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1 **Cost-based analysis of mitigation measures for shallow-landslide risk**
2 **reduction strategies**

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18
19 **Abstract**

20 Landslide risk assessments are usually permeated by a certain degree of
21 subjectivity. In order to reduce it, we have developed an original methodology
22 which enables risk assessments to be carried out in fully quantitative terms,
23 integrating both physical and economic science techniques. This risk
24 assessment combines geomorphological studies, probabilistic modelling and
25 cost-benefit analyses (CBA). We applied the methodology to an area of north-

26 west Italy that was affected in 2011 by a dramatic rainfall-induced landslide
27 event, and where a risk management program is necessary for avoiding future
28 losses. We analyzed the cost-effectiveness of several landslide mitigation
29 measures applying the proposed procedure. The results demonstrate that
30 measures previously considered as suitable for mitigating shallow landslides
31 were inappropriate from the economic viewpoint. The applied techniques also
32 served to optimize economically the most appropriate mitigation measure.
33 Moreover, our methodology allowed to calculate the maximum affordable
34 investment on a cost-effective mitigation measure; this result will be a reference
35 for designing innovative solutions to mitigate landslides in the study area.

36

37 **Keywords:**

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

40

41

42 **1. Introduction**

43 Decisions for managing landslide risk are often made just taking into account
44 the available budget; analysis of the economic suitability or even optimization of
45 the application of the proposed mitigation measures are generally not
46 considered. Thus, the application of costly and oversized structural measures
47 for stabilizing slopes are frequent when funding is available; and landslide risk
48 mitigation does not usually happen when the budget is scarce (cf. Winter and
49 Bromhead, 2012). These situations can be avoided by implementing
50 quantitative landslide risk assessments. However, the latter involve difficult

51 tasks and decisions that should take into account a wide range of issues,
52 including hazard analysis, potential loss estimation and design of mitigation
53 measures (Crozier and Glade, 2005; Gutiérrez et al., 2010; Van Asch et al.,
54 2014). To date, this complex evaluation has commonly been carried out using
55 semi-quantitative approaches; applying qualitative or quantitative procedures in
56 different stages of the assessment according to the available data (e.g. Lateltin
57 et al. 2005). However, nowadays there is an increasing need to perform
58 quantitative risk analysis (Corominas et al., 2014) and, in some cases, the
59 conditions are favourable to develop risk assessments totally based on
60 measurable parameters (see e.g. Galve et al., 2012a, b).

61

62 Among other options, cost-based approaches can be reliable methodologies for
63 developing landslide risk assessment in fully quantitative terms. These
64 techniques can be applied at local and regional scale. The completion of this
65 type of analysis at those scales depends on (1) the production of a sound
66 landslide hazard map and (2) the estimation of costs generated by landslides
67 and those economic losses saved due to the implementation of specific
68 mitigation measures. Currently, procedures for performing comprehensive
69 landslide susceptibility and/or hazard maps (i.e. hazard zoning) are widespread
70 and well developed (e.g. Brenning, 2005; Chung, 2006; Lee et al., 2007; Rossi
71 et al., 2010; Felicísimo et al., 2013; Piacentini et al., 2012; Lari et al., 2014;
72 Piacentini et al., 2015), primarily because they require information currently
73 accessible or easy to produce (DEMs, land use maps, geological information
74 and landslide inventories). However, the usual absence of available information
75 on costs produced by landslide occurrence prevents the calculation of risk in

76 economic terms. This explains the scarce number of articles that describe
77 quantitative approaches aimed at landslide risk estimation (e.g. Remondo et al.,
78 2005; Zêzere et al., 2008; Jaiswal et al., 2010). The same problem also
79 concerns the making available of reliable market prices for mitigation solutions.
80 There is a wealth of literature on landslide mitigation measures and their
81 technical suitability (e.g. Cornforth, 2005; Glade et al., 2005; Huebl and Fiebiger,
82 2005; Highland and Bobrowsky, 2008; Andreu et al., 2008; Bromhead et al.,
83 2012; Mavrouli et al., 2014; Bowman, 2015) but it is difficult to obtain
84 information in detail about their implementation costs. This is a common
85 obstacle to analyze the cost-effectiveness of a proposed measure. For this
86 reason, papers describing cost-benefit analysis (CBA) of landslide mitigation
87 alternatives are rare. This deficit of knowledge on cost-based studies may
88 prevent stakeholders from having an overview of optimum solutions for
89 managing landslide risk. The development of quantitative risk assessment
90 methods, capable of managing landslide problems in different settings,
91 represents a crucial need for landslide risk managers. Among the modest
92 number of papers dealing with cost-based landslide risk assessment the
93 following can be highlighted. Fuchs and McAlpin (2005) analyzed the economic
94 benefits of avalanche defence structures and discussed the protection that the
95 public sector should provide. Holub and Fuchs (2008) used the results of a cost-
96 benefit analysis to demonstrate that local structural measures should be
97 considered as additional or alternative solutions to conventional structures for
98 mitigating torrent-related phenomena (flash floods or debris flow). Agliardi et al.
99 (2009) describe how to integrate rock fall numerical modelling and CBA to
100 evaluate the cost efficiency of two protection scenarios. Lee and Chi (2011)

101 combined geotechnical calculations with a cursory economical evaluation to
102 assess the cost-benefit ratio of a proposed structural solution for stabilize a
103 slope. Chen et al. (2010) and Narasimhan et al. (2015) provide two similar cost-
104 based analyses of strategies to mitigate damages produced by flow-like
105 phenomena. These authors based their assessment on the cost-benefit ratios
106 obtained by implementing a specific mitigation strategy. Ballesteros-Canovas et
107 al. (2013) present a comparable methodology for assessing the best option to
108 reduce flood risk. The cited publications mainly deal with snow avalanches, rock
109 falls and torrent-related hazards that may hit populated areas and describe
110 methodologies aimed at analyzing the cost efficiency of static scenarios (i.e. the
111 proposed protection scenario do not change to achieve the maximum efficiency).
112 The present study attempts to fill a gap on landslide risk assessment and
113 management by describing a methodology based on quantitative techniques to
114 establish appropriate measures for mitigating shallow landslide risk along roads.
115 Moreover, the techniques presented are designed to provide optimized
116 mitigation solutions analyzing dynamic scenarios (i.e. the proposed mitigation
117 solutions can be resized to achieve the maximum efficiency). We applied the
118 procedure to an area of north-west Italy (Vernazza catchment, Cinque Terre
119 National Park), that was affected by an impressive landslide-event on October
120 2011. The proposed methodology is completely based on measurable
121 parameters and reduces the subjectivity that usually permeates risk
122 assessments. It combines both physical and economic issues that make the
123 study a multidisciplinary and a complex analysis. This complexity produces a
124 significant level of uncertainty, but we also adopted a strategy to narrow it down.
125 The case study shows: (1) how quantitative assessments can change local

126 preconceptions about the best way to manage landslides; and (2) the
127 importance of conducting this type of studies for avoiding to divert resources
128 which could be better used. This research has also shown how the methods
129 previously applied by Galve et al. (2012a, b) for analyzing the economic viability
130 of a structural solution to mitigate sinkholes in a roadway may be adaptable to
131 other geomorphic hazards in different environmental contexts.

132

133 **2. Materials and methods**

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

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

149

150 **2.1 Case study**

151 The Vernazza catchment covers approximately 5.7 km² and is located in the
152 easternmost part of Liguria (NW Italy) (Fig. 2). This area was declared as a
153 World Heritage Site by UNESCO in 1997 and it is included in the Cinque Terre
154 National Park. Cinque Terre is an outstanding example of a man-made
155 landscape comprising centuries-old agricultural terraces retained by dry stone
156 walls (Terranova et al., 2006; Brandolini, in press).

157

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

164

165 The bedrock lithology of the Vernazza catchment is mainly comprises
166 sandstones and clayey siltstones flysch (Macigno Fm.) and claystones with
167 limestones and silty sandstones turbidites (Canetolo Shales and Limestones).

168 These formations are part of a wide overturned antiform fold (Regione Liguria,
169 2006). The bedrock is prevalently mantled by low thickness (1–2 m) soil slope
170 covers that have been largely reworked for terracing. About 50% of the slopes
171 were transformed by terracing for olive grove and vineyard cultivations.

172 Currently, following the progressive exodus of farmers since the end of XIX
173 Century, only 8% of the slopes are still cultivated. The remaining 50% of the
174 slopes are located in the upper part of the catchment and are covered by forest
175 and shrub lands.

176

177 The climate of the Cinque Terre coast is Mediterranean, with hot and dry
178 summers and mild winters. The mean annual precipitation is about 1,000 mm
179 and the rainiest month is October, with a mean value of 156 mm.

180 Notwithstanding these average climate conditions, the region has been
181 characterized in the last 25 years by even more frequent high intensity rainfall
182 causing widespread geo-hydrological effects and associate severe damage
183 (Cevasco et al., 2008; Brandolini et al., 2012; Silvestro et al., 2012; Cevasco et
184 al. 2015; Del Monte et al., 2015).

