter (2014) who indicates that installing extensive remedial works over very long lengths of road may be both unaffordable and unjustifiable. We used CBA to calculate the maximum affordable investment on the mitigation measure. The two proposed engineering solutions need a much larger investment than the maximum calculated but this value may be a reference for designing and dimensioning other possible solutions in the future. This proves that only a complete risk assessment based on quantitative data ensures a more efficient allocation of resources for mitigating hazards.

Finally, regarding the applicability of our methodology, the main difficulties the risk analysts will face are those related to (1) the availability of the input data, which is not always easily accessible; and (2) the high degree of uncertainty in quantifying values in some of the involved parameters.

Because of this absence of available data and uncertainty, it is advisable to consult local people involved in the recovering and mitigation of landslide damage: experts on engineering design solutions, building contractors, economists, decision makers, etc. In this complex analysis, its strengths and weaknesses may be highlighted by exchange of views between analysts and decision makers. Additionally, using their expert criteria it is always advisable to carry out a sensitivity analysis. This was our strategy for narrow the uncertainty down in the case study. We tested different values related to the return period of the triggering factor, the average cost of damages due to the hazardous event, the landslide probability, the efficiency of mitigation measures and the discount rate. In fact, some problems can derive from the definition of an updated triggering factor return period, especially when dealing with climate conditions. Other uncertainties can derive from the evaluation of direct and indirect costs of damages produced by a hazardous event. Direct costs are in general easier to evaluate although some problems resulting from the heterogeneity of data sources have frequently to be overcome. Indirect costs are very difficult to assess in the absence of specific data availability. Since landslide probability can vary in relation to the triggering factor magnitude also this aspect must be included in the sensitivity analysis.

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## Tables

**Table 1.** Examples of damages reported in the Cinque Terre National Park caused by the intense rainfall event of October 25, 2011 (extract from DCD n°6, 23 dicembre 2011).

| Municipality | Locality | Landslide type | Damage | Urgent action cost (€) | *Repair cost (€)* |
|---|---|---|---|---|---|
| Monterosso al Mare | Down town (Via Servano) | Rotational slide and shallow landslide | Villages, scattered houses, infrastructure | 910.000 | *80.000* |
| Monterosso al Mare | Down town (Via Magenta) | Shallow landslide | Road | 135.000 | *30.000* |
| …… | …… | …… | …… | …… | …… |
| Monterosso al Mare | Vettora | Shallow landslide | Scattered houses | 150.000 | *80.000* |
| Monterosso al Mare | Acquapendente | Complex roto-traslational slide | Villages, scattered houses, infrastructure | 785.000 | *600.000* |
| Monterosso al Mare | Rio Morrione catchment | Shallow landslide along the river | Villages, scattered houses, infrastructure | 2.480.000 | *1.100.000* |
| …… | …… | …… | …… | …… | …… |
| **Monterosso al Mare** | | | **Total amount (landslides, works along rivers, maritime works)** | **36.445.000** | ***44.760.000*** |
| | | | **Urgent action cost + Repair cost** | ***81.205.000*** | |
| Riomaggiore | Down town (Via dell'amore) | Rockfall | Villages, scattered houses, infrastructure | 3.751 | - |
| Riomaggiore | Manarola | Slide | Road | - | *80.000* |
| Riomaggiore | Palaedo | Slide | Pedonal road | - | *5.000* |
| **Riomaggiore** | | | **Total amount (landslides, works along rivers, maritime works)** | **3.751** | ***85.000*** |
| | | | **Urgent action cost + Repair cost** | ***88.751*** | |
| Vernazza | Massolina | Shallow landslide | Road | 298.000 | - |
| Vernazza | Massolina | Slide | Villages, scattered houses, infrastructure | 525.000 | *210.000* |
| …… | …… | …… | …… | …… | …… |
| Vernazza | Massolina | Rockfall | Road | 350.000 | *320.000* |
| …… | …… | …… | …… | …… | …… |
| Vernazza | Costa Lunga | Earth flow | Road | 191.000 | *76.000* |
| …… | …… | …… | …… | …… | …… |
| Vernazza | Vernazzola | Shallow landslide | Villages, scattered houses, infrastructure, terraced slopes | 52.700 | *21.300* |
| …… | …… | …… | …… | …… | …… |
| Vernazza | Garolla | Shallow landslide | Villages, scattered houses, infrastructure, terraced slopes | 170.000 | *15.000* |
| …… | …… | …… | …… | …… | …… |
| Vernazza | Santuario Nostra Signora di Reggio | Debris flow | Villages, scattered houses, infrastructure, terraced slopes | 250.000 | *9000* |
| …… | …… | …… | …… | …… | …… |
| **Vernazza** | | | **Total amount (landslides, works along rivers, maritime works)** | **57.437.400** | ***46.458.900*** |
| | | | **Urgent action cost + Repair cost** | ***103.896.300*** | |

**Table 2.** Some examples of economic losses caused by landslides

| Location | Period | n° of landslide *in bracket number of landslide inventory | Landslide type | Damages | Economic loss (total)<br>*(direct costs)* | Unit cost per landslide (€) *in bracket cost per landslide in the inventory map | Source of information |
|---|---|---|---|---|---|---|---|
| Emilia-Romagna Region (north Apennines, Italy) | March–April 2013 | 1500 reported - 500 repaired | Earth slides, Earth flows, Rock falls, Shallow landslides | Roads, houses, manufacturing activities | -<br>*140 million €* | -<br>*280000* | Pizziolo et al., 2015; OCDPC n83 del 27 maggio 2013 |
| Lower Saxon Uplands (NW Germany) | 1980-2010 | 33 | Shallow landslides | Roads | -<br>*23,5 million $* | -<br>*633788* | Klose et al., 2014 |
| Majorca (Balearic Islands, Spain) | October 2008 - May 2010 | 34 | Rock falls - rock avalanche (15), Earth slides - earth flows (15), Karstic collapses (4) | Roads, houses, holiday apartment blocks, dwellings, barns, power station | 11 million €<br>*6,4 million €* | 323529<br>*188235* | Mateos et al., 2013 |
| Flanders (Belgium) | 1 year | (291)* | Deepseated landslides (Earth slides), Shallow landslides | Houses, administrative - industrial - commercial buildings, electricity grid, roads, railways and underground cable | 3,020,049 €<br>*688,000 €* | (10378)*<br>(2364)* | Vranken et al., 2013 |
| Nilgiri hills (southern India) | 1987-2007 | 901 | Shallow debris slide | Railways, Roads | 1.907.640 $ - 16.369.500 $<br>*1.743.000 $* | 1884 - 16170<br>*1722* | Jaiswal et al., 2010 |
| Uttarakhand (northern India) | 1994-2008 | 178 | Rock slides, debris slides | Highway | 3,4 million $<br>*3 million $* | 17000<br>*15000* | Nayak, 2010 |
| San Francisco Bay region (U.S.A.) | 1 year | 65 | Debris flows, Earth flows, Complex landslides | - | -<br>*14,8 million $* | -<br>*202646* | Crovelli and Coe, 2009 |
| Lisbon (Portugal) | 1967-1996 | (147)* | Shallow translational slides, Translational slides, Rotational slides | Villages, scattered houses, infrastructure | *5,2 million €* | -<br>*(35374)** | Zezere et al., 2008 |

