Tier-based approaches for landslide susceptibility assessment in Europe

Andreas Günther[1,*], Paola Reichenbach[2], Jean-Philippe Malet[3], Miet Van Den Eeckhaut[4], Javier Hervás[4], Claire Foster[5], Fausto Guzzetti[2]

[1] *Federal Institute for Geosciences and Natural Resources, Hannover, Germany*

[2] *Consiglio Nazionale delle Ricerche, Istituto di Ricerca per la Protezione Idrogeologica, Perugia, Italy*

[3] *Institut de Physique du Globe de Strasbourg (CNRS UMR 7516), Université de Strasbourg / EOST, Strasbourg France*

[4] *Institute for Environment and Sustainability, Joint Research Centre, European Commission, Ispra (VA), Italy*

[5] *British Geological Survey, Nottingham, United Kingdom*

* Correspondence:

Andreas Günther

Federal Institute for Geosciences and Natural Resources
Stilleweg 2, D-30655 Hannover, Germany
Phone: +49 +511 643 2448
Email: a.guenther@bgr.de

Abstract

In the framework of the European Soil Thematic Strategy and the associated proposal of a Framework Directive on the protection and sustainable use of soil, landslides were recognised as a soil threat requiring specific strategies for priority area identification, spatial hazard assessment and management. This contribution outlines the general specifications for nested, Tier-based geographical landslide zonings at small spatial scales to identify priority areas susceptible to landslides (Tier 1), and to perform quantitative susceptibility evaluations within these (Tier 2). A heuristic, synoptic-scale Tier 1 assessment exploiting a reduced set of geo-environmental factors derived from common pan-European data sources is proposed for the European Union and adjacent countries. Evaluation of the susceptibility estimate with national-level landslide inventory data suggests that a zonation of Europe according to e.g. morphology and climate, and performing separate susceptibility assessments per zone could give more reliable results. To improve the Tier 1 assessment, a geomorphological terrain zoning and landslide typology differentiation are then applied for France. A multivariate landslide susceptibility assessment using additional information on landslide conditioning and triggering factors, together with a historical catalogue of landslides, is proposed for Tier 2 analysis. An approach is tested for priority areas in Italy using small administrative mapping units, allowing for relating socio-economic census data with landslide susceptibility, which is mandatory for decision making regarding the adoption of landslide prevention and mitigation measures. The paper concludes with recommendations on further work to harmonise European landslide susceptibility assessments in the context of the European Soil Thematic Strategy.

Keywords: Small-scale landslide zoning, Heuristic Tier 1 assessment, Statistical Tier 2 assessment, European Soil Thematic Strategy, Common landslide susceptibility criteria, Europe.

Introduction

Landslide susceptibility is the likelihood of a landslide occurring in an area controlled by local terrain conditions (e.g., Brabb 1984; Guzzetti et al. 1999; Fell et al. 2008). It is the degree to which a terrain can be affected by future slope movements. Susceptibility does not consider the temporal probability of failure (i.e., when or how frequently landslides occur), or the magnitude of the expected events (i.e., how large or destructive possible failures may be) (Committee on the Review of the National Landslide Hazards Mitigation Strategy 2004). With this respect, landslide susceptibility evaluations resembling basic spatial landslide zoning differ from landslide hazard (e.g., Guzzetti et al. 1999; van Westen et al. 2005), and landslide risk assessments (e.g., Glade et al. 2005; Fell et al. 2008).

The relevance of landslide zoning for environmental policy and decision making in Europe is set forth in the framework of the European Union’s Thematic Strategy for Soil Protection, adopted on 22 September 2006 (EC 2006a). This Strategy considers landslides as one of eight soil threats in Europe for which it is necessary to identify areas where landslides are likely to occur in the future, and where measures to reduce the impact of the threat have to be designed. To achieve these objectives, a Soil Framework Directive was proposed as a legislative initiative (EC 2006b, EC 2012). The importance of landslide zoning through spatial susceptibility assessments in Europe is additionally recognised in the European Commission’s approach to natural and man-made disaster prevention (EC 2009). Furthermore, the production of comparable maps for European Union member countries showing the expected spatial distribution of major threats including landslides has been recommended by the European Commission as a first step towards producing national-level risk maps for disaster emergency management using coherent and consistent risk assessment methodologies (EC 2010).

To identify areas of interest for landslide zonation, the Soil Information Thematic Working Group (SIWG) of the European Soil Bureau Network (ESBN) selected i) a set of *common criteria* (i.e., environmental and thematic factor data to predict landslide susceptibility), including landslide occurrence or density, topography, bedrock, soil type, land cover, land use, climate and seismicity (Eckelmann et al. 2006), and ii) a nested assessment approach based on “Tiers”. In this context, a Tier 1 assessment is aimed at the general identification of priority areas threatened by landslides using *common criteria* derived from available spatial datasets through a qualitative evaluation procedure combined with thresholds. The Tier 2 assessment is intended to perform quantitative landslide susceptibility analyses in priority areas identified by Tier 1 incorporating additional (including not yet existent) data. This framework should allow the EU member countries to delineate priority areas through a Tier 1 assessment exploiting either pan-European, low-resolution data or spatial information with higher resolution available at national or regional levels. For the identification of priority areas through Tier 1, these have to be combined with a suitable threshold to discriminate priority areas against terrains where no further action has to be taken.

Since the two Tiers can be conducted at various spatial scales depending on input data resolution and spatial extent, Tier 2 should not be considered an alternative for priority area delineation through Tier 1 but rather should provide more accurate spatial information for the establishment of targets and programmes of measures to combat soil threats in the EU member states (EC 2006b). The proposal for the soil framework directive attempts to provide a general framework to enable the member countries to identify priority areas, decide on appropriate general measures and targets to fight soil degradation within these, and enable a reporting policy on this (EC 2006b). In terms of landslides, the Tier-based concept for susceptibility evaluation must therefore be regarded to support general EU policy implementation but not as a regulation for measures to mitigate and monitor individual landslides and their consequences.

The initial work of the SIWG was put forward by the European Landslide Expert Group (http://eusoils.jrc.ec.europa.eu/library/themes/Landslides) established in 2007 at JRC Ispra (Hervás et al. 2007). It was recognized that since a comprehensive, distributed landslide inventory does not exist over Europe and many European regions lack information on landslides (Van Den Eeckhaut and Hervás 2012), index-based heuristic susceptibility evaluations calibrated and validated with regional level landslide data should be envisaged for continental-level Tier 1 assessments (Hervás et al. 2007, Günther et al. 2008). It was further specified that Tier 1 should be performed using reduced spatial information on solely three environmental factors supposed to have a major control on all types of landslides (e.g., van Westen et al. 2009): terrain gradient, lithology and land cover.

Important variables merely related to landslide triggering like spatial information on groundwater and soil moisture conditions, precipitation or seismicity were excluded at this stage, because they reveal a high degree of temporal variability and are more suitable for hazard analysis. As a mapping unit, a grid cell with a size depending on input data resolution and analysis extent was recommended. A continental-level Tier 1 assessment should be prepared employing a 1 km x 1 km grid cell (Hervás et al. 2007). Tier 2 evaluations should be carried out through inventory-based, statistical analyses utilizing a wider range of environmental and triggering factor data. To allow for decision on measures/implementation plans for the landslide threat, it was recommended to use terrain units of appropriate size for the analysis. These may consist of administrative, agroeconomic or geomorphometric entities allowing for a direct association of landslide susceptibility with economic or population-based census data.

In this work, we first present and evaluate the results of an experiment carried out in the framework of the European Landslide Expert Group, aimed at producing a preliminary synoptic-scale, index-based, landslide susceptibility assessment for Europe, reflecting a basic continental Tier 1 susceptibility evaluation. Next, we present and discuss two national-scale landslide susceptibility assessments and their associated terrain zonations for France and Italy. The example for France resembles a more advanced Tier 1 assessment since it uses the same type of reduced geo-environmental data and does not necessarily require information on landslide distribution, but introduces a differentiation according to terrain physiography and landside typology. The example for Italy represents a small-scale Tier 2 quantitative susceptibility analysis within priority areas as defined by the continental-level Tier 1 assessment. This analysis is based on distributed landslide information and additional thematic data. We conclude discussing problems and advantages of the presented small-scale landslide susceptibility analyses, and pointing out future work to be done to improve both Tier 1 and Tier 2-compatible attempts for harmonised landslide zoning in the context of the European Soil Thematic Strategy.

Basic continental-level Tier 1 assessment over Europe

We prepared a synoptic-scale landslide susceptibility model and an associated susceptibility map for Europe at 1:1M scale to identify priority areas for landslide zoning. The map covers the 27 EU member countries (except Cyprus) in addition to Norway, Switzerland and the Balkan states (Fig. 1). As mapping unit, a grid cell size of 1 km x 1 km was selected (Hervás et al. 2007). In this section, we first describe the data and the data evaluation approach adopted to prepare the zonation of landslide susceptibility in Europe. Then we discuss the validation of the synoptic landslide susceptibility zonation in France, Great Britain and Italy, three European countries for which comprehensive landslide information was available to us. Last, we compare the continental landslide susceptibility map with other global (Nadim et al. 2006; Hong et al. 2007) and continental (Schmidt-Thomé 2006) landslide susceptibility and hazard evaluations that may also be considered for continental scale Tier 1 assessments.

Data

To model landslide susceptibility in Europe, we used small-scale geo-environmental information available in digital format from public sources, including information on terrain gradient (slope), lithology, and land cover (Table 1). Information on terrain gradient was obtained from the GTOPO30 global elevation model (http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30_info). This global digital coverage of topography has a horizontal grid spacing of 30 arc seconds (approximately 1 km), and was completed in 1996 by the USGS EROS Data Center. Terrain slope was computed from the elevation data in a Geographical Information System (GIS). We acknowledge that the computed slope values, in the range 0 - 38.9° (average = 2.3°, standard deviation = 3.4°), do not represent the actual terrain gradient at any specific point, and we consider the computed slope a proxy for the general topographic gradient in the study area.