185

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

190

191 **2.1.1 The October 25, 2011 landslide event**

192 On October 25, 2011 the Vernazza catchment was affected by a very intense
193 rainfall event. A cumulative rainfall of 382 mm and rainfall intensities reaching
194 90 mm/h, 195 mm/3 h and 350 mm/6 h were recorded in the nearest
195 Monterosso rain gauge. The return period of the recorded peak values was
196 estimated higher than 100 years (ARPAL-CFMI-PC, 2011). Historical archival
197 research revealed that the final tract of the Vernazza valley was affected by a
198 similar event in 1857 and 1859 (Rollando, 2003).

199

200 On the basis of a landslide inventory, carried out by detailed field surveys and
201 analysis of high-resolution aerial photographs, more than 500 shallow
202 landslides triggered by the 25 October 2011 storm were identified in the whole
203 Vernazza catchment (Cevasco et al., 2012; 2013a). A total of 364 landslides
204 were mapped; 174 landslides were not representable to scale. The landslides
205 affected an area of 8.5 ha, corresponding to about 1.5% of the basin area
206 (Cevasco et al., 2014). The average density of landslides was 63 landslides/km².
207 Landslide phenomena that occurred on October 25, 2011 initiated as debris
208 slides (Cruden and Varnes, 1996) and in most of cases evolved into debris
209 avalanches or, sometimes, into debris flows. According to Hungr et al. (2014),
210 debris avalanches are very rapid shallow flows of partially or fully saturated
211 debris on a steep slope, without confinement in an established channel; instead
212 debris flows are very rapid to extremely rapid flow of saturated non-plastic
213 debris in a steep channel. Landslide areal extent ranges between hundreds of
214 square metres up to thousands square metres. The failure surface
215 corresponded, in most cases, to the contact between regolith and bedrock
216 (Cevasco et al., 2013b). The highest density of failures (landslide source area)
217 was observed on slopes with inclinations between 35° and 40° whereas
218 phenomena affected mainly abandoned or poorly maintained terraces in the
219 middle and lower catchment.

220 A disastrous debris flood occurred at the valley floor, affecting the Vernazza
221 village and causing three fatalities. Debris heights up to 5–6 m were deposited
222 in the historical centre of the Vernazza village. The deposition volume on the
223 Vernazza valley floor was estimated about 60,000 m³ (Cevasco and Brandolini,
224 2015). The solid charge of the flood was increased because of the material

225 mobilized by landslides: (1) mainly soil and debris from colluvial deposits; (2)
226 anthropically reworked sediments; (3) stones from terrace walls; and (4)
227 materials from embankments of the roads and from the infill of a car park
228 located in a valley outside the village.

229

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

241

242 **2.2. Input data**

243 The data used for establishing optimum solutions to mitigate the damage
244 produced by future landslides affecting the roads of the described study area
245 include: (i) a digital elevation model (DEM) with a 5 m of resolution and
246 parameters derived from it such as slope angle, aspect angle, slope concavity,
247 and elevation; (ii) geological and land use maps; (iii) a landslide-event inventory
248 including the location of the source and run out areas of 364 shallow landslides
249 (Fig. 4), their characteristics and data of a suitable set of causal factors having a

250 relationship with slope failures; and (iv) location of elements at risk (roads in our
251 case study, Fig. 4). This information was digitized and included in a
252 Geographical Information System (GIS) as different data layers. The inventory
253 and cartographic data about causal factors were transformed into raster format
254 with a pixel size of 5 x 5 m. Furthermore, data were compiled describing the
255 temporal frequency of the studied landslide-event, the cost caused by
256 landslides on roads (see section 2.5) and unit prices of mitigation measures.

257

258 **2.3. Modelling landslide hazard**

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

275 that return period in 100 years according to the estimates of ARPAL-CFMI-PC
276 (2011).

277

278 **2.4. Modelling landslide hazard reduction caused by mitigation measure** 279 **implementation**

280 A reduction in landslide frequency can lead to significant cost savings.

281 Evaluation of potential cost savings was achieved through comparing costs
282 incurred for the current land use with those incurred in response to four different
283 land use scenarios (Galve et al., 2015). The four land use scenarios are:

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

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

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

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

295

296 The percentage of change between the values of landslide frequency in the
297 reference and in the simulated models measures the potential reduction (or
298 increase) of landslide hazard due to the implementation of a mitigation solution.

299 This percentage can be translated into economic terms because the reduction

300 of the hazard could lead to a reduction of the potential losses according to the
301 exposure of the elements at risk. This translation needs a study on the
302 economic losses caused by landslides which is explained in the following
303 section.

304

305 **2.5. Estimation of economic losses produced by landslides**

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

312

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

325 Klose et al., 2015; Pizziolo et al., 2015; Table 2), (2) calculating the average
326 costs for recovering a damaged structure simulating a hypothetical situation (e.g.
327 Giacomelli, 2005; Bonachea, 2006; Galve et al., 2012a) or (3) carrying out a
328 vulnerability analysis of the exposed structures (e.g. Mavrouli and Corominas,
329 2010; Sterlacchini et al., 2014 and references therein) and multiplying the
330 resulting vulnerability with their cost.

331

332 Indirect costs are very diverse, and can include the temporal loss in the
333 serviceability of a road, the health care costs of injured people, depreciation of
334 land values, costs of legal actions, etc. Indirect losses associated to the
335 temporal loss in the serviceability of a road can be calculated using well-
336 established models in the cases in which a specific event or roadblock is
337 analyzed or simulated on a truck or strategic transportation infrastructures
338 where data about traffic flow and types of vehicles is available (e.g. Giacomelli,
339 2005; Galve et al., 2012a and b; Mateos et al., 2013; Winter et al., 2014). Other
340 types of indirect costs usually are not considered nor calculated in many risk
341 analyses because they are very difficult, often impossible, to estimate
342 accurately, as mostly are not registered in market prices. However, indirect
343 costs are usually higher than direct costs (see e.g. Perrin and Jhaveri, 2004;
344 Galve et al., 2012a, b). For this reason, it is advisable, where possible, to
345 estimate these costs; the acceptance of a mitigation measure could be
346 conditioned by the incorporation of this information in the assessment. A
347 sensitivity analysis considering virtual indirect costs equal to direct costs is also
348 advisable in the case that there is not enough data to estimate the former.
349 Indirect losses are commonly greater than direct losses, but it is difficult to

350 establish by how much. Therefore, a pragmatic estimate of minimum costs can
351 be achieved by taking indirect costs as being equal to direct costs.

352

353 The cost-based assessments only take into account economic losses. Personal
354 losses, i.e. injuries and casualties due to landslides, are not considered,
355 although their economic consequences may be contemplated (see e.g.
356 Corominas et al., 2005). Personal or social losses can be transformed into
357 monetary figures using the debatable concept of the Value of Statistical Life
358 (VSL). Porter (2002) discussed this concept and reports that VSL can vary from
359 1 to 10 million US\$. We prefer to perform a cost-based analysis without
360 assigning a controversial economic value to human lives.

361

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

375

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

383

384

385 **2.6. Cost-benefit analysis of mitigation measures**

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

400

401 In general, the analysis follows the classical with- and without- approach; CBA
402 compares the landslide-related damages (generated over a specific time and
403 transformed in monetary terms) in a “without mitigation” situation and multiple
404 “with mitigation” scenarios. In our case, CBA was used to compare the
405 damages estimated by using the landslide hazard model (“without mitigation”
406 situation) and three simulated hazard models (“with mitigation” scenarios).

407 These simulated models take account of the mitigation measures proposed to
408 reduce landslide hazard in the road network. The zones where these corrective
409 measures are applied reduce their propensity to be affected by landslides.

410 Obviously, this reduction on landslide susceptibility produces a diminution of the
411 associated economic losses, in other words, the amount of money not spent for
412 recovering road stretches affected by landslides is considered as a benefit. On
413 the other hand, the mitigation measures have an associated cost and we
414 analyzed the equilibrium between these costs (i.e. investment for carrying out
415 the proposed mitigation measures); the benefit derived from these changes in
416 losses savings; and the residual risk that the changes cannot be avoided.

417 Examples of calculations for a simple CBA are shown in Table 3.

418

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

421

$$422 \quad Z(p) = \sum_{t=1}^n \frac{B_t(p) - D_t(p)}{(1+i)^t} - C(p) \quad (1)$$

423

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

448 the increase in the NPV value. The investment reaches its optimum when the
449 NPV value passes from negative to positive values.