**Table 3**. Cost-benefit analysis illustration for a landslide mitigation measures implementation. The values of the table are fictitious; they are only used to exemplify the calculations.

| **Year** | 1 | 2 | 3 | 4 | 5 | .......... | 50 |
|---|---|---|---|---|---|---|---|
| **Situation without countermeasures** | | | | | | | |
| Landslide damage costs (landslide risk) (1) | 150,000 | 150,000 | 150,000 | 150,000 | 150,000 | .......... | 150,000 |
| **Situation with countermeasures** | | | | | | | |
| Landslide damage costs (residual risk) (2) | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | .......... | 30,000 |
| **Damage costs saved (Benefits)** | | | | | | | |
| Costs saved (3) | 120,000 | 120,000 | 120,000 | 120,000 | 120,000 | .......... | 120,000 |
| Discount factor (4) | 0.952 | 0.907 | 0.864 | 0.823 | 0.784 | .......... | 0.087 |
| Discounted costs saved (5) | 114,286 | 108,844 | 103,661 | 98,724 | 94,023 | .......... | 10,464 |

| | |
|---|---|
| **Investment on mitigation measures** (6) | 1,500,000 |

| | |
|---|---|
| **NPV** (7) | 690,711 |

(1) Landslide risk = Hazard (landslides/year) x Potential Loss (Euros/landslide)
A landslide event produce 50 landslides; Landslide event return period = 100 years; Hazard = 0.5 Landslides/year; Potential loss = 300,000 Euros/Landslide ; Landslide risk = 150,000 Euros/year
(2) Residual risk = Residual hazard (landslides/year) x Potential Loss (Euros/landslide)
A specific measure mitigate 80% of landslides; Residual Hazard = 0.1 Landslides/year; Residual risk = 30,000 Euros/year
(3) Cost saved = Landslide risk - Residual risk = 120,000 Euros/year
(4) Discount factor = (1/(1+*i*))^Year; Discount rate (*i*) = 5% in this example
(5) Discounted cost saved = Cost saved × Discount factor
(6) Investment on mitigation measures: Cost of measures for reducing landslide by 80%. This is inversely proportional to the residual risk. The greater the investment, the lower the residual risk.
(7) NPV: Net Present Value = ∑ Discounted cost saved - Investment on mitigation measures.

**Figure captions**

Figure 1. Methodological flow chart diagram.

Figure 2. Location of the study area.

Figure 3. Examples of damages produced by shallow landslides on the road network in the Vernazza catchment. A: debris avalanche (Piculla landslide) affecting a partially abandoned terraced slope and a road running at the slope foot in the middle catchment; B), C), D): debris slides accumulations littering the roadway in the middle (B, D) and lower catchment (C). The scoured slopes under the roads shown in B) and C) are effects of erosional processes along streams.

Figure 4. Location of the inventoried source landslide points and analyzed roads and slopes. These slopes cover the hillsides oriented towards the roads where it is expected that 90% of the landslides affecting the roads will be concentrated. Digital Elevation Model (DEM) and road network were derived from the 1:5,000-scale topographic map of Liguria region.

Figure 5. A - Total economic losses. B - Economic damage in the catchment hillsides: caused by NCSL affecting roads (1), by CP affecting roads (2), by NCSL and CP affecting slope terracing and buildings (3), by NCSL and CP affecting other assets (sewerage system and rack network) (4). C - average extent of NCSL: debris slides (1) and debris avalanches (2) affecting slope

terracing and/or buildings; debris slides (3) and debris avalanches (4) affecting roads. D - average cost of interventions for NCSL: debris slides (1) and debris avalanches (2) affecting slope terracing and/or buildings; debris slides (3) and debris avalanches (4) affecting roads. E - Relationships between damage economic cost along roads and NCSL extent. F – Relationships between the cost of some intervention of terracing restoration designed after 2011 event and dry stone walls volume ($m^3$).

Figure 6. Risk map produced for the analyzed slopes.

Figure 7. Evolution of the savings through time applying the reforesting alternative taking into account the progressive forest growth and associated reduction of the landslide areal frequency.

Figure 8. Reforested area simulated (i.e. slopes occupied by abandoned terraces).

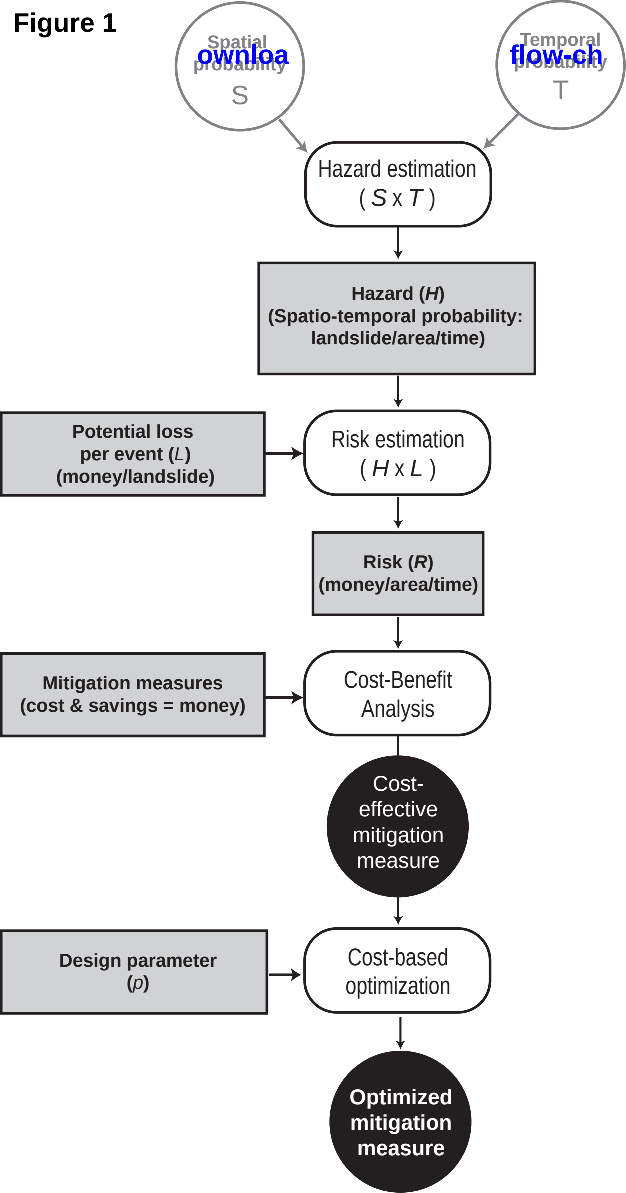
Figure 9. Structural bioengineering solutions to stabilize the most susceptible slopes oriented towards the roads of the Vernazza catchment. A - Dry stone wall reinforced with a live crib wall. B - Vegetated rock gabions.