Spatial information on lithology was obtained exploiting the European Soil Database (ESDB) (Heineke et al. 1998; Panagos et al. 2012; http://eusoils.jrc.ec.europa.eu/ESDB_Archive/ESDB/index.htm). The geometry of the ESDB is provided by soil mapping units (SMU), which can be related to more than 20 attributes of so-called Soil Typological Units (STU) describing several properties of dominant and co-dominant soils. To obtain the lithological information required for the analysis, the attribute “dominant parent material” at level 2 (MAT12), subdivided in 41 classes of soil parent material, was selected. The SMU polygons attributed to MAT12 have been rasterized at a 1 km × 1 km grid resolution. The soil parent material information attributed in the ESDB comprises first-order genetic and petrologic information on geological materials on which soils evolve, derived from different European geological map datasets (Finke et al. 2001). We have chosen the dominant parent material data from the ESDB against alternative digital data (e.g., solid bedrock geology from the International Geological Map of Europe; Asch 2005) as a proxy for near-surface lithology because of its higher resolution and because it also renders spatial information on the distribution of quaternary and unconsolidated geological materials.

We obtained spatial information on land cover from the Pan-European Land Cover Monitoring Project (PELCOM) which produced a gridded, 1 km × 1 km resolution land cover database for the period 1996-1999 (http://www.geo-informatie.nl/projects/pelcom/). The land cover information, in 14 classes, was obtained from multi-temporal and multi-spectral NOAA-AVHRR satellite imagery and other ancillary data (namely CORINE and Digital Chart of the World). For the purpose of this study, terrains covered by the three classes ice and snow, sea, and inland waters were excluded from the analysis, and eleven classes of land cover were considered.

For the synoptic-scale analysis of landslide susceptibility in Europe, we re-classified the terrain gradient, lithological, and land cover information in a reduced number of classes, including: (i) five classes of terrain slope, (ii) five lithological classes representing major lithological complexes as derived from the soil parent material information, and (iii) five land cover classes (Fig. 2). The reclassification of the input data was based on our understanding of the landslide phenomena in Europe, and on the known or expected relevance of the three considered environmental factors in controlling the susceptibility to landslides. However, it should be mentioned that the proposed parameter classification tries to globally specify the input data for all types of landslides and has clear limitations with respect to regionally differentiated interpretations (see further).

In addition to the mentioned environmental data, we used national-scale landslide information for France, Great Britain, and Italy (Fig. 3) to evaluate the preliminary European susceptibility zonation. The three countries cover 22% of the study area. For France, we used the national landslide database BDMvT (a French acronym for *Base de Données Nationale Mouvements de Terrain,* http://www.bdmvt.net/) (Fig. 3A). The inventory is the result of a joint effort of the Bureau de Recherches Géologiques et Minières, the Laboratoire des Ponts et Chaussées, and the Restauration des Terrain en Montagne. The database contains information on 17,598 landslides (June 2010), including movement type (Varnes 1978), geographical location, date and time of occurrence, state of activity, and damage caused by the collected landslides. For Great Britain, we used the National Landslide Database produced and maintained by the British Geological Survey, which lists detailed information on 15,897 landslides (October 2011). Compilation of the database started in the late 1980's through a combination of existing data sources. Since then, information on more than 6,000 additional landslides was added to the database (Foster et al. 2008; Evans et al. 2011) (Fig. 3B). For Italy, we used the catalogue of historical landslides compiled by the AVI project (an Italian acronym for *Aree Vulnerate Italiane*, Areas Affected by Landslides and Floods in Italy, http://sici.irpi.cnr.it/) through a methodical search of national, regional, and local chronicles and historical archives (Guzzetti et al. 1994; Guzzetti and Tonelli 2004). Landslides listed in the catalogue were mapped as points at 1:25,000 or 1:100,000 scale, and a level of geographic accuracy, in five classes, was attributed to each mapped landslide. The original AVI catalogue covers the period from pre-1900 to 2002. To minimize the effects of incompleteness in the early period of the catalogue, for the assessment of landslide susceptibility we selected 15,503 landslides in the 52-year period 1950-2001 (Fig. 3C). We chose this historical dataset against a more recent and more exhaustive national-level landslide inventory prepared by the IFFI project (http://www.isprambiente.gov.it/site/en-GB/Projects/IFFI_Project/default.html, Trigilia et al. 2010) because this data was not completely available for this study. Moreover, we preferred to use the historical catalogue for Italy to allow for temporal validation of a statistical Tier 2 example discussed below.

Methodology

We adopted a heuristic approach, quantified through an Analytic Hierarchy Process (AHP) technique for susceptibility evaluation. This is an expert-based, stepwise classification technique designed to hierarchically organize criteria (here: environmental variables influencing landslide susceptibility) to solve complex decisions through pairwise comparisons of their relative importance on a scale from 1 - 9 (Saaty 1980). AHP has been applied for heuristic landslide susceptibility zoning lacking extensive inventory information (e.g., Barredo et al. 2000; Gorsevski et al. 2006; Yalcin 2008; Castellanos Albella and van Westen 2008).

For organizing the three equally classified spatial criteria for landslide susceptibility used in this study, first the relative weights for the five individual classes of each criterion (i.e., slope gradient, lithology, and land cover) were directly assigned based on our understanding of landslide susceptibility over Europe as predicted by the data used in this study. Steeper terrain was attributed a higher susceptibility than gentle terrain. Soft materials (e.g., predominantly clayey and unconsolidated lithologies) known to be prone to failure were assigned a high weight, and strong lithologies (e.g., metamorphic and highly consolidated rocks) were attributed a low weight. Forests and grasslands were considered more prone to landslides than croplands and wetlands. For convenience, all factor weights were normalized (Table 2).

Next, the relative importance of the three used criteria in conditioning slope instability in Europe was decided. For this instance, pairwise comparisons of the three factors were performed within the AHP giving slope a moderately higher importance than lithology, slope a strongly higher importance than land cover, and lithology a moderately higher importance than land cover. This operation results in normalized weight values of 0.64 for slope, 0.26 for lithology, and 0.10 for land cover (Table 2), with an consistency ratio of 0.03 indicating a valid pairwise comparison matrix (Saaty and Vargas, 1984). We acknowledge that the relative importance of the single criteria may not work everywhere in the study area, and the corresponding weights assigned to the criteria may result in local inconsistencies. However, we maintain that the assigned normalized relative weights are reasonable for most of Europe.

The integration of the weighted parameter classes into a landslide susceptibility index *S* was determined using their weighted linear sum (Voogd 1983) with

$$S = \sum_{j=1}^{n=3} w_j \cdot x_{ij} \qquad (1)$$

where w_j is the weight of criterion j and x_{ij} is the weight of class i for criterion j. Finally, the continuous susceptibility index resulting from the weighted linear summation of the criteria classes with Eq. 1 was classified into five levels through equal-interval slicing, used to prepare the synoptic-scale landslide susceptibility zonation of Europe shown in Fig. 4A. In Fig. 4B, total area and landslide proportions of the five susceptibility categories are shown, together with the frequency distribution of the continuous landslide susceptibility index S. From this is can be inferred that 41.1% of the landslide locations in Britain, France and Italy are within the two highest susceptibility classes covering an area of 16.6%, and only 7.9% of landslides are present in the majority of the study area attributed to the lowest susceptibility class (39.3%). We therefore suggest the applied classification of *S* resulting from trivial equal-interval slicing capable to produce a reasonable synoptic landslide susceptibility zonation.

Landslide susceptibility map

The resulting synoptic-scale landslide susceptibility map for Europe (Fig. 4A) can be evaluated qualitatively and quantitatively. For a qualitative evaluation, a visual inspection of Fig. 4A reveals that areas where susceptibility to landslides is high or very high concentrate in the main European mountain chains, including the Alps, the Apennines, the Pyrenees, the Dinarides and the Carpathians. Susceptibility is also high or very high in the mountains and hills of Greece and Crete, in southern Spain, in southern Norway, and in western Scotland. Further inspection of Fig. 4A shows that areas where susceptibility to landslides is low or very low concentrate in Central and Northern Europe, include large portions of the Iberian Peninsula, and ample parts of the Eastern European lowland. Comparison of the susceptibility map (Fig. 4A) with the terrain gradient map (Fig. 2A) reveals that more than 50% of the highly susceptible terrain (3.0% of Europe) exhibits terrain gradients exceeding 15° and more than 95% of the area classified as having a very low landslide susceptibility (39.3% of Europe) has a terrain gradient lower than 1°. Visual inspection of Fig. 4A also reveals areas where the continental-scale susceptibility assessment underestimates the propensity of the terrain to generate landslides. This is particularly evident in generally low-relief areas of northern Europe (e.g., southern England, northern France) and Central European highlands known to be landslide-prone. Additionally, many coastal areas in e.g. England, France and Italy are underrepresented in terms of landslide susceptibility. These circumstances result from the global susceptibility evaluation that does not incorporate physiography-specific class weights of the geo-environmental data used.