450

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

453

$$454 \quad B(p) = H_a(p) * L \quad (2)$$

455

$$456 \quad D(p) = H_r(p) * L \quad (3)$$

457

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

464

$$465 \quad L = V * E \quad (4)$$

466

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

472

473 $R = H * V * E$ (5)

474

475 $R = H * L$ (6)

476

477 $H = H_a(p) + H_r(p)$ (7)

478

479 $R = [H_a(p) + H_r(p)] * L = H_a(p) * L + H_r(p) * L = B(p) + D(p)$ (8)

480

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

485

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

497

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

505

506 **2.6.1 Sensitivity analysis**

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

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

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

526 *2. Average cost of damages due to shallow landslides.* The uncertainty over the
527 average direct losses caused by landslides in Vernazza is very low. However,
528 the CBA only considers direct costs and ignores indirect costs. We do not have
529 data for estimating indirect costs, but we speculated that these costs were
530 almost in the same order than direct costs. Thus, we assessed the impact on
531 the NPV if the average losses due to shallow landslide were to be doubled. This
532 is reasonable because in most of the cases the indirect costs are greater than
533 direct costs (Table 2), and we only equal these values. The scenario
534 considering total costs may be believed conservative, but it is closer to reality.
535 On the other hand, it may change the perception about the suitability of a
536 measure under certain conditions. In our case, a clearly cost-effective measure
537 considering direct and (figured) indirect costs were also taken into account as a
538 suitable alternative against landslide processes. Additionally, we consider a
539 lower average landslide cost calculating the overestimation of the economic
540 losses provided by municipal and provincial administrations. The average unit
541 cost, derived from the analysis of seven projects of terracing reconstruction
542 planned after 2011 event, was calculated in about 500 Euros/m³ (Fig. 5.F). This
543 cost is 30% higher than the unit cost calculated by the regional price list (380
544 Euros/m³). This increase in the cost estimations should be attributed to more
545 complex and onerous intervention conditions. Thus, we also carried out the
546 calculations using an average landslide cost 30% lower than the best estimate.

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

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

560 5. *Discount rate*. The selection of an appropriate discount rate is always
561 questionable. We used the modelled discount rate according to Lentz's
562 proposal (Lentz, 2006) as best estimate. Nevertheless, it is acceptable to apply
563 a wide range of values from 2 to 12% as discount rates. We have used as
564 reference for the case study the Italy long-term interest rates which vary
565 between 2% and 13% during the last 20 years (European Central Bank, 2015).
566 The average Italian interest rate in the latter time span was 5.5%; a similar
567 value recommended by Nordhaus (2004) as discount rate for long-term projects.
568 Thus, the NPV of the different alternatives using discount rates ranging between
569 2% and 13% was calculated.

570

571 **3. Results**

572 **3.1. Impact of mitigation measures on landslide areal frequency**

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

576 1. Abandoned terraces are critical elements in the Vernazza catchment as they
577 are very susceptible to collapse when heavy/intense rainfalls occur. Cultivated
578 terraces, although more stable, show instability problems due to the lack of
579 maintenance. Analysis of the estimated spatial probability of landslide
580 occurrence for different land uses shows that terraced land displays values
581 approximately one order of magnitude higher than non-terraced land. Terraces
582 abandoned for a long time (> 50 years) and re-colonised by natural vegetation
583 show lower landslide probabilities than do cultivated or recently abandoned
584 terraces. However, if there is no intervention on these elements a more
585 hazardous situation than the present could result.

586 2. The restoration of abandoned terraces seems to be not very effective in
587 reducing landslide areal frequency. This measure only can reduce the
588 frequency of landslide by up to 1.5%.

589 3. The frequency of landslides that may affect roads can be reduced by up to
590 24% by reforesting abandoned terraces.

591 4. Apparently, the most suitable solution for reducing landslide damage in the
592 study area is to design local structural works on unstable slopes. It was
593 estimated that the protection of 23% of the roads stretches could reduce the
594 number of landslides that affect this infrastructure by 66%.

595

596 **3.2. Economic losses produced by landslides**

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

615

616 Relations landslide type / average extent (Fig. 5C) and landslide type /
617 economic cost (Fig. 5 D) were analyzed for NCSL. The landslide that affected
618 roads had an average extent of about 660 m² for debris avalanches and about
619 220 m² for debris slides (Fig. 5.C). Although debris slides affected smaller areas
620 than debris avalanches, the average cost of interventions for NCSL affecting
621 roads (Fig. 5. D) was higher for the former (about 300,000 Euros) than for the

622 latter (about 200,000 Euros). This is due to landslide geometry; the width is
623 greater in the debris slides than in the debris avalanches and consequently the
624 length of road destroyed from the former during an event is longer. In regard to
625 NCSL affecting slope terracing and/or buildings, costs of interventions are
626 higher for debris avalanches (about 330,000 Euros) than for debris slides (about
627 140,000 Euros). In figure 5.E the relation between of the economic cost damage
628 along roads and shallow landslide extent are shown. Significant differences in
629 the trend of the economic costs of damage / landslide extent ratio, depending
630 on the landslide type, were identified. The higher economic cost of damage /
631 landslide extent ratio was found for debris slides. However, strong correlations
632 were not found between landslide size and damage cost and we decided not to
633 integrate these data in the CBA. Our analysis was finally performed using the
634 average damage cost produced by one landslide (debris slide/avalanche) in the
635 study area (250,000 Euro). Using this value we have produced the risk model of
636 the study area (Fig. 6).

637

638 **3.3. Cost-effectiveness of the proposed mitigation measures**

639 The results of the CBA can be summarized as follows:

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

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

649

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

667

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

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

677

678 CBA shows that the maximum investment affordable in cost-effective terms for
679 the corrective works is ~3 MEuro implementing an engineering solution over the
680 most landslide-prone 57 ha (57%) of the slopes oriented towards roads
681 (~52,000 Euro/ha) (Fig. 10). Thus, the combination of wood crib walls with dry
682 stone walls or the green gabions do not achieve the cost-effectiveness
683 requirements; the application of these bioengineering solutions is clearly
684 unprofitable. In contrast to earlier ideas (see Galve et al., 2015), actions using
685 structural measures on the most unstable slopes of the Vernazza catchment are
686 not suitable for reducing landslide risk.

687

688 **3.3.1 Sensitivity analysis of CBA**

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

697 Reforesting is not profitable if a discount rate of 13% is considered but this is a
698 very extreme condition (Fig. 11). Regarding the use of local structural works on
699 unstable slopes, the proposed measures are too expensive for being cost-
700 effective solutions. Even in the case of green gabions and considering the most
701 favourable situations (e.g. return period = 50 yrs; landslide costs = 500,000
702 Euro), these measures must have an efficiency of almost 100% for being cost-
703 effective. Moreover, in this case, this solution would be implemented only in the
704 5% most potentially unstable slopes (Fig. 12) with a total cost no more than
705 ~1.5 MEuro (~250,000 Euro/ha). Therefore, this is another piece of evidence
706 indicating that the engineering solutions seem to be economically unsuitable for
707 mitigating shallow landslides in the study area because the simulated situations
708 under which these measures are cost-effective are unlikely.

709

710 **4. Discussion and conclusions**

711 The performed analysis has shown that the most cost-effective measure to
712 stabilize the slopes in the study area is reforestation. This is not a surprising result
713 because reforestation is frequently the initial response in managing shallow
714 landslide processes, also decreasing both runoff and sediment loss (Trimble,
715 1990; Kosmas et al., 2000; Grove and Rackam, 2001; Nunes et al., 2010),
716 particularly in humid areas where the establishment of vegetation is rapid.
717 Reforestation is not a panacea as exemplified by Winter and Corby (2012)
718 because this measure effectively contributes to stability only on a decadal scale.
719 However, our study supports the suitability of this solution also taking into
720 account the transition period between planting and establishment of the
721 vegetation. The analysis also defined the areas to be reforested and the

722 maximum affordable investment; this is a step towards improving landslide risk
723 assessment. It is worth noting that nature itself reforested (and stabilized) most
724 of the abandoned terraced slopes in the Vernazza catchment, particularly
725 during the last sixty years. This reduced noticeably the instability of the slopes.
726 We can estimate, using our hazard model, that currently this reduction at basin
727 scale is ~35%. This nature-guided process favoured by the humid climate of the
728 study area prevented a major disaster in Vernazza.

729

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

747 limitation because it has considered a landslide event with 100 year-return
748 period and not other single landslides that can occur within this 100 years
749 period. This may underestimate landslide risk in the study area.

750

751 Terraces are efficient soil conservation structures to raise crop output, reduce
752 erosion and intercept runoff water (Parrotta and Agnoletti 2012, Stanchi et al.,
753 2012). However, these structures may become unstable under extreme
754 conditions (i.e. intense rainfall events or earthquakes) and if their maintenance
755 is rejected. Galve et al. (2015) pointed out that, currently, terraced terrain is the
756 most unstable zone in the Vernazza catchment. In fact, the calculated spatial
757 probability of landslides on terraced slopes displays values approximately one
758 order of magnitude higher than that on non-terraced slopes. In long-abandoned
759 terraced areas with terraces that have been re-colonised by natural vegetation a
760 lower landslide probability was found than for cultivated or recently abandoned
761 terraces. These results are consistent with previous studies developed in
762 different poorly maintained terraced landscapes distributed worldwide where
763 terraced slopes are usually described as the most landslide-prone areas (e.g.
764 Tamura 1996; Lasanta et al. 2001; Terranova et al. 2002; Crosta et al. 2003;
765 Canuti et al. 2004; Cao et al. 2007; Brancucci and Masetti 2008; García-Ruiz
766 and Lana-Renault 2011; Kitutu et al. 2011). These results seem to indicate that
767 the maintenance of the terrace system should be a priority for avoiding losses
768 caused by landslides. As the Vernazza case demonstrates, the abandonment of
769 terraces produces a hazardous situation, but their restoration is expensive. On
770 the other hand, the economic analysis performed in this study demonstrates
771 that landslide hazard reduction cannot be used as the unique criterion for

772 supporting the recovery of the terrace system in Vernazza. This action should
773 be also supported using other arguments such as cultural, historical and
774 environmental issues.