Figure 10. A - $Z(p)$ functions obtained to identify the maximum investment affordable for the corrective works (~52,000 Euro/ha). B - Area defined by the $Z(p)$ to apply structural measures in cost-effective terms.

Figure 11. Net Present Value ranges obtained in the sensitivity analysis for the reforesting alternative.

Figure 12. Slopes where green gabions may be installed instead of dry stone walls at a maximum cost of 250,000 Euro/ha considering a ca. 100% efficiency.

Figure 1



Spatial probability
S
Temporal probability
T
Hazard estimation
( S x T )
Hazard (H)
(Spatio-temporal probability: landslide/area/time)
Potential loss per event (L)
(money/landslide)
Risk estimation
( H x L )
Risk (R)
(money/area/time)
Mitigation measures
(cost & savings = money)
Cost-Benefit Analysis
Cost-effective mitigation measure
Design parameter
(p)
Cost-based optimization
Optimized mitigation measure

Figure 2

ITALY
N
W
E
S
Genova
Savona
Imperia
Ligurian Sea
Monterosso rain gauge
Vernazza catchment
La Spezia
km
0
25
50

Figure 3

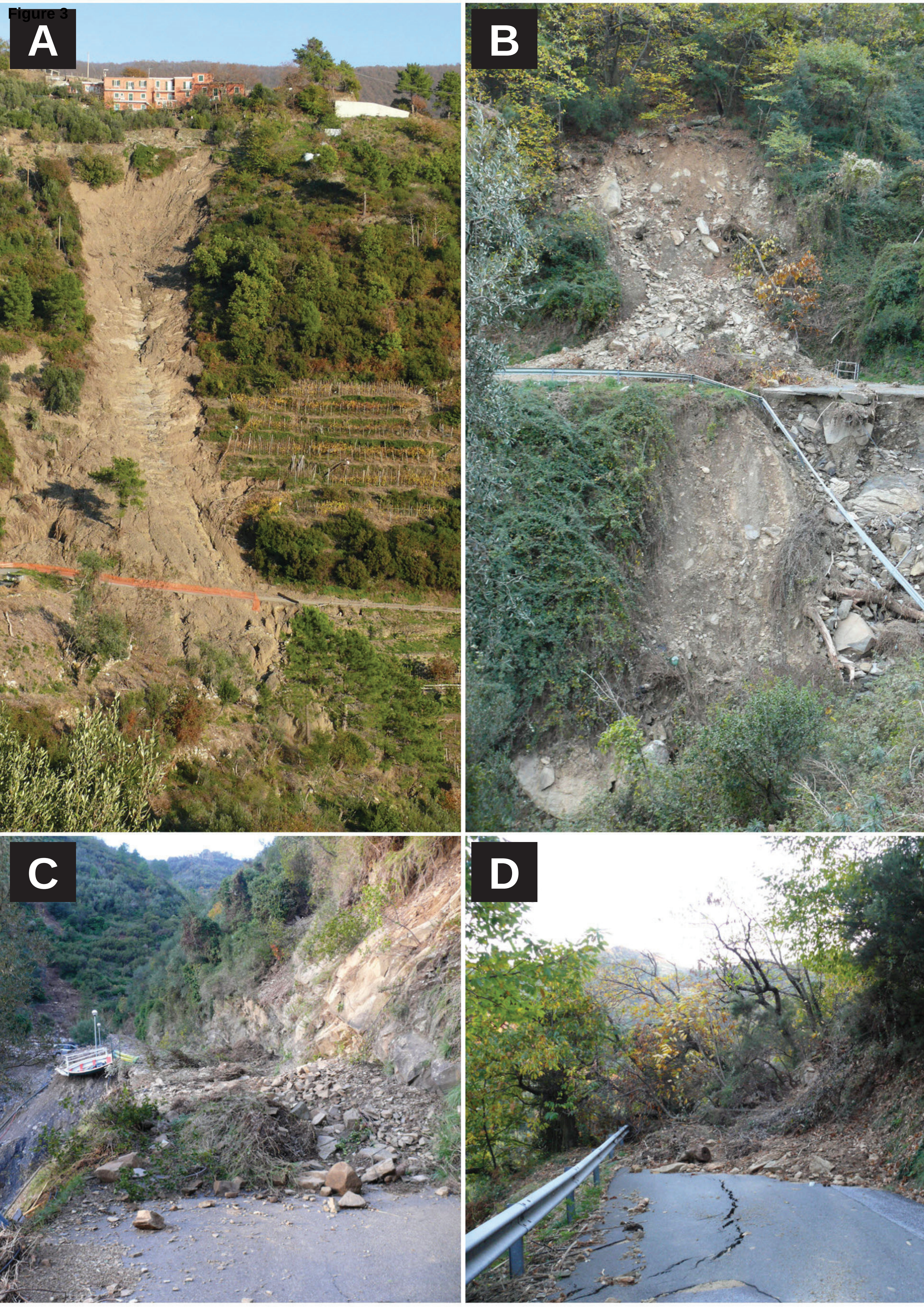
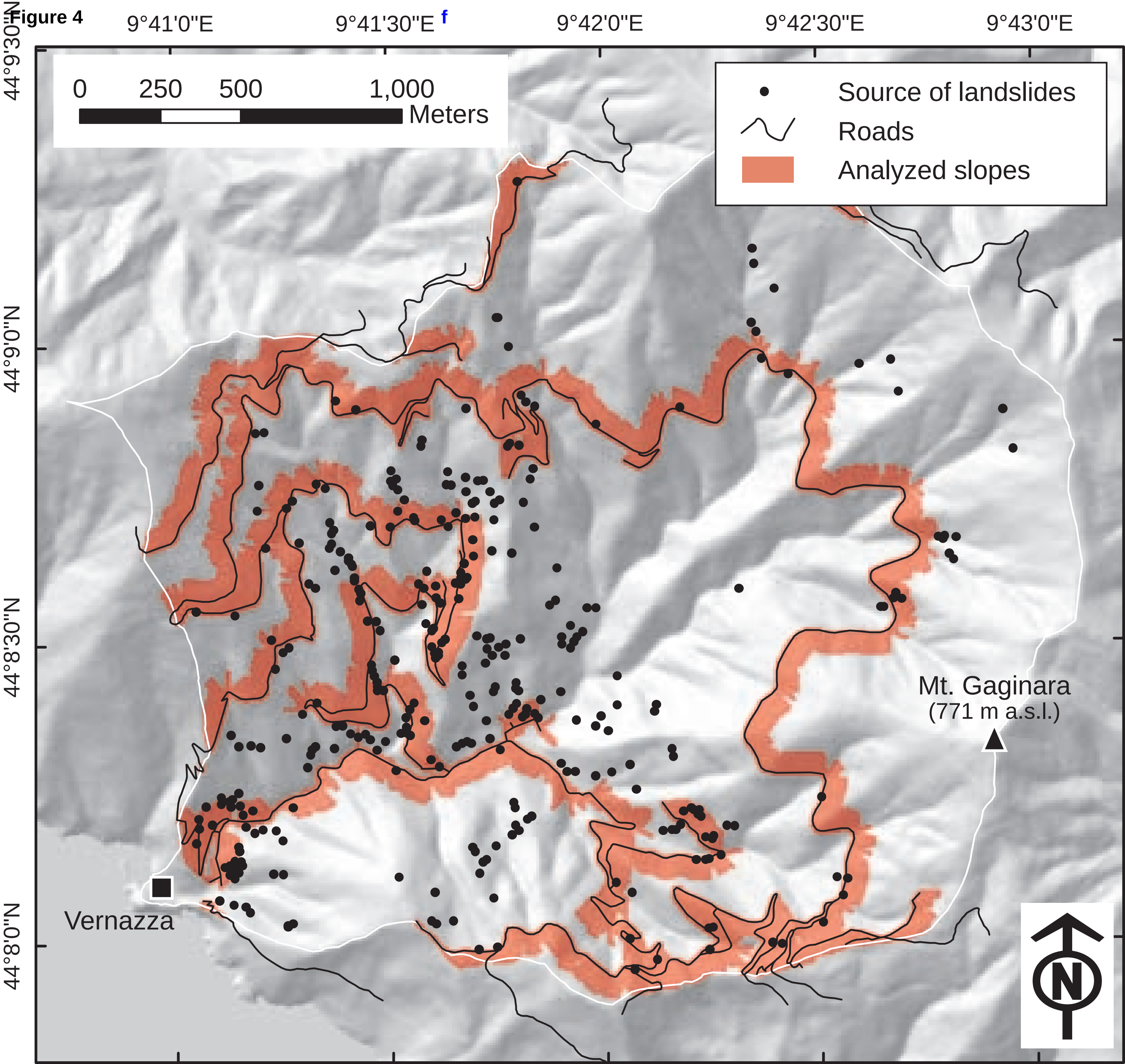
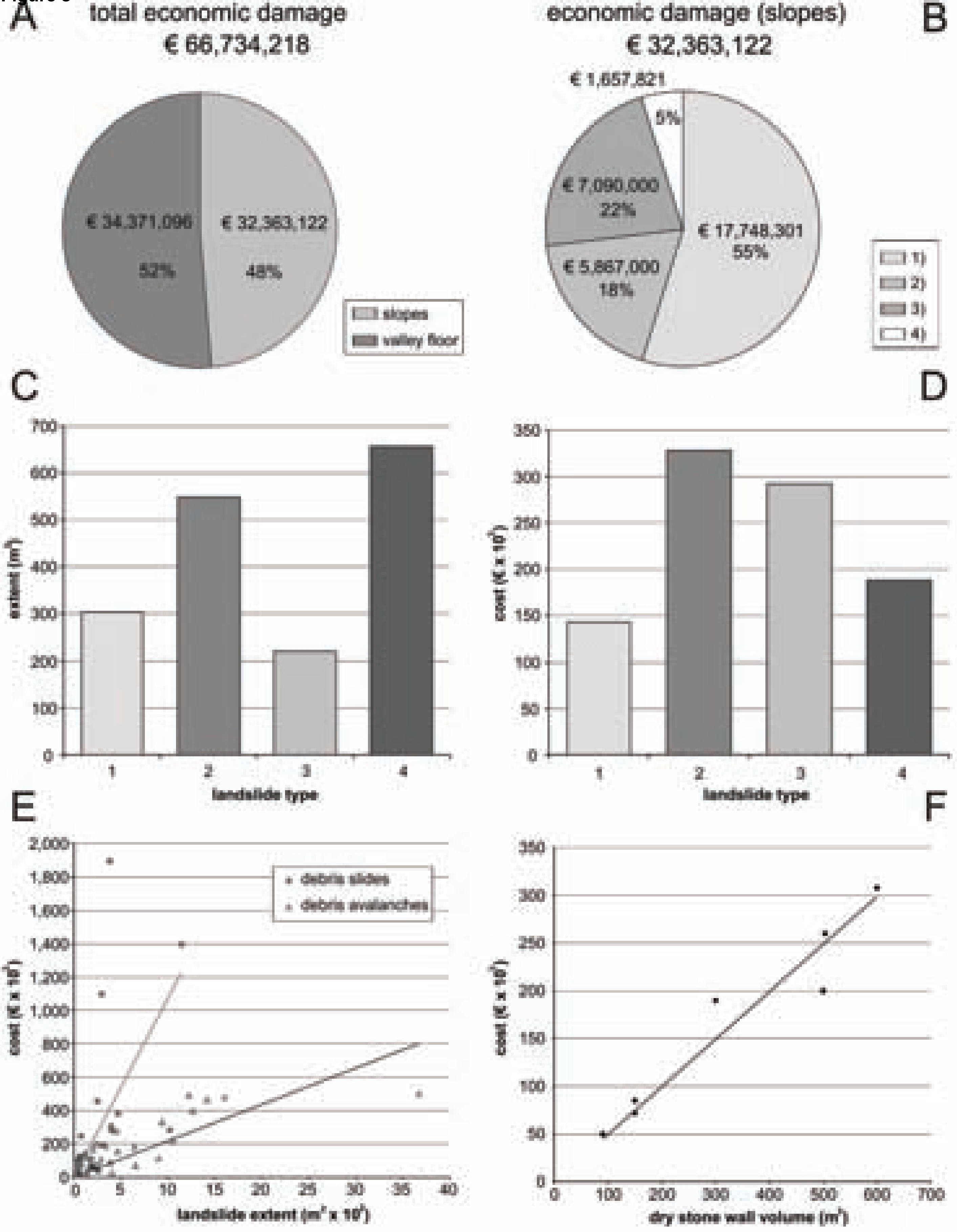