A quantitative evaluation of the performance of the synoptic landslide susceptibility zonation of Europe can be performed exploiting the landslide information available for France, Great Britain and Italy (Fig. 3). For the purpose, we prepared Receiver Operating Characteristics (ROC) curves (Metz 1978; Mason and Graham 2002; Fawcett 2006) using the three individual national landslide datasets and the ensemble of the three datasets (Fig. 4C). Adopting the Area Under the ROC Curve (AUC) metric as a quantitative measure of the ability of the susceptibility model to predict the landslide locations, we notice that the synoptic-scale susceptibility zonation performed best in France (AUC = 0.75), followed by Great Britain (AUC = 0.64) and Italy (AUC = 0.61). Considering the ensemble of the landslide information in the three countries, the metric was AUC = 0.72. It has to be emphasized that the ROC evaluation can only be considered as an indication of model performance in areas where distributed landslide information is available, and cannot be used as a quality criterion for the overall susceptibility map.

An additional quantitative evaluation of the susceptibility model consists in comparing the performance of the susceptibility zonation with the performance of a classification based solely on slope gradient (Remondo et al. 2003). Dashed lines in Fig. 4C show ROC curves obtained comparing the spatial distribution of landslides with the distribution of terrain gradient in France, Great Britain, and Italy. The AUC metrics for the three individual countries (France AUC = 0.73, Great Britain AUC = 0.60, Italy AUC = 0.60), and for the combined landslide dataset (AUC = 0.67), show that the performance of the AHP-based multi-criteria classification model was consistently higher than the performance of the corresponding classifications obtained using solely the terrain slope. The differences in the AUC values measure the improvement in the terrain classification resulting from the use of the lithology and the land cover information, in addition to the slope information. We acknowledge that the size of the improvement is partly dependent on the relative weights attributed heuristically to the three susceptibility criteria (i.e., 0.64 for terrain gradient, 0.26 for lithology, and 0.10 for land cover).

To use our continental-level evaluation for the delineation of priority areas against terrains where no further action is necessary, a suitable susceptibility index threshold value has to be established. Based on our synoptic scale analysis, we conservatively consider areas classified as very high, high and moderate susceptibility as priority areas subjected to quantitative, inventory-based landslide susceptibility evaluations (Tier 2). Application of this threshold classifies 36% of the analysed area as subjected to Tier 2 (Fig. 4). Because it is not known to what extent landslides can be expected in specific areas classified as moderately susceptible, we used a precautionary principle to identify priority areas over Europe.

Comparison with continental and global landslide susceptibility models

The ability of our synoptic-scale landslide susceptibility assessment for Europe (Fig. 4A) to predict the landslide locations in Great Britain, France and Italy collected for this study can be compared to that of existing continental (Schmidt-Thomé 2006) and global (Nadim et al. 2006; Hong et al. 2007) assessments of landslide susceptibility and hazard (Fig. 5). In the context of the European Spatial Planning Observation Network (ESPON) Programme, Schmidt-Thomé (2006) published a map showing the distribution of landslide "hazard" in Europe (Fig. 5A). The map adopted the NUTS (*Nomenclature des Unités Territoriales Statistiques*) level 3 administrative units, and showed the propensity to landslides for these mapping units in two classes: "low hazard" and "high hazard". Although solely based on the opinion of experts of European geological surveys and suffering from data gaps, the resulting continental map was the first to recognize the importance and extent of landslide problems in Europe. A comparison of the new synoptic-scale landslide susceptibility zonation (Fig. 4A) with the ESPON "hazard" map of Europe (Fig. 5A) indicates that the ESPON zonation predicted correctly nearly 80% of the locations of the known landslides in France (Fig. 3A), Great Britain (Fig. 3B) and Italy (Fig. 3C). However, the number and areal extent of the NUTS 3 units predicted as landslide prone by the ESPON model and for which no information is available in the three national inventories (i.e., false positives) is large, reducing the credibility of the map. We attribute this overestimation of landslide susceptibility to the large average size of the mapping units, and we conclude that a NUTS level 3 mapping unit is inadequate (too large) for the accurate definition of landslide susceptibility in Europe.

Hong et al. (2007) produced a global landslide susceptibility assessment exploiting geo-environmental information obtained from a variety of geospatial data sources, including (i) the GTOPO30 elevation dataset, (ii) land cover information obtained by processing data captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor aboard the NASA Terra and Aqua satellites, and (iii) soil information extracted from the 2003 edition of the Digital Soil of the World (FAO, http://www.fao.org) and from a soil database of the International Satellite Land Surface Climatology Project Initiative (ISLSCP, http://www.gewex.org/islscp.html). The coarse resolution geo-environmental information was combined using a weighted linear combination method proposed by Ayalew et al. (2004), with the weights attributed to the different landslide-controlling factors decided heuristically. The result consisted in a low-resolution (15 arc minutes, approx. 28 km) global map showing landslide susceptibility in five classes, from very low to very high susceptibility. Kirschbaum et al. (2009) used this global landslide susceptibility zonation combined with satellite-derived rainfall estimates to provide dynamic forecasts of landslide hazard in near real time. Visual comparison of the European portion of the global landslide susceptibility zonation of Hong et al. (2007) (Fig. 5B) with the new synoptic-scale landslide susceptibility assessment for Europe made for this study (Fig. 4A) indicates that, apart from their incompatible resolution, the resulting maps show a certain degree of coincidence. However, in contrast to the susceptibility estimate presented here, the map from Hong et al. (2007) is more pessimistic in Southern Europe (e.g., the Iberian Peninsula and the East European basins).

Nadim et al. (2006) were first to produce a global map showing landslide (and snow avalanche) hazard areas and risk hotspots. Their pioneering worldwide hazard assessment was prepared through a linear combination of conditioning and triggering factors modulated by weights decided on expert opinion (e.g., Mora and Vahrson 1994). The factors considered in the analysis included (i) terrain slope computed from the GTOPO30 elevation dataset, (ii) lithology obtained simplifying the 1:25M scale Geological Map of the World (CGMW 2000), and (iii) soil moisture characteristics extracted from a moisture index global archive for the period 1962-1990 (Willmot and Feddema 1992). The triggering factors included (i) estimates for the 100-year extreme monthly rainfall obtained from the Global Precipitation Climatology Centre managed by the German National Meteorological Service (Rudolf et al. 2005), and (ii) the expected Peak Ground Acceleration with a return period of 475 years, obtained from the Global Seismic Hazard Programme (http://www.seismo.ethz.ch/static/GSHAP/). The resulting global map with a resolution of 30 arc seconds (approx. 1 km x 1 km) was classified into nine hazard classes, where only the values from six through nine are downloadable as a raster dataset from http://www.ldeo.columbia.edu/chrr/research/hotspots/coredata.html. Visual comparison of our landslide susceptibility zonation for Europe (Fig. 4A) with the section for Europe of the four highest hazard classes of the global map of Nadim et al. (2006) (Fig. 5C) indicates that the latter exclusively delineates areas in high mountainous regions having moderately to high landslide hazard and renders no information for more than 90% of the area, including many European countries also facing landslide problems (e.g., Great Britain, Germany, Belgium).

We evaluated the capability of the continental (Schmidt-Thomé 2006) and the global (Nadim et al. 2006; Hong et al. 2007) assessments of landslide susceptibility and hazard to predict the landslide locations in Great Britain, France and Italy in comparison to the new synoptic-scale susceptibility assessment for Europe (Fig. 4). For this purpose, we compared the extent of the various susceptibility classes with the location of slope failures in the ensemble of the three historical landslide inventories available for France (Fig. 3A), Great Britain (Fig. 3B) and Italy (Fig. 3C). This was used to construct the ROC curves shown in Fig. 5D. Inspection of the ROC curves shows that the performance of the susceptibility classification in France, Great Britain and Italy (AUC = 0.72) was larger than the performance of the global classification of Hong et al. (2007) (AUC = 0.68) for the same three countries. Further analysis of the ROC curves reveals that the global hazard classification of Nadim et al. (2006) exhibited a “j”-

shaped ROC curve with AUC = 0.45, mostly attributed to the fact that the map only covers 3% of the area with more than 70% of the landslides outside the hazard classes.

The continental and global landslide susceptibility and hazard zonations discussed above may be alternatively considered as Tier 1 assessment for the delineation of priority areas over Europe. The ESPON map (Fig. 5A) could be straightforwardly used for this purpose since it directly aims to delineate “hazard” zones against “no hazard” terrains. However, size and geometry of the mapping units (NUTS 3), data gaps and the general spatial overestimation of threatened terrain portions (58%) makes the use of this map problematic. A possible threshold to identify priority areas through the global susceptibility map of Hong et al. (2007) (Fig. 5B) would be the aggregation of the terrains classified as very highly, highly and moderately susceptible. Although the spatial distribution of these areas has clear significance for landslide zoning over Europe, the resolution of the map is too low (28 km) and the estimate is pessimistic, resulting in the assignment of 61% percent of the area for Tier 2 zoning. In contrast, the “hotspot” map of Nadim et al. (2006) has the same resolution as the map proposed here. The map only assigns a relatively small proportion (3%) of the analysed area over Europe as priority terrains for Tier 2 landslide zoning when considering the spatial distribution of the available classes medium to very high (Fig. 5C). This disagreement mostly results from the fact that the “hotspot” map represents a hazard scenario map rather than a susceptibility map (through e.g. the incorporation of landslide triggering factors as precipitation and seismicity), classified on a global landslide hazard scale. However, since the map does not identify priority areas in many European countries facing landslide problems, it should not be used as a Tier 1 evaluation.

Differentiated national-level Tier 1 assessment: Application over France

In accordance to the general specifications for heuristic Tier 1 landslide susceptibility modelling proposed by Hervás et al. (2007), the national assessment for France is based on the same reduced *common criteria* (e.g., spatial information on terrain gradient, soil parent material as a proxy for lithology, and land cover), but the input data sets differ in terms of resolution and taxonomy. Additionally and most importantly, the susceptibility evaluation employs a differentiation according to landslide typology (flows, slides and falls), and terrain physiography (coasts, mountains and plains).