775

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

793

794 Finally, regarding the applicability of our methodology, the main difficulties the
795 risk analysts will face are those related to (1) the availability of the input data,

796 which is not always easily accessible; and (2) the high degree of uncertainty in
797 quantifying values in some of the involved parameters.

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

817

818

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833

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1141 **Tables**

1142 **Table 1.** Examples of damages reported in the Cinque Terre National Park
 1143 caused by the intense rainfall event of October 25, 2011 (extract from DCD n°6,
 1144 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	-
Riomaggiore	Palaedo	Slide	Pedonal road	80.000
Riomaggiore				-
Riomaggiore				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	-
Vernazza	Massolina			525.000
Vernazza	Massolina			210.000
Vernazza	Massolina	Rockfall	Road	350.000
Vernazza	Massolina			320.000
Vernazza	Costa Lunga	Earth flow	Road	191.000
Vernazza	Costa Lunga			76.000
Vernazza	Vernazzola	Shallow landslide	Villages, scattered houses, infrastructure, terraced slopes	52.700
Vernazza	Vernazzola			21.300
Vernazza	Garolla	Shallow landslide	Villages, scattered houses, infrastructure, terraced slopes	170.000
Vernazza	Garolla			15.000
Vernazza	Santuario Nostra Signora di Reggio	Debris flow	Villages, scattered houses, infrastructure, terraced slopes	250.000
Vernazza	Santuario Nostra Signora di Reggio			9000
Vernazza				Total amount (landslides, works along rivers, maritime works)
				57.437.400
				46.458.900
				Urgent action cost + Repair cost
				103.896.300

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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		Unit cost per landslide (€) "in bracket cost per landslide in the inventory map"	Source of information
					(total)	(direct costs)		
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	-	-	-	Pizzolo et al., 2015; OCDFC n.83 del 27 maggio 2013
					140 million €	280000	280000	
Lower Saxon Uplands (NW Germany)	1980-2010	33	Shallow landslides	Roads	-	-	-	Klose et al., 2014
					23,5 million \$	633788	633788	
Majorca (Balearic islands, Spain)	October 2008 - May 2010	34	Rock falls - rock avalanches (15), Earth slides - earth flows (15), Karstic collapses (4)	Roads, houses, holiday apartment blocks, dwellings, barns, power station	11 million €		323529	Mateos et al., 2013
					6,4 million €		188235	
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 €		(10378)*	Vranken et al., 2013
					688,000 €		(2364)*	
Nilgiri hills (southern India)	1987-2007	901	Shallow debris slide	Railways, Roads	1,907,640 \$ -		1884 - 16170	Jaiswal et al., 2010
					16,369,500 \$		1722	
Uttarakhand (northern India)	1994-2008	178	Rock slides, debris slides	Highway	3,4 million \$		17000	Nayak, 2010
					3 million \$		15000	
San Francisco Bay region (U.S.A.)	1 year	65	Debris flows, Earth flows, Complex landslides	-	-		-	Crovello and Coe, 2009
					14,8 million \$		202646	
Lisbon (Portugal)	1967-1996	(147)*	Shallow translational slides, Translational slides, Rotational slides	Villages, scattered houses, infrastructure	-		-	Zezere et al., 2008
					5,2 million €		(35374)*	

1150 **Table 3.** Cost-benefit analysis illustration for a landslide mitigation measures
 1151 implementation. The values of the table are fictitious; they are only used to
 1152 exemplify the calculations.

1153

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
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NPV ⁽⁷⁾	690,711
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⁽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 = $(1/(1+i))^{\text{Year}}$; Discount rate (i) = 5% in this example

⁽⁵⁾ Discounted cost saved = Cost saved x 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 = \sum Discounted cost saved - Investment on mitigation measures.

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1157 **Figure captions**

1158

1159 Figure 1. Methodological flow chart diagram.

1160

1161 Figure 2. Location of the study area.

1162

1163 Figure 3. Examples of damages produced by shallow landslides on the road
1164 network in the Vernazza catchment. A: debris avalanche (Piculla landslide)
1165 affecting a partially abandoned terraced slope and a road running at the slope
1166 foot in the middle catchment; B), C), D): debris slides accumulations littering the
1167 roadway in the middle (B, D) and lower catchment (C). The scoured slopes
1168 under the roads shown in B) and C) are effects of erosional processes along
1169 streams.

1170

1171 Figure 4. Location of the inventoried source landslide points and analyzed roads
1172 and slopes. These slopes cover the hillsides oriented towards the roads where
1173 it is expected that 90% of the landslides affecting the roads will be concentrated.
1174 Digital Elevation Model (DEM) and road network were derived from the 1:5,000-
1175 scale topographic map of Liguria region.

1176

1177 Figure 5. A - Total economic losses. B - Economic damage in the catchment
1178 hillsides: caused by NCSL affecting roads (1), by CP affecting roads (2), by
1179 NCSL and CP affecting slope terracing and buildings (3), by NCSL and CP
1180 affecting other assets (sewerage system and rack network) (4). C - average
1181 extent of NCSL: debris slides (1) and debris avalanches (2) affecting slope

1182 terracing and/or buildings; debris slides (3) and debris avalanches (4) affecting
1183 roads. D - average cost of interventions for NCSL: debris slides (1) and debris
1184 avalanches (2) affecting slope terracing and/or buildings; debris slides (3) and
1185 debris avalanches (4) affecting roads. E - Relationships between damage
1186 economic cost along roads and NCSL extent. F – Relationships between the
1187 cost of some intervention of terracing restoration designed after 2011 event and
1188 dry stone walls volume (m³).

1189

1190 Figure 6. Risk map produced for the analyzed slopes.

1191

1192 Figure 7. Evolution of the savings through time applying the reforestation
1193 alternative taking into account the progressive forest growth and associated
1194 reduction of the landslide areal frequency.

1195

1196 Figure 8. Reforested area simulated (i.e. slopes occupied by abandoned
1197 terraces).

1198

1199 Figure 9. Structural bioengineering solutions to stabilize the most susceptible
1200 slopes oriented towards the roads of the Vernazza catchment. A - Dry stone
1201 wall reinforced with a live crib wall. B - Vegetated rock gabions.

1202

1203 Figure 10. A - $Z(p)$ functions obtained to identify the maximum investment
1204 affordable for the corrective works (~52,000 Euro/ha). B - Area defined by the
1205 $Z(p)$ to apply structural measures in cost-effective terms.

1206

1207 Figure 11. Net Present Value ranges obtained in the sensitivity analysis for the
1208 reforestation alternative.

1209

1210 Figure 12. Slopes where green gabions may be installed instead of dry stone
1211 walls at a maximum cost of 250,000 Euro/ha considering a ca. 100% efficiency.