**Figure 4**



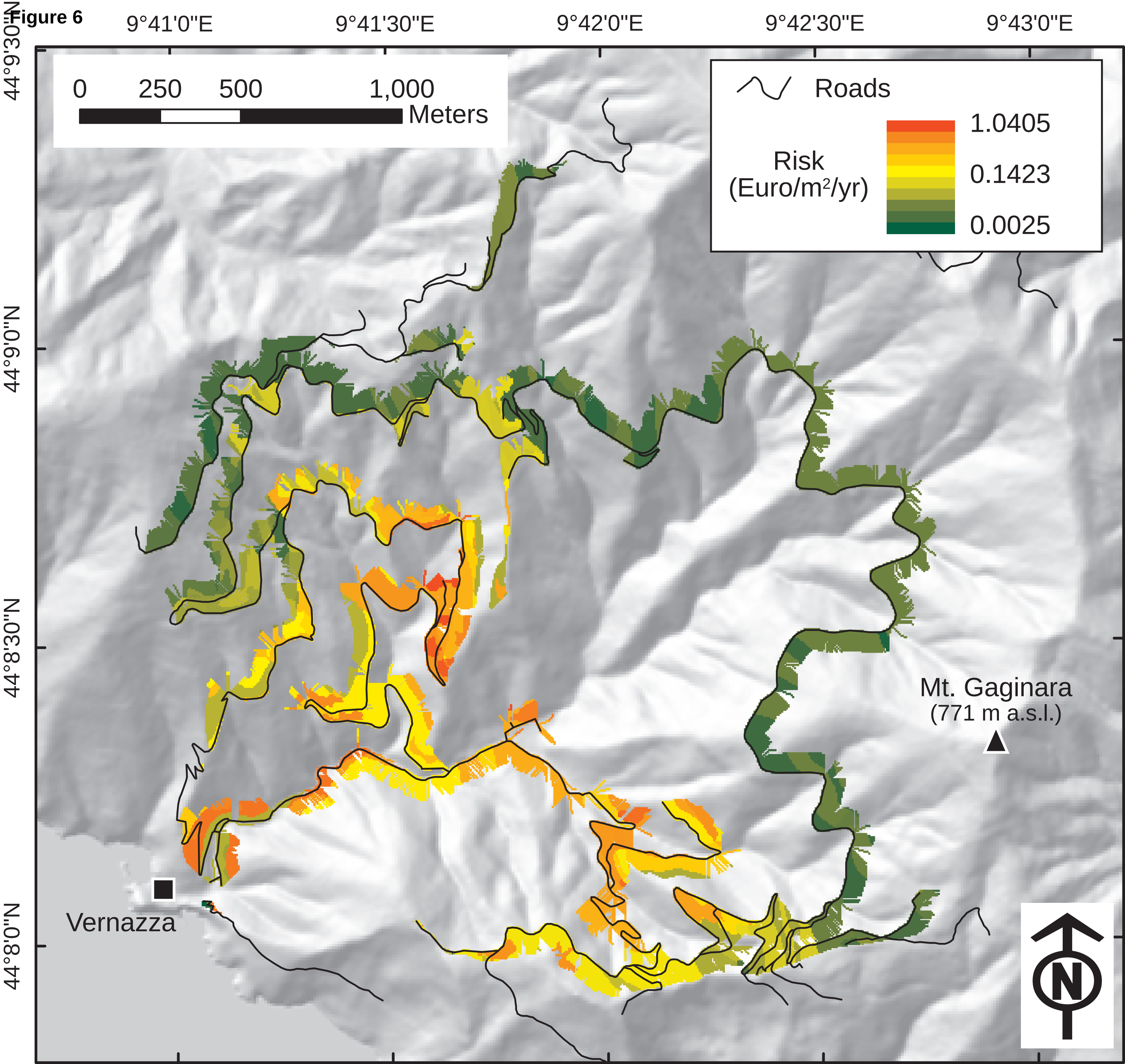
9°41'0"E
9°41'30"E
9°42'0"E
9°42'30"E
9°43'0"E
44°9'30"N
44°9'0"N
44°8'30"N
44°8'0"N
0
250
500
1,000
Meters
Source of landslides
Roads
Analyzed slopes
Mt. Gaginara
(771 m a.s.l.)
Vernazza
N

Figure 5



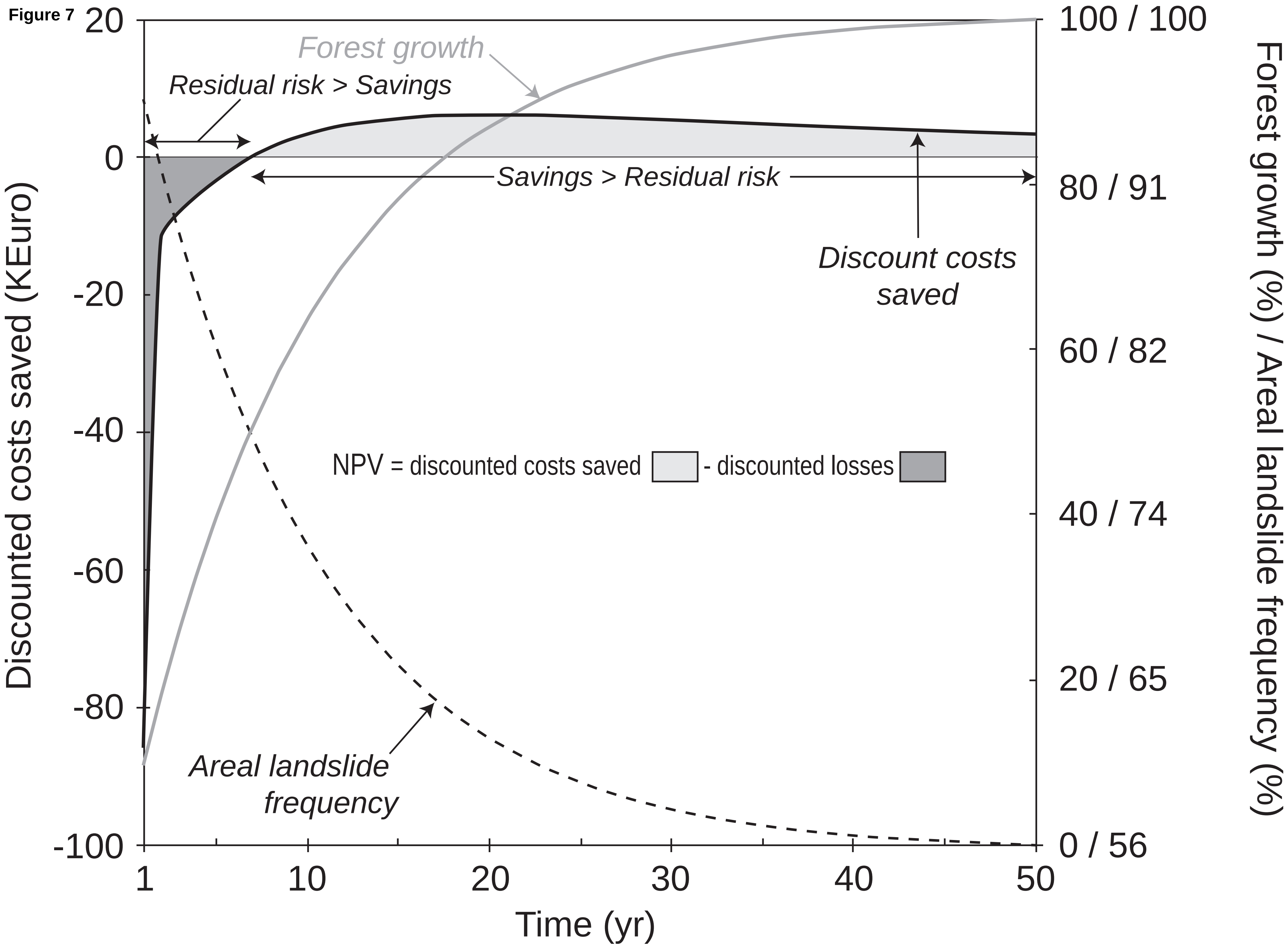
A
total economic damage
€ 66,734,218
€ 34,371,096
52%
€ 32,363,122
48%
slopes
valley floor
B
economic damage (slopes)
€ 32,363,122
€ 1,657,821
5%
€ 7,090,000
22%
€ 5,867,000
18%
€ 17,748,301
55%
1)
2)
3)
4)
C
extent ($m^2$)
landslide type
D
cost (€ x $10^3$)
landslide type
E
debris slides
debris avalanches
cost (€ x $10^3$)
landslide extent ($m^2$ x $10^3$)
F
cost (€ x $10^3$)
dry stone wall volume ($m^3$)