Data

Information on slope gradient was derived from the French elevation database (BD-Alti®), at 50 m × 50 m ground resolution. For susceptibility modelling, terrain slope was computed and reclassified in 13 equally spaced classes (5° interval), from 0° to > 60°. Information on soil parent material was obtained from the 1:1M scale digital Geological Map of France, and the associated digital database prepared by BRGM (2005). Since the original lithological information was too complex (and too detailed) for the purpose of the study, the data was grouped in 24 lithological classes based on information on lithology, structure, and age of the rocks. Also, the lithological information originally available in vector format was transformed to a 50 m × 50 m resolution grid spatially coherent with the terrain gradient data. Information on land cover was obtained from the CORINE Land Cover 2000 and 2006 databases (CLC2000, CLC2006) available at 1:100,000 scale. For France, the databases show land cover characteristics in ten classes, for terrain units larger than 0.25 km^2. Information on landslides for model calibration was obtained from the French national BDMvT inventory (Fig. 2A). This is the same inventory used for the evaluation of the synoptic-scale landslide susceptibility assessment for Europe. All the slope failures listed in the BDMvT inventory were classified as falls, flows, or slides, depending on their primary type of movement (Varnes 1978).

Methodology

To evaluate landslide susceptibility in France, a Spatial Multi-Criteria Evaluation (SMCE) technique (Figueira et al. 2005) as implemented in the ILWIS® software was adopted (Castellanos Abella and van Westen 2008; Malet et al. 2009). The technique is conceptually and operationally based on an AHP to decide on criteria and criteria class weights as also used to determine landslide susceptibility over Europe in this paper. Specifically, SMCE is used to hierarchically organize the criteria classes and to associate normalized weight values through pairwise comparisons, rank ordering or direct assignments. In our analysis, we directly assigned class weights taken into consideration the frequency ratio of landslides from the French inventory over the criteria classes. Susceptibility was ascertained utilizing the following procedure: First, the French territory (excluding Corsica, the overseas territories and other minor islands) was partitioned into three main physiographic units: (i) mountains, (ii) plains, and (iii) coastal areas. This was done to respect the fact that same criteria classes have a different influence on landslide susceptibility based on their specific physiographic setting. Moreover, coastal regions were treated separately since coastal landslides can hardly be compared to inland mass movements because of their different controlling characteristics. Mountains and plains were outlined using the general criteria proposed by Nordregio (2004). Coastal areas were defined geometrically, constructing a 1-km wide buffer along the coastline.

After partitioning the French landslide inventory into three types (i.e., slides, flows and falls), weights for the individual criteria classes (i.e., 13 classes of terrain slope, 24 classes of lithology, and 10 classes of land cover) were assigned for each landslide type. Next, using a pairwise comparison approach similar to the European example, normalized relative weights were assigned to the ensembles of terrain gradient (0.58), lithology (0.28), and land cover (0.13) classes. These weights measure the relative importance of the three geo-environmental factors, and modulate the weights assigned to the individual criteria classes.. For simplification, the same parameter weights were assigned to the geo-environmental controlling factors for the three different landslide types.

A set of typology-specific susceptibility maps (i.e., for slides, flows and topples) was produced for each physiographic region (i.e., coasts, mountains and plains) using a weighted linear summation of the established weights following (1). The terrain-specific susceptibility maps for each landslide type were spatially combined, and the typology-specific susceptibility indices were classified into four susceptibility levels (very low, low, moderate, and high) using a Jenks natural breaks classification (Jenks 1967). More information on the national level landslide susceptibility map for France can be found in Malet et al. (in revision).

Landslide susceptibility maps

Map results of the modelling approach described above for the national-scale susceptibility to falls, flows, and slides are portrayed in Fig. 6A-C. In the three maps, susceptibility is shown in four classes, from very low (VL) to high (H). Visual inspection of Fig. 6A-C shows that the geographical pattern of susceptibility varies for the three considered landslide types. Susceptibility to falls (Fig. 6C) is largest in areas where the terrain is steep and rock slopes are widespread, favouring the occurrence of rock falls, topples, and minor rock slides. Susceptibility to slides (Fig. 6A) is moderate to high in the French Alps and the Pyrenees, and in hilly areas where terrain slope and associations of rock types control the susceptibility to slides. Areas exhibiting a moderate to high susceptibility to landslides of the flow type (Fig. 6B) are widespread in France and more abundant than the corresponding areas for falls and slides. Susceptibility to flows is generally large in areas with soft rocks..

Based on the three separate susceptibility zonations for falls, flows and slides (Fig. 6A-C), an attempt was made to produce a single, comprehensive zonation of landslide susceptibility for France (Fig. 6D). For the purpose, the three susceptibility maps prepared for the three landslide types were combined to obtain a single map that considers the susceptibility to all landslide types. This was performed using a very conservative approach (Fig. 6E): for each grid cell, the three different susceptibility values for falls, flows and slides (in four classes) were compared, and the largest cell value was attributed to the grid cell as a measure of the general susceptibility. This association approach was selected to respect the precautionary principle that guides the French legislation on natural hazard and risk assessment, and the production of Risk Prevention Plans (MATE/METL 1999). Inspection of Fig. 6D reveals that the majority of the French territory (75%) is classified as having moderate (31%) or high (44%) susceptibility. The remaining territory (25%) is attributed a low (19%) or very low (6%) susceptibility. We acknowledge that the significant proportion of territory classified as having a moderate or high susceptibility largely depends on the conservative technique adopted to associate the individual zonations, which favoured the attribution of high values of susceptibility to the individual grid cells.

To better illustrate the distribution of the compound susceptibility classes over France we compared the relative spatial proportions of the individual susceptibility levels in plain and mountain sub-units and the areal percentages of all susceptibility classes for the two physiographic units (Fig. 7A). It can be observed that the three lowest susceptibility classes reveal very similar relative proportions, but the percentages of grid cells attributed to high susceptibility is equal in the plain and the much smaller mountain units. The fact that a much higher area proportion in the mountain unit is attributed to high landslide susceptibility when compared to the plain unit is also illustrated when comparing the areal percentages of all susceptibility classes for the two physiographic units (Fig. 7B). Again, the high spatial extents of terrains classified as highly susceptible to landslides result from the conservative association procedure applied to combine the individual susceptibility estimates for flows, slides and falls.

To evaluate the national-scale landslide susceptibility zonation shown in Fig. 6D, we compared the distribution of the areas where landslide susceptibility is considered high (red areas in Fig. 6D) with the distribution of small administrative units (municipalities) where at least one landslide event is reported in the national BDMvT inventory. Results are summarized in Fig. 8, which shows that many municipalities affected by historical landslides were correctly predicted as highly susceptible by the comprehensive national-scale model. However, the susceptibility model also attributes high level of susceptibility to areas where information on historical landslides is not present in the BDMvT inventory. The main cause for this discrepancy is the fact that the BDMvT database is incomplete and has a low accuracy in many regions (departments) in France, especially in highly landslide-prone regions like the Pyrenees or the French Alps (Fig. 8).

A possible susceptibility threshold for the delineation of priority areas subjected to the Tier 2 evaluation differs from the value applied at European-level. The conservative association scheme applied to derive the composite susceptibility map for France from the three typology-specific assessments result in a more pessimistic (but probably more reasonable) evaluation, and for this reason we recommend to consider only the highest susceptibility level (44% of the territory) for a Tier 2 evaluation here (Fig. 8A).

Generalized Tier 2 assessment for priority areas in Italy

For Italy, geo-environmental and distributed landslide information is available to attempt a national-scale, statistically-based, landslide susceptibility zonation as an example for a Tier 2 evaluation. Even though the synoptic assessment described below does not account for differentiation according to landslide typology or terrain physiography, it demonstrates that statistical landslide susceptibility analyses can be conducted over entire nations at small spatial scales if the required geo-environmental (spatial predictors) and thematic (distributed and accurate landslide data) information is available. The example below also incorporates additional spatial data that should be used for Tier 2 assessments, and employs a different mapping unit (municipality) for susceptibility estimations following the general requirements for Tier 2 landslide susceptibility evaluations (Hervás et al. 2007). In the Tier 2 example discussed below, only those municipalities identified as susceptible to landslides by the continental Tier 1 evaluation were analyzed. The municipalities were selected following a conservative approach that identifies municipalities having one or more grid cells classified as moderately to very high susceptible by the synoptic continental Tier 1 evaluation as priority areas (82% of the Italian territory).

Data

The geo-environmental information consists of medium to coarse resolution topographic (elevation), lithological, soil type, and climate data shown in Table 4. Elevation information is represented by a 90 m × 90 m DEM acquired by the Shuttle Radar Topography Mission (SRTM) in February of 2000, and distributed by the U.S. Geological Survey (http://srtm.usgs.gov/) in 91 adjacent tiles. The DEM was used to obtain raster GIS morphometric maps including (i) maps of descriptive statistics (i.e., minimum, maximum, range, mean, standard deviation) of elevation and terrain gradient (slope), and (ii) a map showing topographic subdivisions i.e., highlands, uplands and lowlands (Guzzetti and Reichenbach 1994). Information on rock types was obtained from the Geological Map of Italy published at 1:1M scale by Compagnoni et al. (1976-1983). For the susceptibility modelling, the 145 rock units shown in this map were grouped into 10 main lithological complexes comprising similar rock types. Information on soil types was obtained from the Soil Map of Italy published at 1:1M scale by Mancini (1966). For the susceptibility analysis, the original soil information shown in the small-scale scale map was grouped into eight classes of soil thickness and 11 classes of soil types. Climatic information for Italy, including mean cumulated annual rainfall and mean annual temperature for the period 1961-1990 was obtained from the Centro Nazionale Cartografia Pedologica (L'Abate and Costantini 2004). The landslide information used for susceptibility modelling was the catalogue of historical landslides in Italy compiled by the AVI Project (Guzzetti et al. 1994; Guzzetti and Tonelli 2004). This is the same landslide information used for the evaluation of the synoptic-scale landslide susceptibility assessment for Europe discussed above.