Figure 1

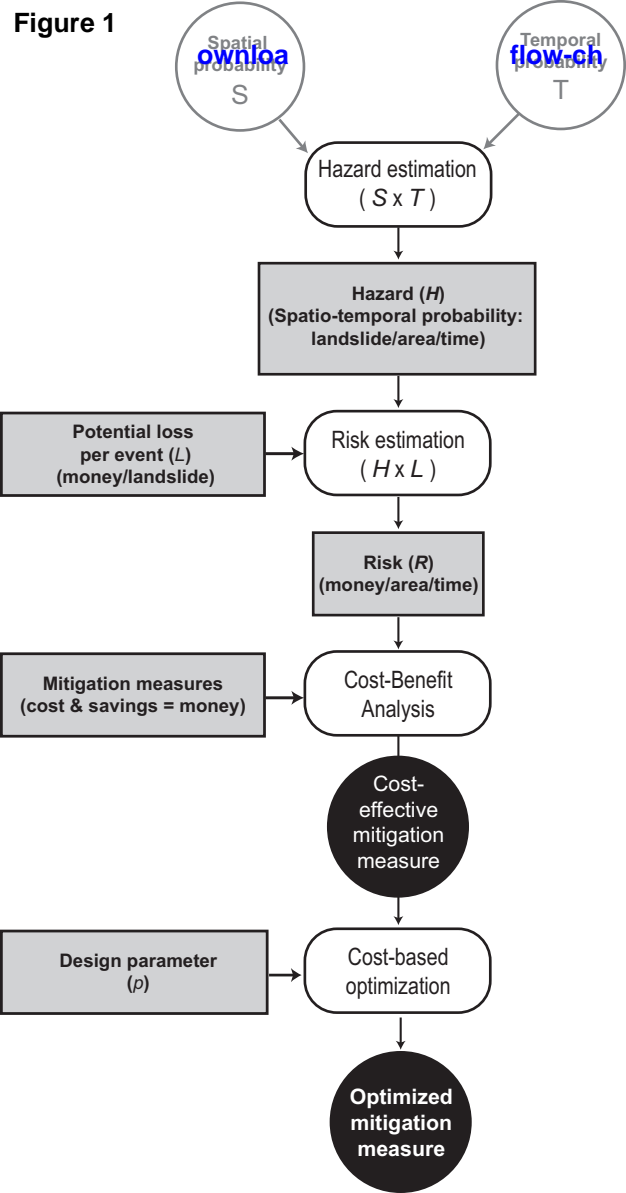




Figure 3

A



B



C



D



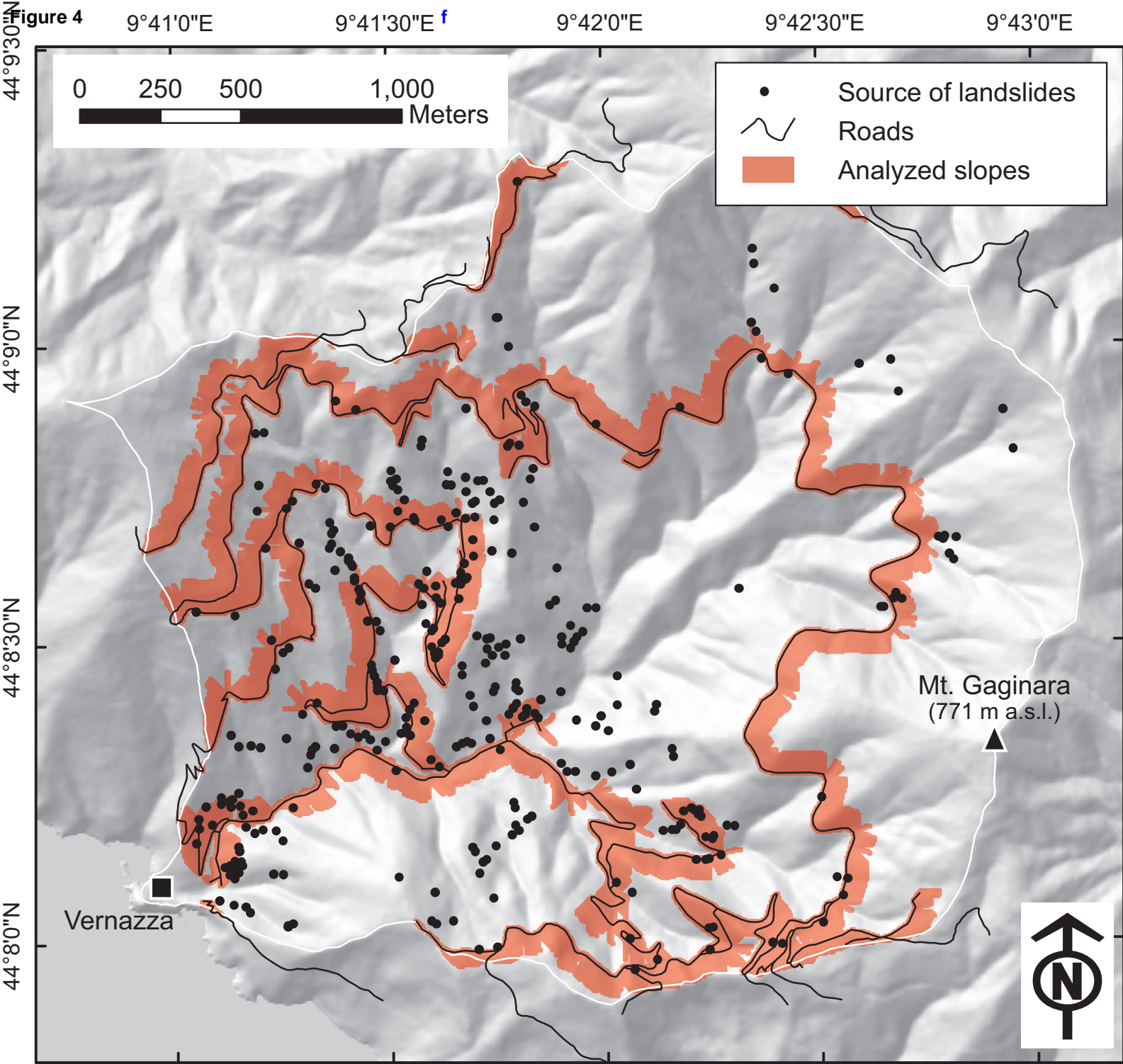
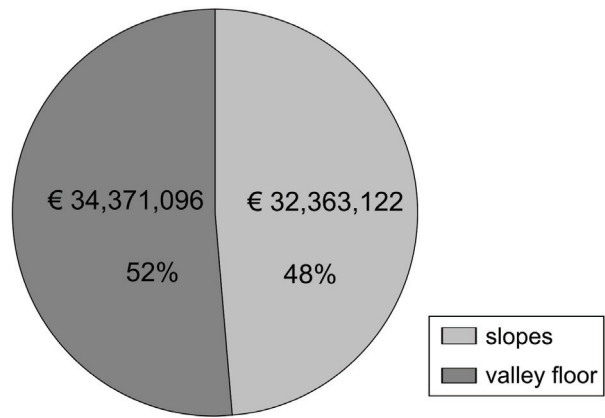
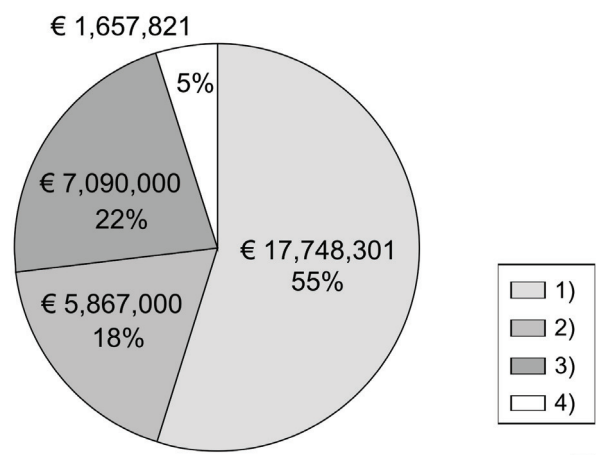
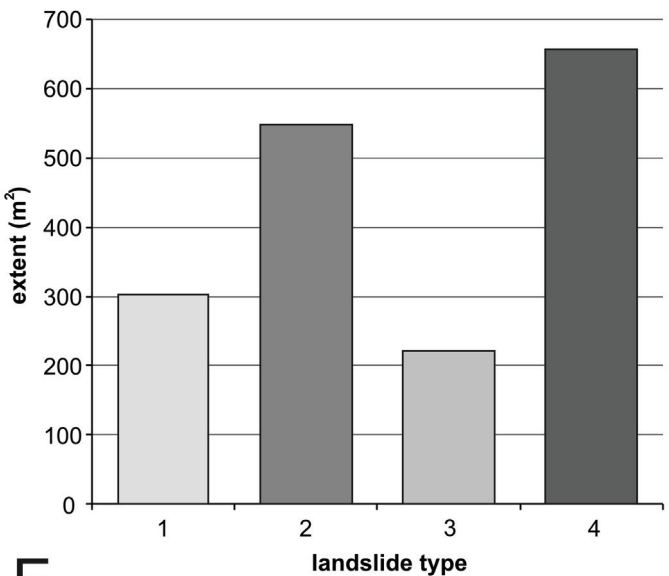
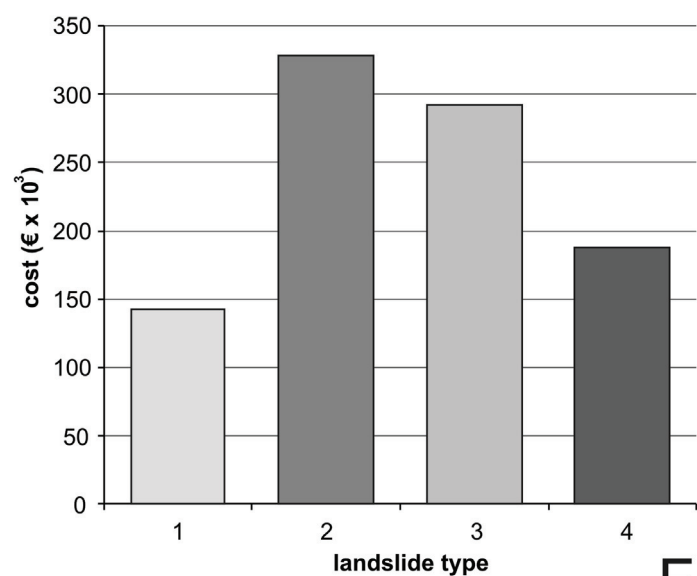
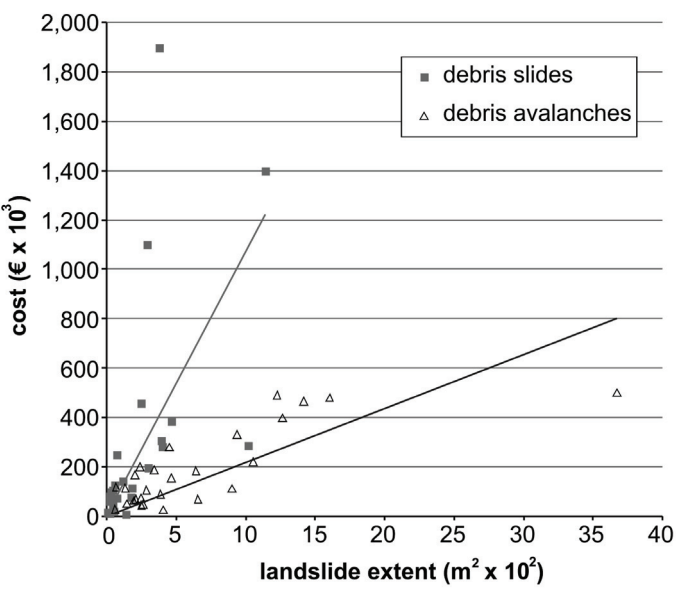
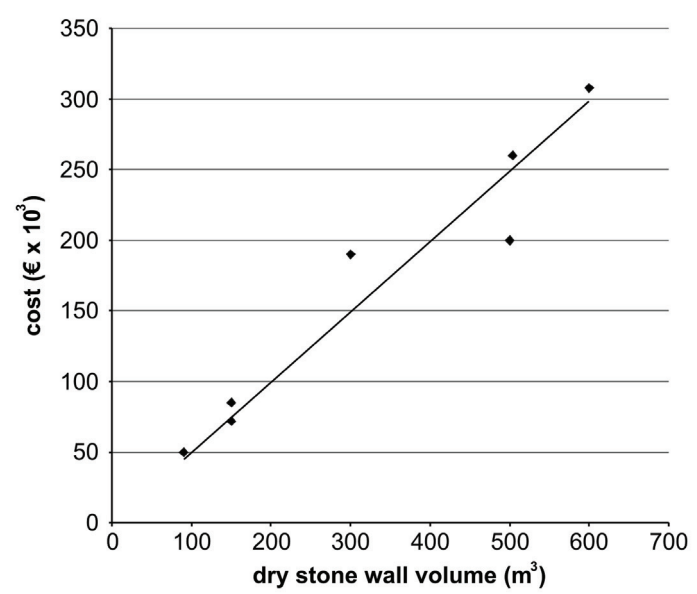