**Figure 6**



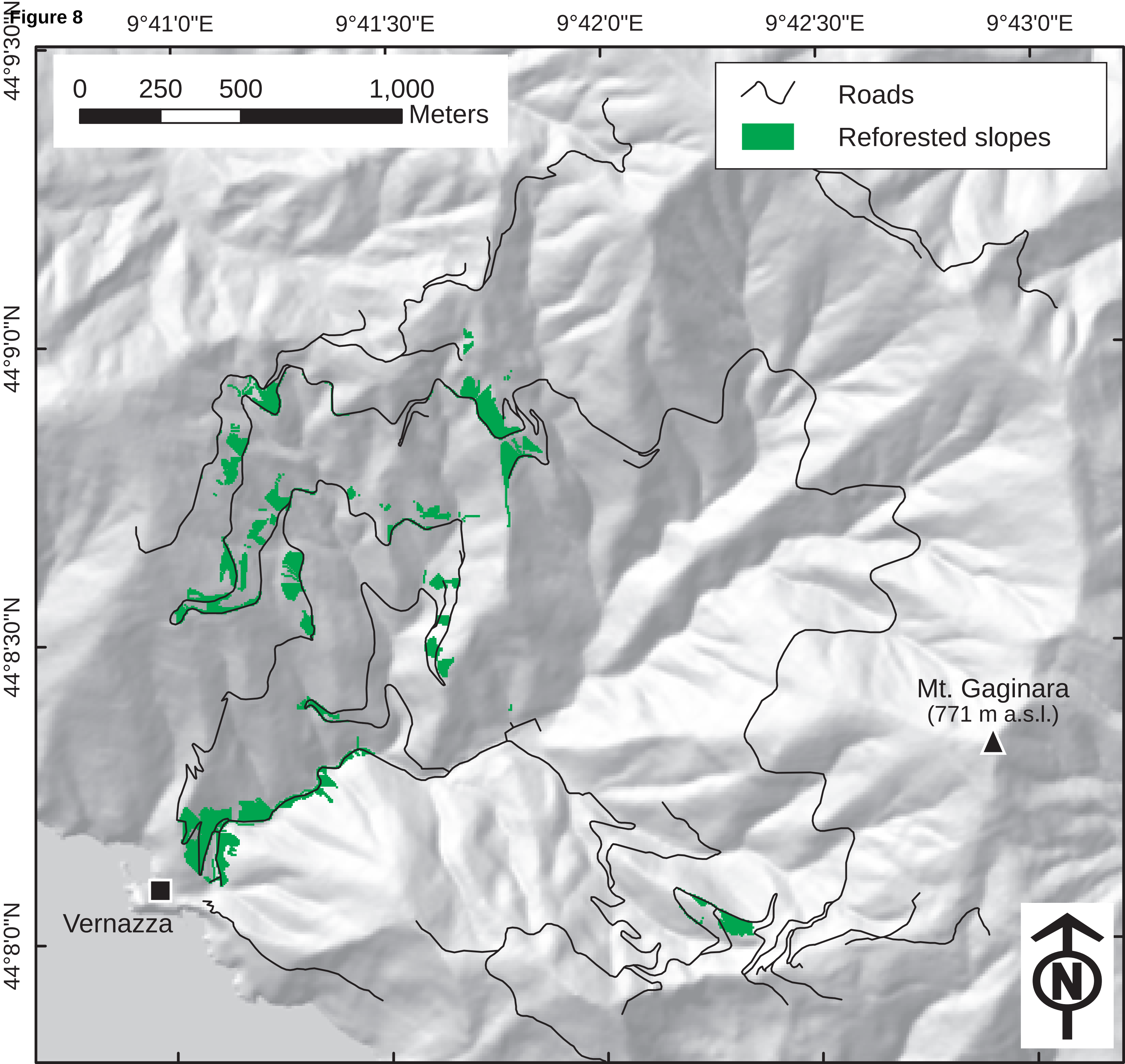
9°41'0"E
9°41'30"E
9°42'0"E
9°42'30"E
9°43'0"E
44°9'30"N
44°9'0"N
44°8'30"N
44°8'0"N
0
250
500
1,000
Meters
Roads
Risk
(Euro/m2/yr)
1.0405
0.1423
0.0025
Mt. Gaginara
(771 m a.s.l.)
Vernazza
N

Figure 7



20
0
-20
-40
-60
-80
-100
Discounted costs saved (KEuro)
100 / 100
80 / 91
60 / 82
40 / 74
20 / 65
0 / 56
Forest growth (%) / Areal landslide frequency (%)
1
10
20
30
40
50
Time (yr)
Forest growth
Residual risk > Savings
Savings > Residual risk
Discount costs saved
NPV = discounted costs saved - discounted losses
Areal landslide frequency

Figure 8



9°41'0"E
9°41'30"E
9°42'0"E
9°42'30"E
9°43'0"E
44°9'30"N
44°9'0"N
44°8'30"N
44°8'0"N
0
250
500
1,000
Meters
Roads
Reforested slopes
Mt. Gaginara
(771 m a.s.l.)
Vernazza
N