To define landslide susceptibility in Italy, the municipality was selected as the mapping unit of reference. Italy is subdivided into 8102 municipalities, administrative subdivisions ranging in size from 0.1 km^2 (Atrani, Campania) to 1,285 km^2 (Rome) (mean area = 37.3 km^2, std. dev. = 50.0 km^2). For the 6159 (76,0%) municipalities identified as susceptible to landslides by the continental Tier 1 evaluation, we computed from the criteria in Table 4 the following 61 variables: (i) 10 variables describing descriptive statistics for terrain morphometry (minimum, maximum, range, mean, standard deviation of elevation and slope), (ii) three variables showing topographic setting (i.e., highlands, uplands, and lowlands), (iii) the percentage of the10 main lithological complexes aggregated from the Geological Map of Italy of Compagnoni et al. (1976-1983), (iv) the percentage of the eight classes of soil thickness and of the 11 classes of soil types derived from the Soil Map of Italy of Mancini (1966), (v) 18 variables describing meteorological and climate conditions obtained through ordinary kriging of the long term annual values of about 1000 reference meteorological stations (L'Abate and Costantini 2004, http://abp.entecra.it/soilmaps/ita/pedoclima30.html), and (vi) one variable for the presence or absence of historical landslide events in the neighbouring municipalities. The presence (or absence) of one or more of the landslides listed in the AVI catalogue (Guzzetti et al. 1994; Guzzetti and Tonelli 2004) in each of the 6159 municipalities selected for the Tier 2 analysis was adopted as the dependent, classification variable for the multivariate modelling. For the purpose, the landslide information in the historical catalogue was split into two sets: (i) a training set covering the 41-year period 1950-1990 was used to construct (train) a multivariate classification model (7704 landslide events in 2608 municipalities), and (ii) a validation set covering the 11-year period 1991-2001 was used to validate (evaluate) the model prediction skills (10750 landslide events in 2801 municipalities).

Methodology

Landslide susceptibility in Italy was determined applying linear discriminant analysis, a consolidated multivariate technique introduced by Fisher (1936) to classify samples into alternative groups on the basis of a set of measurements (Michie et al. 1994; Brown 1998), and commonly adopted by geomorphologists to determine landslide susceptibility at different spatial scales (e.g., Guzzetti et al. 1999). For landslide susceptibility assessment, the two groups (G) commonly established, are: (i) mapping units free of landslides (G_0, municipalities without landslide events), and (ii) mapping units having landslides (G_1, municipalities with landslide events).

The scope of discriminant analysis is to determine the group membership of a mapping unit by finding a linear combination of the geo-environmental variables which maximizes the differences between the populations of stable and unstable mapping units, with minimal error. To obtain this, consider a set of m environmental variables $v_1, v_2, \ldots, v_m$ for each mapping unit, r, by means of which it is desired to discriminate the region between the groups of stable (G_0) and unstable (G_1) units, and let Z be the linear combination of the input variables, such as

$$Z = \beta_1 v_1(r) + \beta_2 v_2(r) + \ldots + \beta_m v_m(r) \qquad (2)$$

For discriminant analysis, the task is to determine the coefficients β_i enabling Z to serve as an index for differentiating between members of the two groups. The relative contribution of each independent geo-environmental variable to the discriminating function can be evaluated by the standardized discriminant function coefficients (SDFC). The SDFC show the relative importance (i.e. the "weight") of each variable as a predictor of slope instability. Variables with large coefficients (in absolute value) are more strongly associated with the presence or the absence of landslides, with positive and negative coefficients indicating respectively positive and negative correlation with instability within a mapping unit. It should be noted that this model is highly similar to SMCE. However, the important difference is that the coefficients in Eq. 2 are obtained through a quantitative statistical analysis.

Through a step-wise procedure, the linear discriminant function selected 18 variables out of the 61 variables described above as the best predictors of the presence (or absence) of historical landslides in the 6159 Italian municipalities, in the training period 1950-1990. The selected geo-environmental variables indicated in Table 5 include seven morphological, three lithological, one soil type, six climate-related, and one variable describing the presence/absence of historical landslides in the neighbouring municipalities.

Landslide susceptibility map

Fig. 9A portrays the landslide susceptibility map obtained for the Italian territory that has been identified as susceptible to landslides by the continental-level Tier 1 evaluation. In the map, the individual municipalities are classified based on their probability of pertaining to the group of municipalities that have experienced (or have not experienced) one or more historical landslides listed in the AVI catalogue in the training period 1950-1990. To decide the levels of landslide susceptibility, the inference was made that if a municipality was predicted to have a high or very high probability of containing a historical landslide, the same municipality is expected to have a high (orange) or very high (red) susceptibility, i.e. a high or very high propensity to generate future landslides. Similarly, if a municipality has a low or very low probability of containing a known historical landslide, the same municipality was attributed a low (light green) or very low (green) susceptibility, i.e. a low or very low propensity to generate future landslides. Areas attributed moderate susceptibility in the map (Fig. 9A) represent a special case. These are municipalities for which the linear discriminant model was unable to decide convincingly (i.e. with a probability $P > |0.55|$) if the municipality pertains to the unstable (having historical landslides) or the stable (not having historical landslides) groups. These municipalities are of uncertain attribution and further information is necessary to decide their level of landslide susceptibility.

Overall, the linear discriminant model has classified correctly 3999 (64.9%) of the 6159 Italian municipalities evaluated in the Tier 2 analysis. This is a quantitative measure of the degree of fit of the susceptibility model, i.e. of the ability of the statistical classification procedure to match the geographical distribution of the known historical landslides. Of the correctly classified municipalities, 2272 (64.0%) were classified as unstable (i.e., prone to landsliding) and 1727 (66%) were classified as stable (i.e., not prone to landslides) by the model. With the information above, a contingency table was created that illustrates the significance of the model (Fig. 9B).

Inspection of Fig. 9A reveals the geographical distribution of the predicted landslide susceptibility. The Tier 2 model predicts susceptibility to be high to very high in 2369 municipalities (29,3% of the total number of analyzed muncipalities. In particular, susceptibility is predicted to be very high in the Alps, the Apennines, and in parts of Sicily. Fig. 9A further shows local problems with the national assessment. As an example, the Calabria region, southern Italy, is attributed susceptibility levels lower than expected. This is a consequence of the incompleteness of the historical landslide information in the AVI catalogue in this region.

Availability of an independent landslide validation set covering the period 1991-2001 allowed evaluating the prediction skill of the susceptibility model. By substituting the model training (1950-1990) dataset with the model validation (1991-2001) dataset, the linear discriminant model classified correctly 3800 (61.7%) of the 6159 municipalities. This is a quantitative measure of the prediction skill of the national-scale susceptibility assessment (e.g., Chung and Fabbri 2003; Guzzetti et al. 2006). Of the 3800 municipalities that were correctly predicted by the model, 1724 were predicted unstable (i.e. landslide prone), and 2076 were predicted stable by the model.

As a further quantitative test of the model fitting performance and prediction skills, we prepared ROC curves both for the training set (continuous line in Fig. 9C) and for the validation set (dashed line in Fig. 9C). The resulting quality metric are AUC = 0.70 for the training set and AUC = 0.66 for the validation set. We consider these values satisfactory with respect to the quality and resolution of the available geo-environmental and landslide information, and the difficulty of the prediction, limited to a 11-year period 1991-2001.

Discussion

The continental-level Tier 1 assessment presented in this work shows that both thematic information and methods are available to produce a harmonised, small-scale susceptibility map over Europe that allows for the identification of priority areas when evaluated with exemplary national-level landslide inventory data. According to the draft of the European Soil Framework Directive, those priority areas represent terrains that should be subjected to detailed spatial evaluations of soil threats, i.e. landslide susceptibility (EC 2006b). A comparison with already available global and continental landslide susceptibility and hazard zonations alternatively considered for Tier 1 analyses further indicates the advanced validity of the proposed map. However, other European-level landslide susceptibility, hazard and risk zonations as prepared in the framework of the EU-FP7 SafeLand project (Jaedicke et al. 2011; Van Den Eeckhaut et al. 2011) could provide alternatives to the continental-level assessment presented here, if evaluated better. In any case, generalized landslide susceptibility modelling over highly complex areas like Europe generally proves difficult, also when considering the diversity of landslide phenomena. This is also true for the pan-European susceptibility map presented here, as evidenced by the ROC analyses illustrating predictive capabilities that should be improved. A solution may consist in preparing different susceptibility zonations for different climatic and physiographical regions, adopting specific sets of weights decided on regional climato-physiographical conditions.

The main reason for selecting an expert-based approach – as opposed to e.g., a statistically based approach – for Tier 1 analyses was the lack of sufficient landslide information. For Europe, a complete coverage of landslide information is not available, and will not be available in the near future. However, information on landslides exists for many countries or regions in Europe (Van Den Eeckhaut and Hervás 2012). Since landslide information is the major prerequisite for all kinds of susceptibility assessments (e.g., van Westen et al. 2009), availability of extended data over Europe will allow determining new and improved weights for the susceptibility criteria considered, especially when a climato-physiographic terrain zoning is introduced. However, it can be suspected that even if more landslide information is collected and harmonised, it will still remain incomplete and inaccurate in many areas. This is illustrated by the Tier 1 application over

France, where many highly landslide prone areas lack distributed landslide data and straightforward, inventory-based statistical assessments are hampered even though a harmonised national-level inventory is available. It can be suspected that both the lack and spatial heterogeneity of landslide information will require expert knowledge in many European regions even in the near future. In turn, more detailed information in areas representative for specific climato-physiographic settings over Europe could allow for calibration of statistical landslide susceptibility models through careful selection of landslide- and landslide-free terrain elements, as recently demonstrated by Van Den Eeckhaut et al. (2011). We suppose that such computations will provide a clue for cross-validation of heuristic assessments through data-driven techniques and will enhance the robustness of the models in the future.