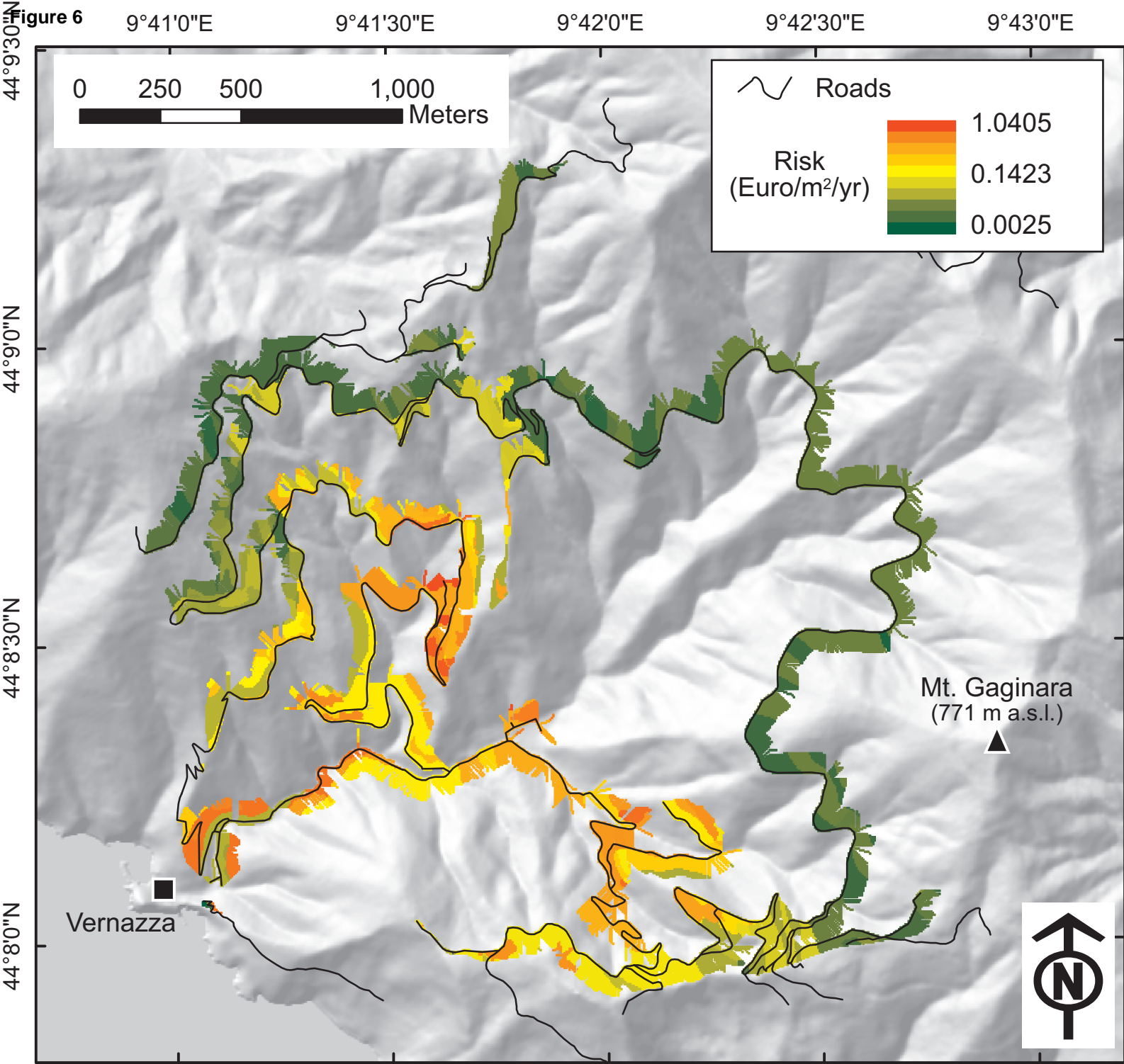
Figure 5

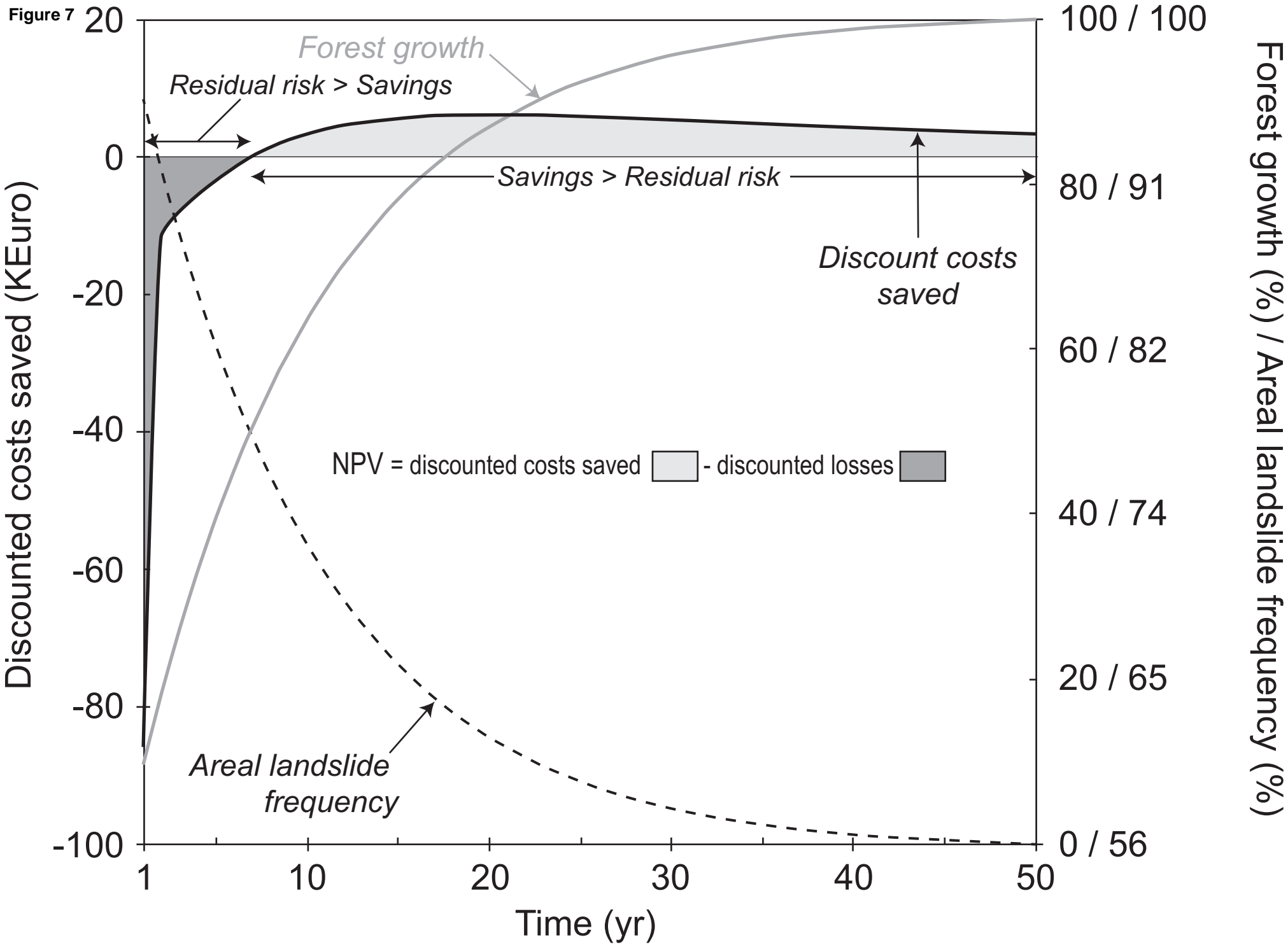
A total economic damage
€ 66,734,218