Figure 9

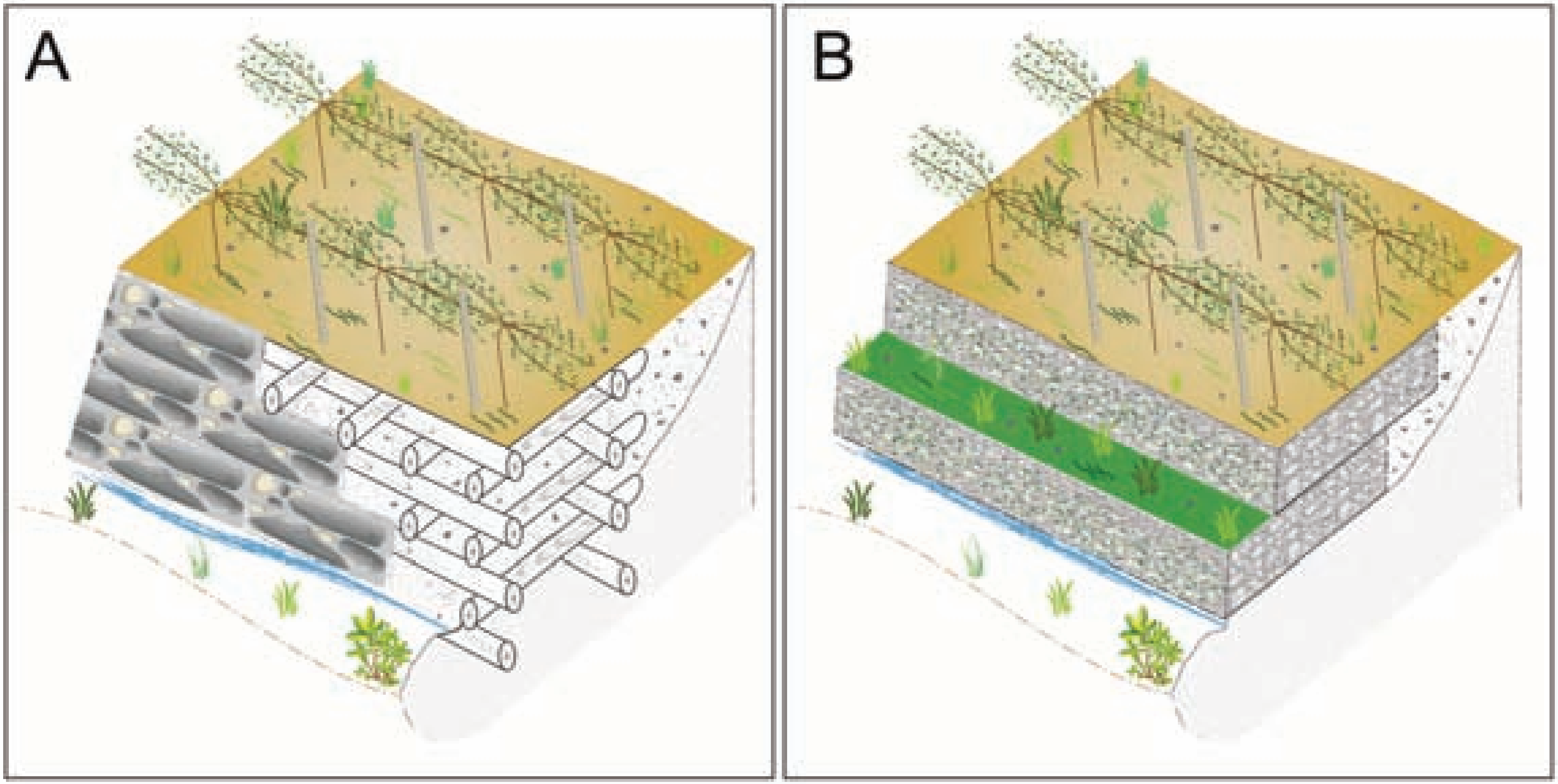


Figure 10

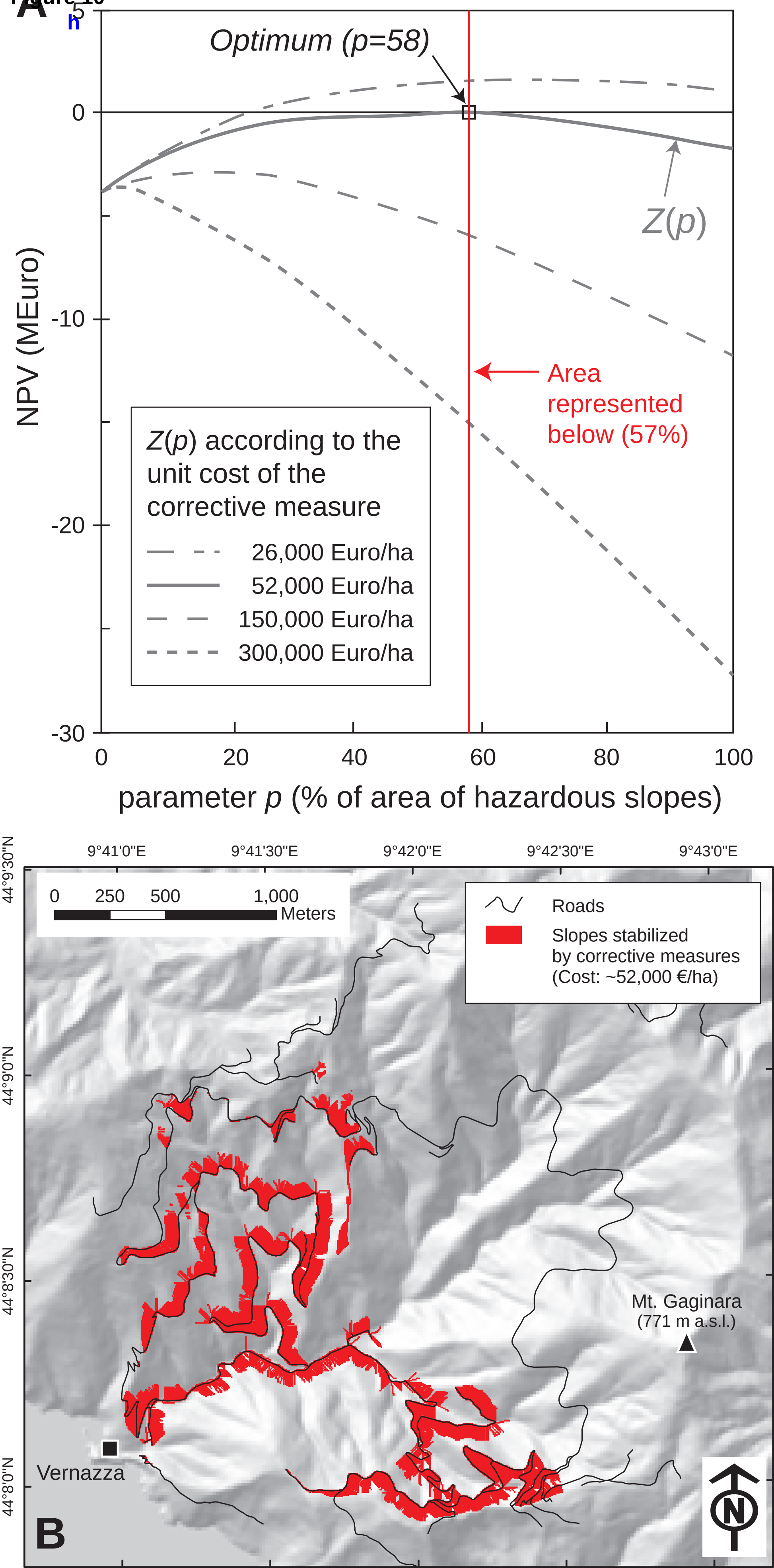
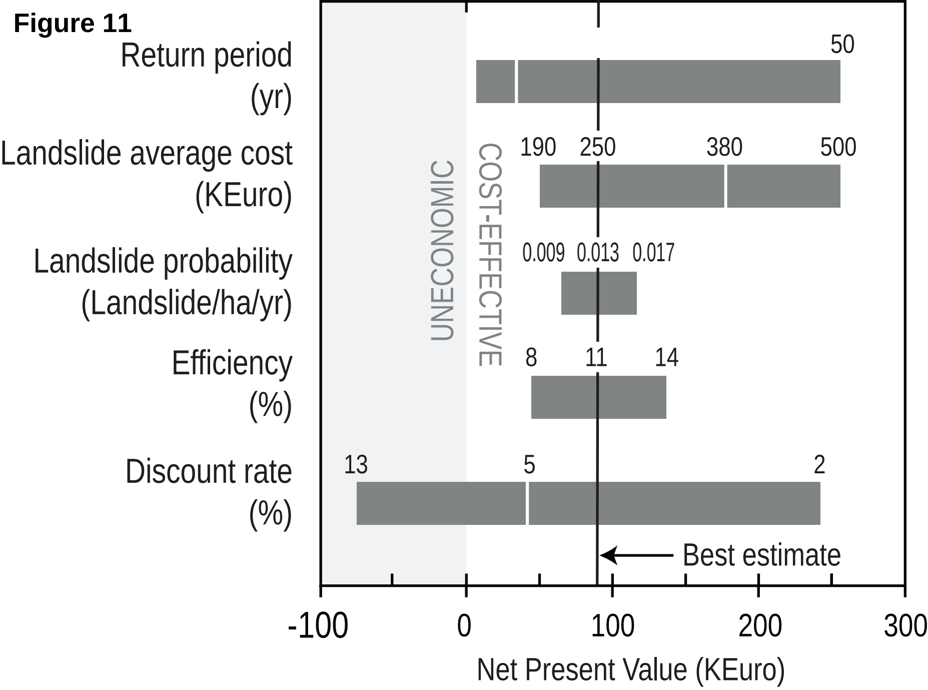
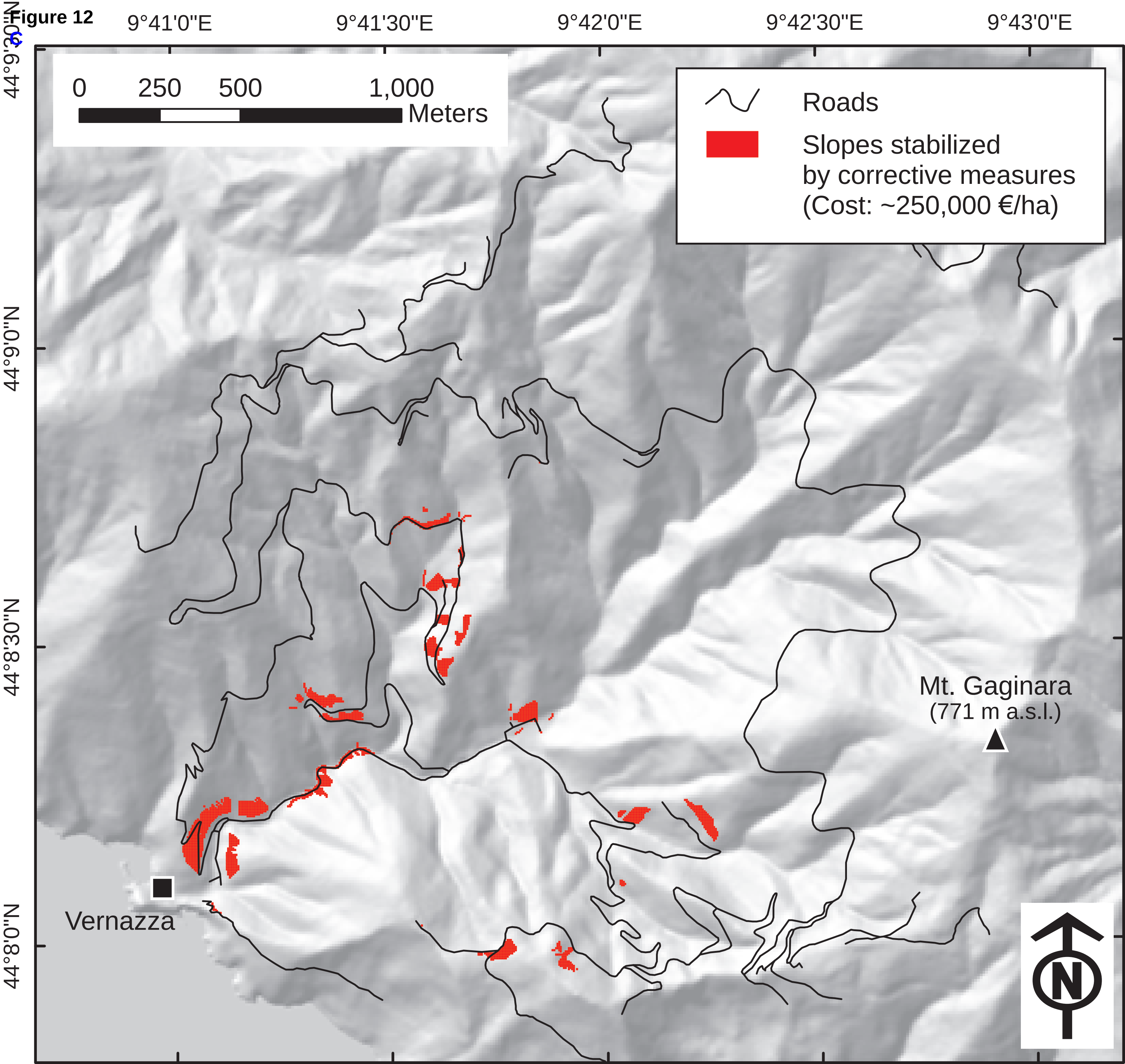

A
Optimum (p=58)
Z(p)
Area
represented
below (57%)
Z(p) according to the
unit cost of the
corrective measure
26,000 Euro/ha
52,000 Euro/ha
150,000 Euro/ha
300,000 Euro/ha
NPV (MEuro)
5
0
-10
-20
-30
0
20
40
60
80
100
parameter p (% of area of hazardous slopes)
B
9°41'0"E
9°41'30"E
9°42'0"E
9°42'30"E
9°43'0"E
44°9'30"N
44°9'0"N
44°8'30"N
44°8'0"N
0
250
500
1,000
Meters
Roads
Slopes stabilized
by corrective measures
(Cost: ~52,000 €/ha)
Mt. Gaginara
(771 m a.s.l.)
Vernazza
N

Figure 11



Return period
(yr)
Landslide average cost
(KEuro)
Landslide probability
(Landslide/ha/yr)
Efficiency
(%)
Discount rate
(%)
50
190
250
380
500
0.009
0.013
0.017
8
11
14
13
5
2
UNECONOMIC
COST-EFFECTIVE
Best estimate
-100
0
100
200
300
Net Present Value (KEuro)

Figure 12


9°41'0"E
9°41'30"E
9°42'0"E
9°42'30"E
9°43'0"E
44°9'30"N
44°9'0"N
44°8'30"N
44°8'0"N
0
250
500
1,000
Meters
Roads
Slopes stabilized
by corrective measures
(Cost: ~250,000 €/ha)
Mt. Gaginara
(771 m a.s.l.)
Vernazza
N