The continental-level Tier 1 landslide susceptibility zonation prepared in this work considers all types of landslides. However, the national Tier 1 modelling of landslide susceptibility in France has shown unambiguously that the susceptibility to different major landslide types (i.e., slides, flows, falls/topples) varies geographically. Also future continent-wide Tier 1 landslide susceptibility assessments should be prepared accordingly. However, this will require a typologically separated landslide inventory for model calibration and evaluation.

Where multiple susceptibility assessments are available for different landslide types and climato-physiographic regions, the problem consists in combining the individual assessments into a single (comprehensive) Tier 1 landslide susceptibility assessment. The experiment conducted in France adopting a conservative combination through the assignment of the highest susceptibility pixel value obtained for one of the three landslide types, based on the precautionary principle underpinning the French legislation on natural hazards, resulted in a significantly large portion of the territory classified as susceptible to landslides (75% of the area classified as “high” and “moderate”, Fig. 6). Even though this result may be considered unrealistic in places, combinations of individual landslide susceptibility evaluations will most probably always be more pessimistic than generalized assessments which in most cases underestimate the propensity of non-mountainous terrains to generate landslides. We therefore conclude that spatially combined, climato-physiographically and typologically specific susceptibility assessments will offer a better insight in the spatial distribution of the landslide problem over Europe at the synoptic scale and hence enable a better delineation of priority areas through Tier 1 assessments. However, this requires appropriate spatial association and classification schemes for the combination of specific susceptibility estimates such as e.g. summation or reclassification of typology-specific susceptibility estimates.

For the delineation of priority areas subjected to quantitative Tier 2 analyses against areas where no further action has to be taken, appropriate threshold levels have to be defined for any Tier 1 analysis. Our Tier 1 assessments show that the definition of such thresholds may be determined by the kind of Tier 1 analysis, e.g. whether a differentiated or undifferentiated analysis in terms of landslide typology is conducted. In the synoptic continental-level evaluation presented here (Fig. 4), it seems appropriate to use the three highest susceptibility levels (i.e., very high, high, moderate) as a threshold for areas in which Tier 2 analyses should be performed. The application of this threshold assigns 36% of the analysed area as to be subjected to Tier 2. In contrast, the differentiated Tier 1 analysis over France (Fig. 6) calls for a rather different susceptibility threshold due to the conservative association method applied to produce the compound susceptibility map. We recommend to exclusively use the highest susceptibility class here (resulting in 44% of the area subjected to Tier 2) since this is suggested to provide a reliable overview of the main areas known to be prone to landslides. For comparison, the synoptic continental-level Tier 1 assessment with the threshold specified above delineates 33% of the French continental territory as subjected to Tier 2. Albeit the priority areas defined by both assessments show a good first-order correlation (compare Fig. 4 and 6), this discrepancy is mainly due to the rather different Tier 1 evaluations (e.g., synoptic vs. differentiated) conducted at continental and national levels.

Following the general specifications for the assessment of soil threats, Tier 2 analyses should allow to decide on appropriate programmes of measures to evaluate and combat soil threats as proposed in the draft of the Soil Framework Directive (EC 2006b), but should not be considered alternative to Tier 1 in terms of delineation of priority areas (Eckelmann et al. 2006; Hervás et al. 2007). Additionally, a Tier 2 analysis should provide quantitative measures on the spatial distribution of landslide susceptibility, and can incorporate data that is not yet available. We have presented a quantitative, statistical landslide susceptibility analysis for priority areas in Italy, based on distributed and multitemporal landslide information allowing for establishment and validation of the inventory-based assessment through a multivariate classification technique. The evaluation is based on an administrative mapping unit (municipality), having the advantage of allowing for a direct association between the landslide susceptibility information and societal and (agro)economical data, including population census data. These associations must be considered essential for the effective evaluation of any soil threat at small spatial scales, and therefore we argue that the kind of mapping unit is, together with the application of quantitative evaluation techniques based on distributed landslide information, considered the major specification for Tier 2 analyses. Our Tier 2-compatible analysis over susceptible terrains in Italy therefore demonstrates that such evaluations can be conducted even at small spatial scales if the required geo-environmental and landslide information is available together with a mapping unit of a suitable size.

The exemplary Tier 2 analysis presented employs an administrative mapping unit that does not reflect the geo-environmental conditions controlling the geographical and temporal occurrence of landslides in an area. For this reason, further geomorphographic subdivision based on the specific (local) geo-environmental settings would be required.. Alternatively, the establishment of appropriate geographical management units for the general assessment of soil threats (including landslides) in the context of Tier 2 evaluations may be enforced within the further development of the Soil Thematic Strategy. In any case, application of Tier 2 should not be conducted using terrain units larger than municipalities.

The example for a synoptic Tier 2 evaluation presented here does not account for a differentiation according to landslide typology. However, for future development of the Tier 2 approach, it seems very important to claim for typologically-specific landslide susceptibility evaluations. Since a Tier 2 assessment also calls for additional spatial data to assess landslide susceptibility, the *common criteria* for Tier 2 should be reconsidered in such that the most important geo-environmental factors governing the susceptibility to at least a basic typological landslide differentiation according to slides, falls and flows should be identified and specified, apart from the requirement of distributed landslide inventories in areas subjected to Tier 2. It should also be noted that a further testing on the compatibility between Tier 1 and Tier 2 at small spatial scales should be conducted for a geomorphological unit (e.g., Alpine chain) rather than on national levels. However, since the required data (distributed landslide information and an appropriate mapping unit) was exclusively available for Italy in this study, this could not be achieved here.

Based on the examples shown in this paper, Tier-based assessments may not be considered as strictly scale-dependent. In fact, both Tier 1 and Tier 2 compatible assessments can be conducted at several spatial scales as determined by the scale of the input data and the scale/size of the mapping unit of reference. This is demonstrated by the different Tier 1 evaluations presented in this work where the continental-level evaluation uses a 1 km x 1 km grid cell as a mapping unit, whereas the national-level evaluation for France utilizes a 50 m x 50 m grid cell. Both evaluations aim to delineate priority areas and do not necessarily require landslide information to be carried out. In contrast, any Tier 2 evaluation should be based on distributed landslide information and should allow for the decision on measures/implementation plans to mitigate landslides. In this context, it depends on data availability and purpose for the user to perform any of the two Tier evaluations.

Conclusions

After having presented and discussed examples for small-scale landslide susceptibility analyses at continental and national levels, we conclude our contribution specifying the major requirements for future developments of the Tier-based landslide zoning approaches in the context of the European Union's Soil Thematic Strategy.

A Tier 1 landslide susceptibility analysis is aimed at the identification of priority areas (Eckelmann et al. 2006). It should be based on a reduced set of *common criteria* considering three geo-environmental factors (terrain gradient, lithology, and land cover) and evaluated/validated with representative landslide information (Hervás et al. 2007). Based on a synoptic analysis at the continental level and a differentiated evaluation at the national level for France considering major landslide types and physiographic regions, we conclude that landslide susceptibility can be successfully evaluated for the delineation of priority areas with the reduced environmental information. However, any synoptic analysis at the continental level can be supposed to give a biased overview on landslide susceptibility since not considering specific landslide types or climato-physiographic settings. At present, we continue gathering locational and typological information on landslide events in Europe at national and regional levels (Van Den Eeckhaut and Hervás 2012) and elaborating a climato-physiographic terrain delineation allowing for specification of model regions throughout Europe. This will allow for a differentiated Tier 1 modelling approach at the continental level. First preliminary results are promising and indicate that a more advanced continental scale susceptibility evaluation suitable for better delineation of priority areas can be elaborated in the future (Günther et al. in press).

In the context of a Tier 2 landslide susceptibility evaluation to be conducted in priority areas identified by Tier 1, our Tier 2 attempt for Italy shows that quantitative, statistical landslide susceptibility evaluations can be conducted even at small spatial scales, provided that enhanced geo-environmental data on landslide controlling factors, together with (most importantly) distributed and harmonised landslide data is available. Considering the latter, we conclude that Tier 2 areas as identified by Tier 1 should delineate regions where distributed, multi-temporal landslide inventory data with typological information should be gathered as required for inventory-based, statistical Tier 2 evaluations. For the exemplary Tier 2 evaluation presented here, we recommend a small administrative mapping unit (municipality) for spatial evaluation since the decision on measures/implementation plans based on Tier 2 analysis to assess the landslide threat requires an association of landslide susceptibility with (agro) economic or population-related census data. However, since geo-environmental conditions are in most cases not associated with administrative units, we conclude that the definition of suitable Tier 2 mapping units should be enforced within the further development of the Soil Thematic Strategy for general Tier 2-based assessments of soil threats. Furthermore, we conclude that Tier 2 evaluations in terms of landslides should be conducted individually for at least three major types of landslides (e.g., slides, flows and falls).

Finally, it is important to mention that the spatial assessment of rather localized soil threats like landslides cannot be sufficiently addressed through small-scale evaluations as the Tier-based concept proposed in the framework of the Soil Thematic Strategy. Therefore, it does not substitute landslide-specific statistical or physically-based susceptibility modelling in local, highly landslide affected areas as indicated by Tier 2 (i.e., “Tier 3”, Hervás et al. 2007) necessary for local landslide mitigation plans.