B economic damage (slopes)
€ 32,363,122

**C****D****E****F**





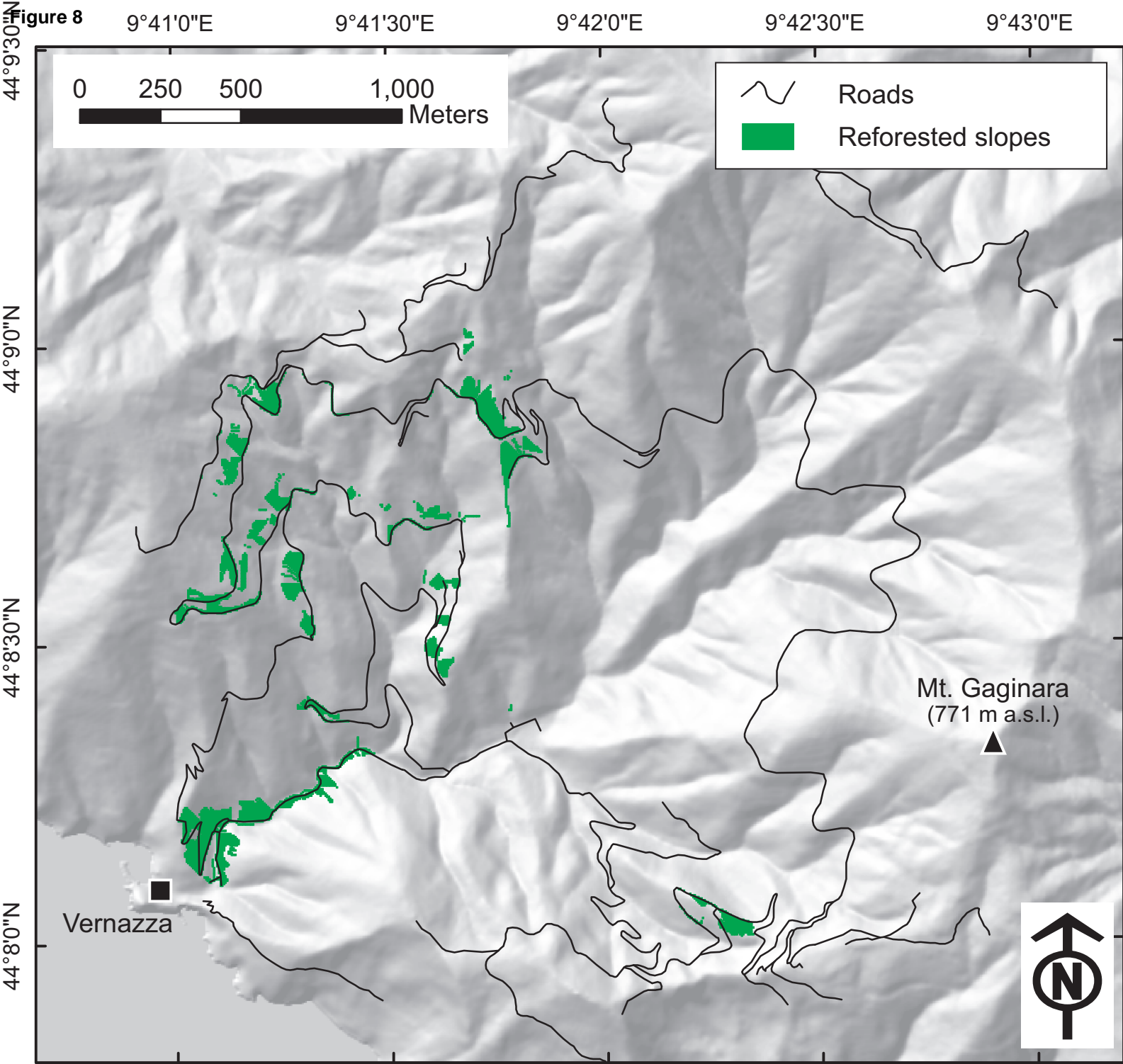
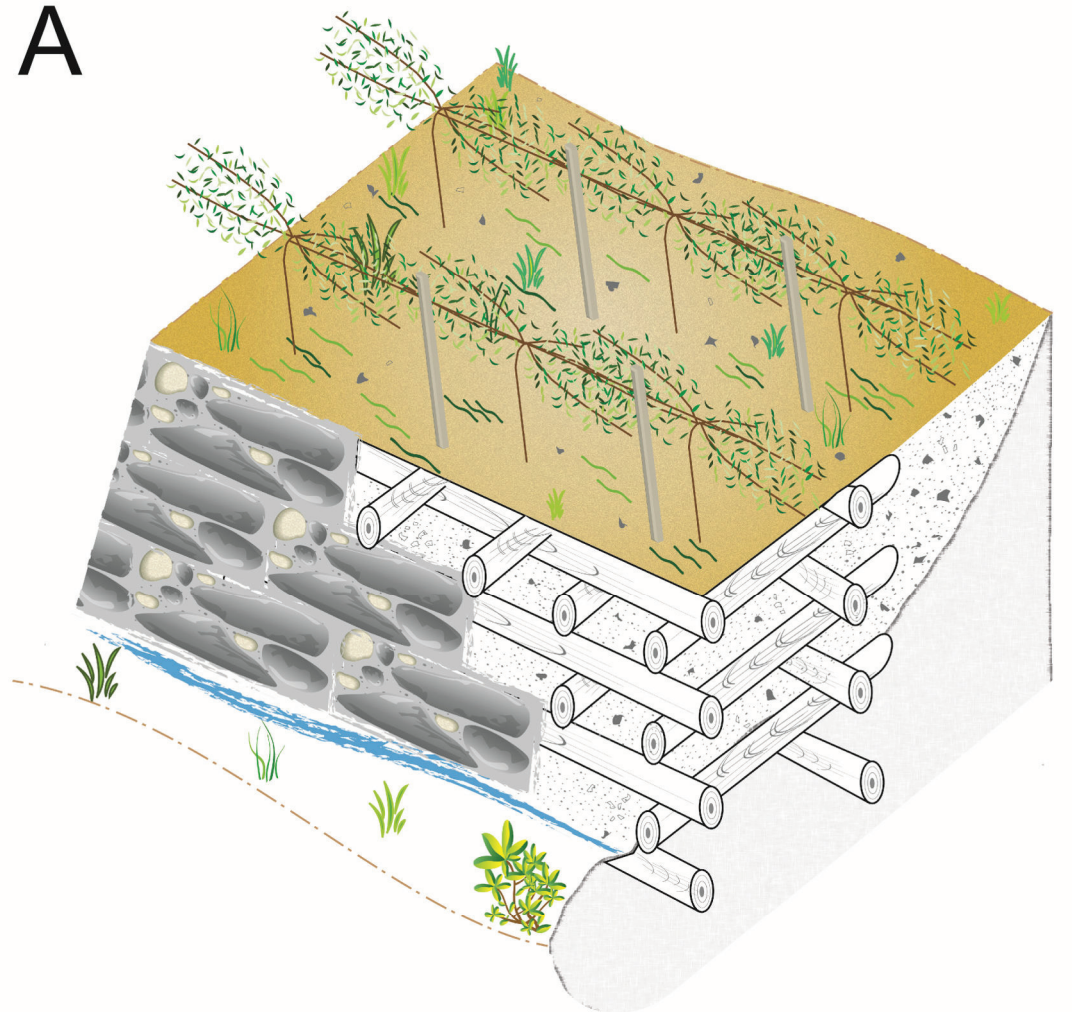