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Figure Captions

Fig. 1 Location and extent of study areas

Fig. 2 Spatial data used for the synoptic-scale analysis of landslide susceptibility in Europe grouped into five classes. (A) Terrain slope, obtained from the global GTOPO 30 terrain elevation dataset. (B) Lithological complexes in Europe, obtained from the “dominant soil parent material” information of the Soil Geographical Database of Eurasia. (C) Land cover information in five classes, obtained from the PELCOM dataset

Fig. 3 Landslide inventory maps for three European countries. (A) National landslide database for France (BDMvT) showing 17,598 landslides (June 2010). (B) National Landslide Database for Great Britain, showing 15,897 landslides (October 2011). (C) National archive of historical landslides in Italy, compiled by the AVI project, showing 15,503 landslides for the period 1950 - 2001

Fig. 4 Basic Tier 1 landslide susceptibility assessment for Europe. (A) Synoptic-scale landslide susceptibility map. (B) Histogram showing the frequency distribution of the computed values of the normalized landslide susceptibility index S in Europe and pie charts reflecting total area and landslide frequencies of the five susceptibility levels. (C) Receiver Operating Characteristics (ROC) curves of susceptibility estimates and slope raster for three countries with landslide information and for the whole analysed area using the combined inventory information

Fig. 5 Continental scale and global scale landslide susceptibility assessments. (A) ESPON landslide hazard zonation of Schmidt-Thomé (2006). (B) Portion of Europe of the global landslide susceptibility map of Hong et al. (2007). (C) Portion of Europe of Global landslide "hotspot" map of Nadim et al. (2006), without the four lowest susceptibility classes. (D) ROC plots comparing the performance of the different susceptibility zonations against the distribution of landslides in France (Figure 3A), Great Britain (Figure 3B), and Italy (Figure 3C)

Fig. 6 Differentiated Tier 1 landslide susceptibility assessment for France. (A-C) Individual landslide susceptibility maps for slides, flows, and falls. (D) Compound landslide susceptibility map. (E): Association method employed to produce the compound susceptibility map from the typology-specific maps

Fig. 7 Distribution of susceptibility classes of the compound Tier 1 landslide susceptibility map for France. (A) Relative proportions of plain and mountain areas in the different susceptibility classes. (B) Areal percentages of susceptibility levels in plain and mountain areas. Coastal areas were not analysed here due to their small spatial extent (0.15% of study area)

Fig. 8 Evaluation of the differentiated Tier 1 susceptibility assessment in France: (A) Compound landslide susceptibility map classified in susceptible and non susceptible areas. (B) Representation of municipalities (red dots) affected by at least one landslide event

Fig. 9 Tier 2 landslide susceptibility assessment for Italy. (A) Map showing municipalities classified by the multivariate statistical analysis (colour coded: municipalities identified as priority areas by the continental-level evaluation in Fig. 4; gray : municipalities outside the priority areas). (B) Confusion matrix showing municipalities with/without landslide events against the prediction from the statistical model. (C) Analysis of the prediction skill of the landslide susceptibility model. The continuous ROC curve shows the model fitting performance (AUC = 0.70); the dashed line shows the prediction-rate curve (AUC = 0.66) obtained considering the number of events of the landslide validation set

Author reply letter
Manuscript LASL-461, Version 2
“Tier-based approaches for landslide susceptibility assessment in Europe”
A. Günther et al.

Dear Editor,

Thank you very much for the re-evaluation of our manuscript. We highly appreciate the comments and have revised the manuscript accordingly, together with additional checking of typos and language. We hope that this improved version can be accepted.

Sincerely Yours,

Andreas Günther (on behalf of all authors)

Reply to comments

“Page 2 (abstract), line 15. "a historical ..." (not "an historical")

Corrected.

“ibid, line 16. doubled commas”

Corrected.

“Page 23, line 7 and page 24, line 2. First time you right "6159 Italian municipalities?? second time "6160 Italian municipalities?? What No is correct?”.

It is 6159 municipalities, we have corrected that throughout.

“Page 23, line 9 (+ Table 5). One soil type. Is it correct that only one siol type is included? Are other types of soils indifferent for landsliding? And what about soil thickness? May be I'm wrong, but in Table 4 this parameter is indicated”

In Table 4, the spatial criteria used for the Tier 2 analysis are indicated, from which 61 variables for the statistical modelling were derived. They are outlined on page 21. In Table 5 and the paragraph at page 23 are listed only those variables that have been selected by the stepwise procedure. We have made this clearer now in the “Data” and “Methodology” sections describing the Tier 2 model on page 20 – 23.

In a stepwise discriminant function analysis, a model of discrimination is built step-by-step. Specifically, at each step variables are reviewed and evaluated to determine which one will contribute most to the discrimination between groups. The Wilks' Lambda is the statistical procedure that we have selected in SPSS to add or remove variables from the analysis.

Table 1 Landslide susceptibility criteria used for the synoptic-scale landslide susceptibility model and associated terrain zonation for Europe. The number of classes corresponds to expert-based susceptibility reclassification of the thematic variables

Factor	*Source*	*Scale*	*Resolution*	*Classes*
Slope angle	GTOPO30	1:1M	1 × 1 km	5
Lithology	European Soil Database	1:1M	vector map	5
Land cover	PELCOM	1:1M	1 × 1 km	5

Table 2 Weights attributed to the landslide susceptibility criteria used for the assessment of landslide susceptibility in Europe through an Analytic Hierarchy Process (AHP) technique

Factor	*Factor weight*	*Class*	*Class weight*
Slope angle	0.64	< 1°	0.07
		1 ≤ 2°	0.13
		2 ≤ 5°	0.20
		5 ≤ 15°	0.27
		> 15°	0.33
Lithology	0.26	Organic/detrital	0.07
		(Glacio)fluvial/sandy/loamy	0.13
		Volcanic/crystalline	0.20
		Schists/alluvium/colluvium	0.27
		Clayey/flyschoid/calcareous	0.33
Land cover	0.10	Urban/wetlands	0.07
		Arable/shrubs	0.13
		Crops/barren	0.20
		Coniferous/mixed forests	0.27
		Grassland/deciduous forests	0.33

Table 3 Spatial criteria used for the national-scale Tier 1 landslide susceptibility model for France. The number of classes is the result of a reclassification of the original thematic variables

Factor	*Source*	*Scale*	*Resolution*	*Classes*
Slope	IGN DEM (BD-Alti®)	1:100,000	50 × 50 m	13
Soil parent material	BRGM Geological Map, 6th ed.	1:1 M	vector map	24
Land cover	Corine Land Cover	1:100,000	50 × 50 m	10

Table 4 Spatial criteria used for the Tier 2 landslide susceptibility model in priority areas of Italy. The number of classes is the result of a reclassification of the original thematic variables

Factor	*Source*	*Scale*	*Resolution*	*Classes*
Elevation	SRTM		90 × 90 m	n.a.
Slope	SRTM		90 × 90 m	n.a.
Lithology	Compagnoni et al. (eds) (1976-1983)	1:1M	vector map	10
Soil thickness	Mancini (ed) (1966)	1:1M	vector map	8
Soil type	Mancini (ed) (1966)	1:1M	vector map	11
Mean cumulated annual rainfall	L'Abate and Costantini (2004)			9
Mean annual temperature	L'Abate and Costantini (2004)			9
Landslide in the neighboring municipalities	AVI catalogue			2

Table 5 List of the 18 variables entered in the Tier 2 discriminant model of landslide susceptibility in Italy. Positive coefficients are correlated to the presence of landslides. Negative coefficients are correlated to the absence of landslides

Factor	*Variable description*	*SDFC*
Morphology	Municipality mean elevation	-.443
	Standard deviation of municipality elevation	-.724
	Municipality minimum slope angle	-.206
	Municipality mean slope angle	.243
	Standard deviation of municipality slope angle	-.647
	Municipality slope range	1,070
	Municipality elevation range	1,125
Lithology	Continental deposits	-.252
	Sandstone	.132
	Limestone	-.261
Soil Type	Brown soils	.140
Climate	Mean annual temperature (range 9.5-12.0)	.123
	Mean annual temperature (range 12.0-13.5)	.270
	Mean annual temperature (range 13.5-15.0)	.260
	Mean annual temperature (range 17.7-20.0)	-093
	Annual rainfall (range 698-809)	-.133
	Annual rainfall (range 973-1213)	-.116
Neighboring	Historical landslide event in the neighbor municipality	.190

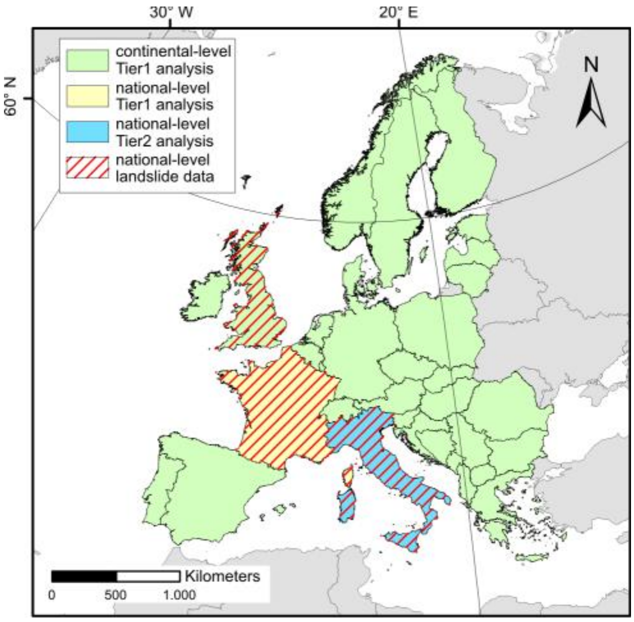

30° W
20° E
60° N
continental-level Tier1 analysis
national-level Tier1 analysis
national-level Tier2 analysis
national-level landslide data
N
Kilometers
0
500
1.000