Figure 9

A



B

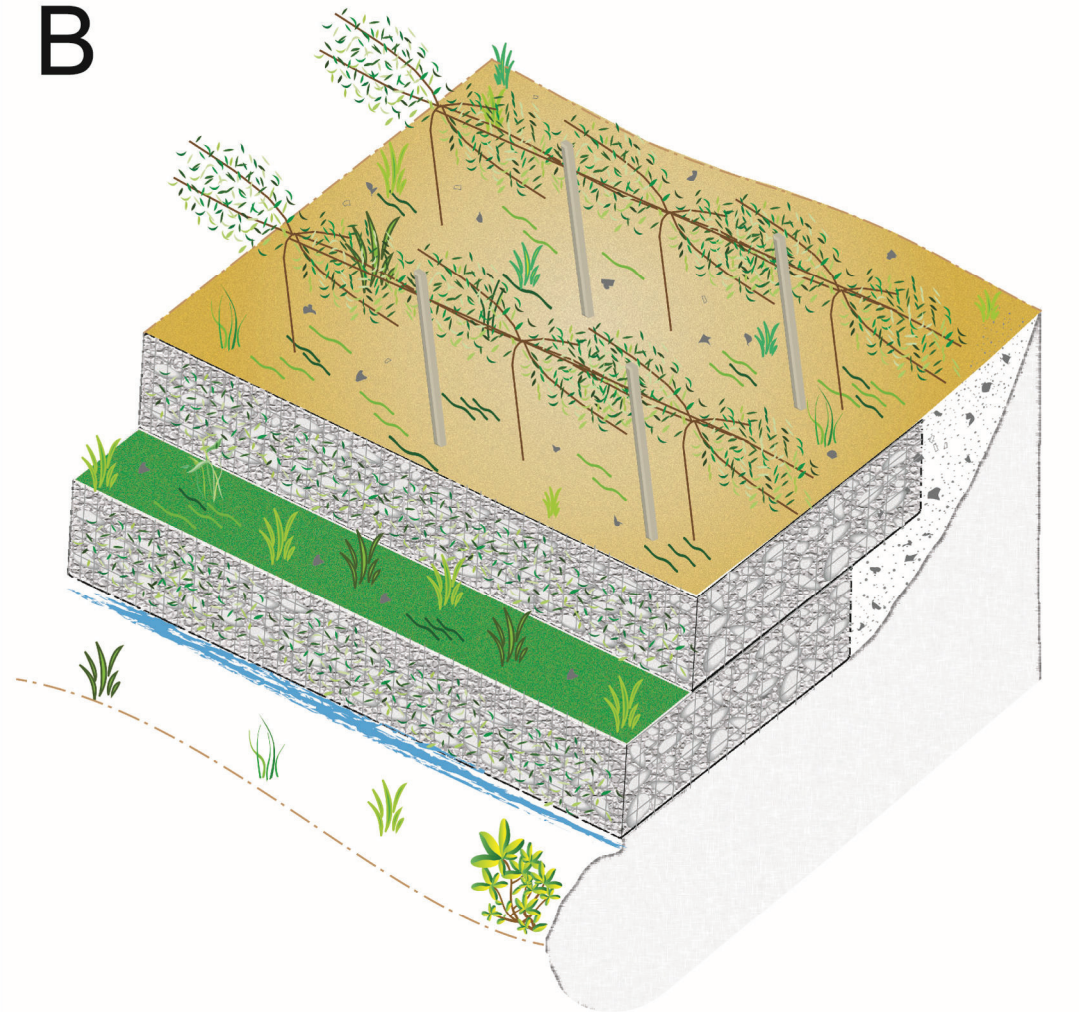


Figure 10

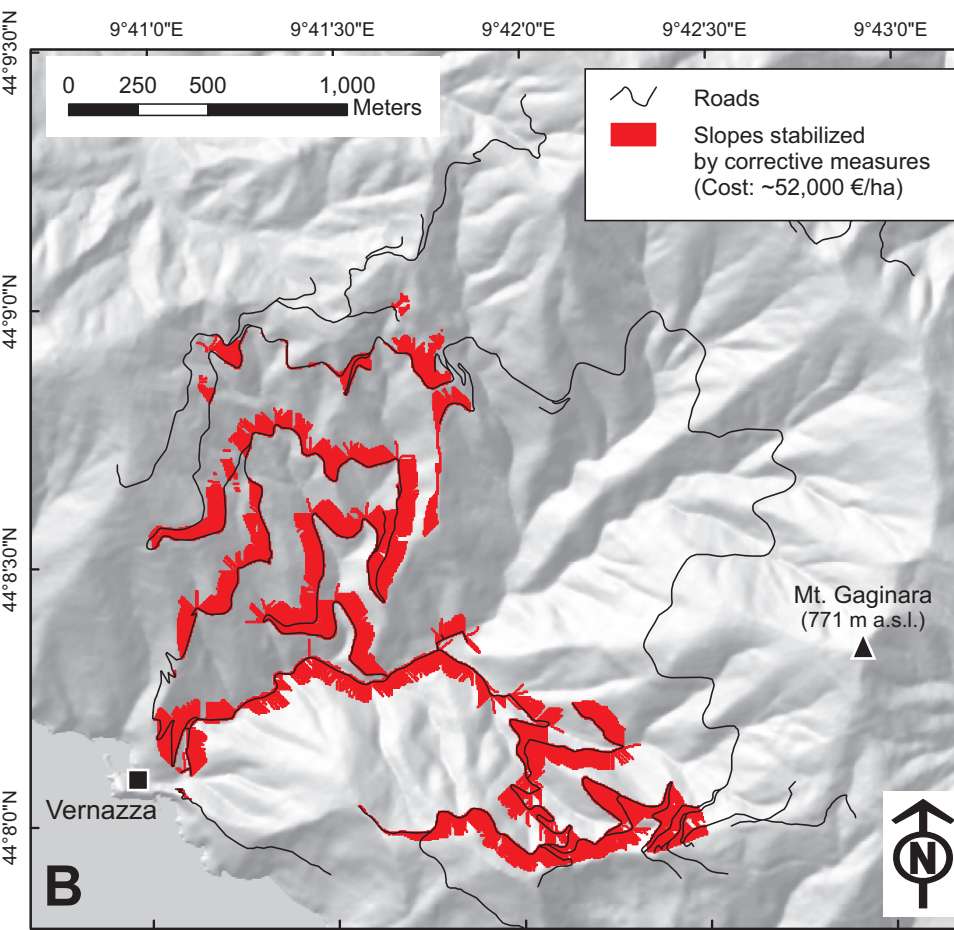
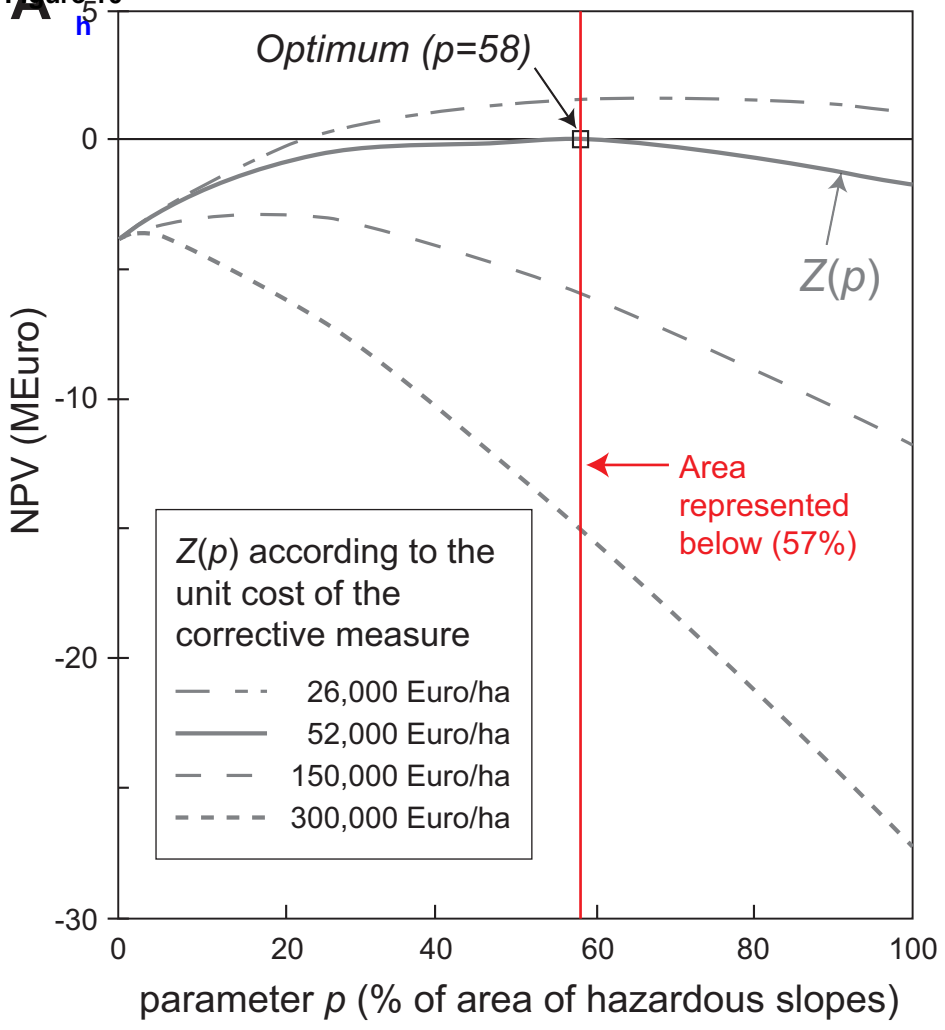


Figure 11