Figure 1

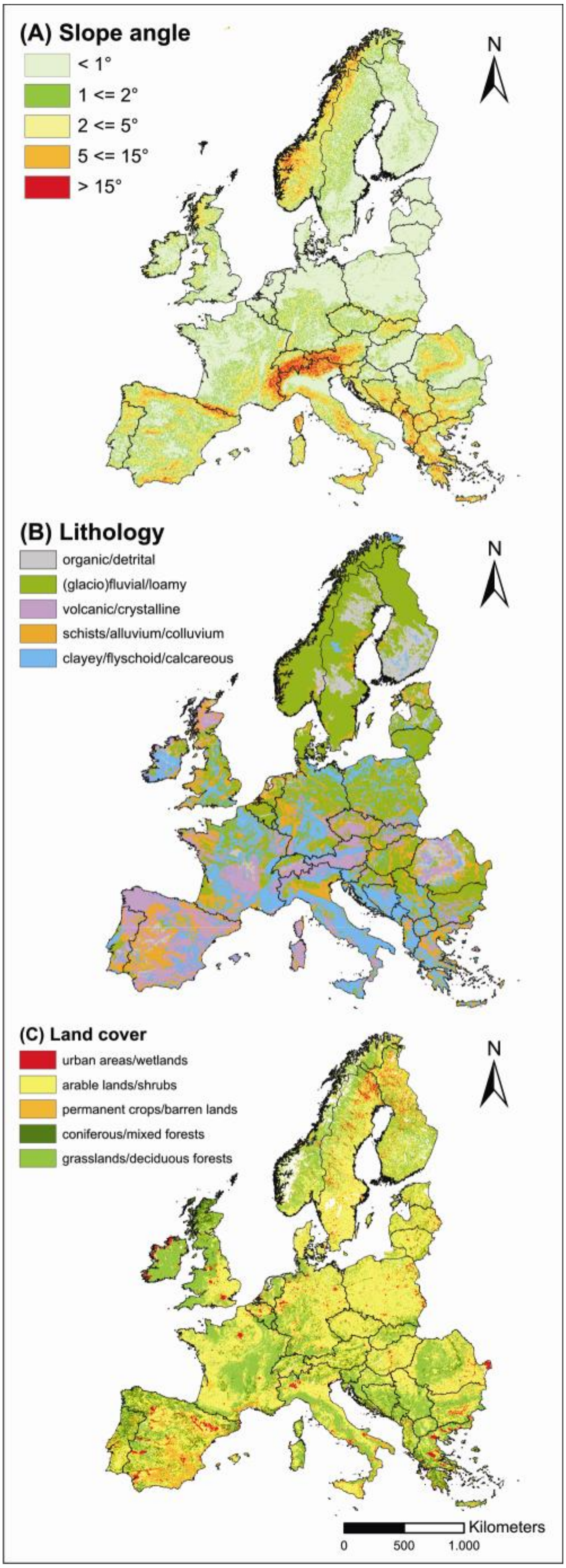

(A) Slope angle
< 1°
1 <= 2°
2 <= 5°
5 <= 15°
> 15°
N
(B) Lithology
organic/detrital
(glacio)fluvial/loamy
volcanic/crystalline
schists/alluvium/colluvium
clayey/flyschoid/calcareous
N
(C) Land cover
urban areas/wetlands
arable lands/shrubs
permanent crops/barren lands
coniferous/mixed forests
grasslands/deciduous forests
N
Kilometers
0
500
1.000

Figure 2

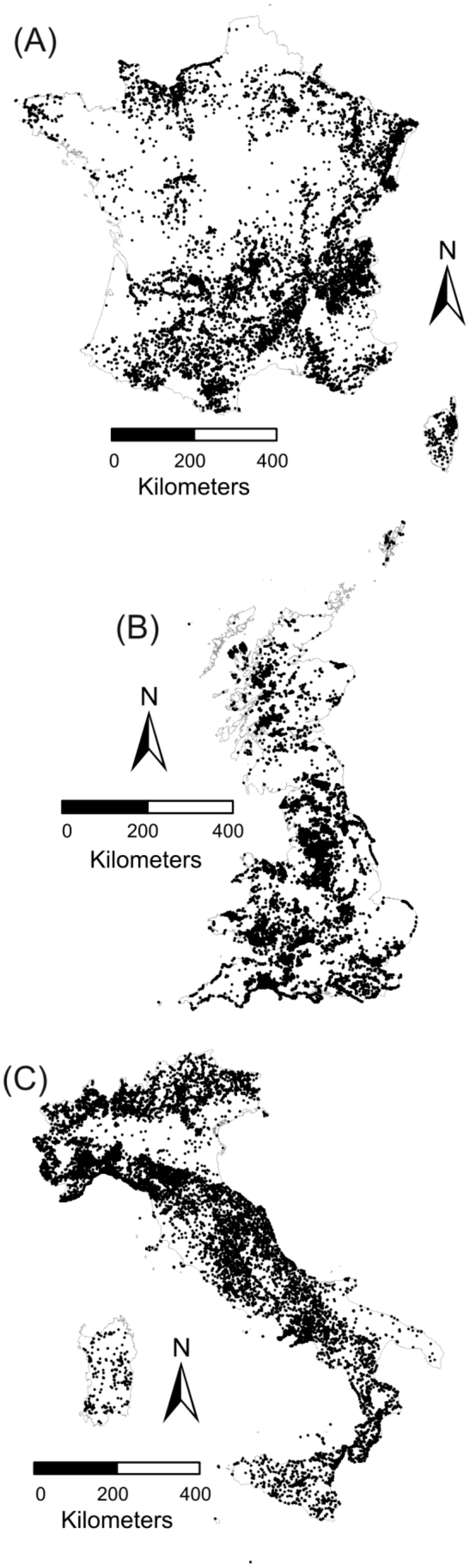

(A)
N
0
200
400
Kilometers
(B)
N
0
200
400
Kilometers
(C)
N
0
200
400
Kilometers

Figure 3

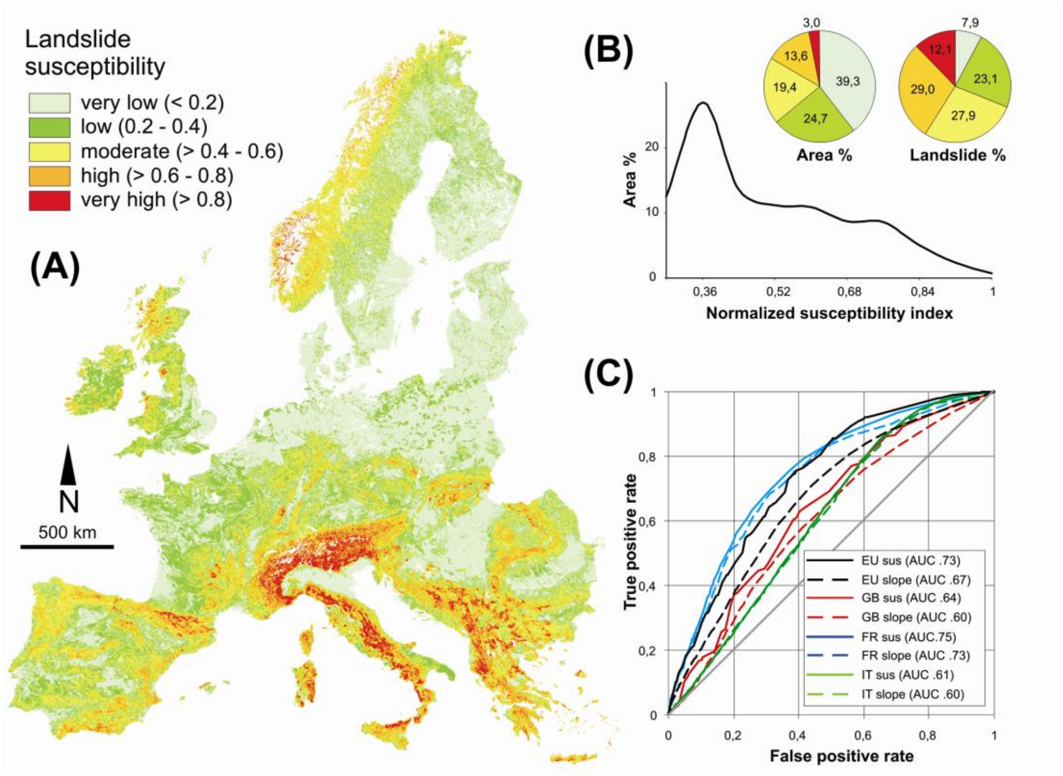

Landslide susceptibility
very low (< 0.2)
low (0.2 - 0.4)
moderate (> 0.4 - 0.6)
high (> 0.6 - 0.8)
very high (> 0.8)
(A)
N
500 km
(B)
3,0
13,6
19,4
24,7
39,3
Area %
7,9
12,1
29,0
27,9
23,1
Landslide %
Area %
0
10
20
0,36
0,52
0,68
0,84
1
Normalized susceptibility index
(C)
True positive rate
False positive rate
0
0,2
0,4
0,6
0,8
1
EU sus (AUC .73)
EU slope (AUC .67)
GB sus (AUC .64)
GB slope (AUC .60)
FR sus (AUC.75)
FR slope (AUC .73)
IT sus (AUC .61)
IT slope (AUC .60)

Figure 4

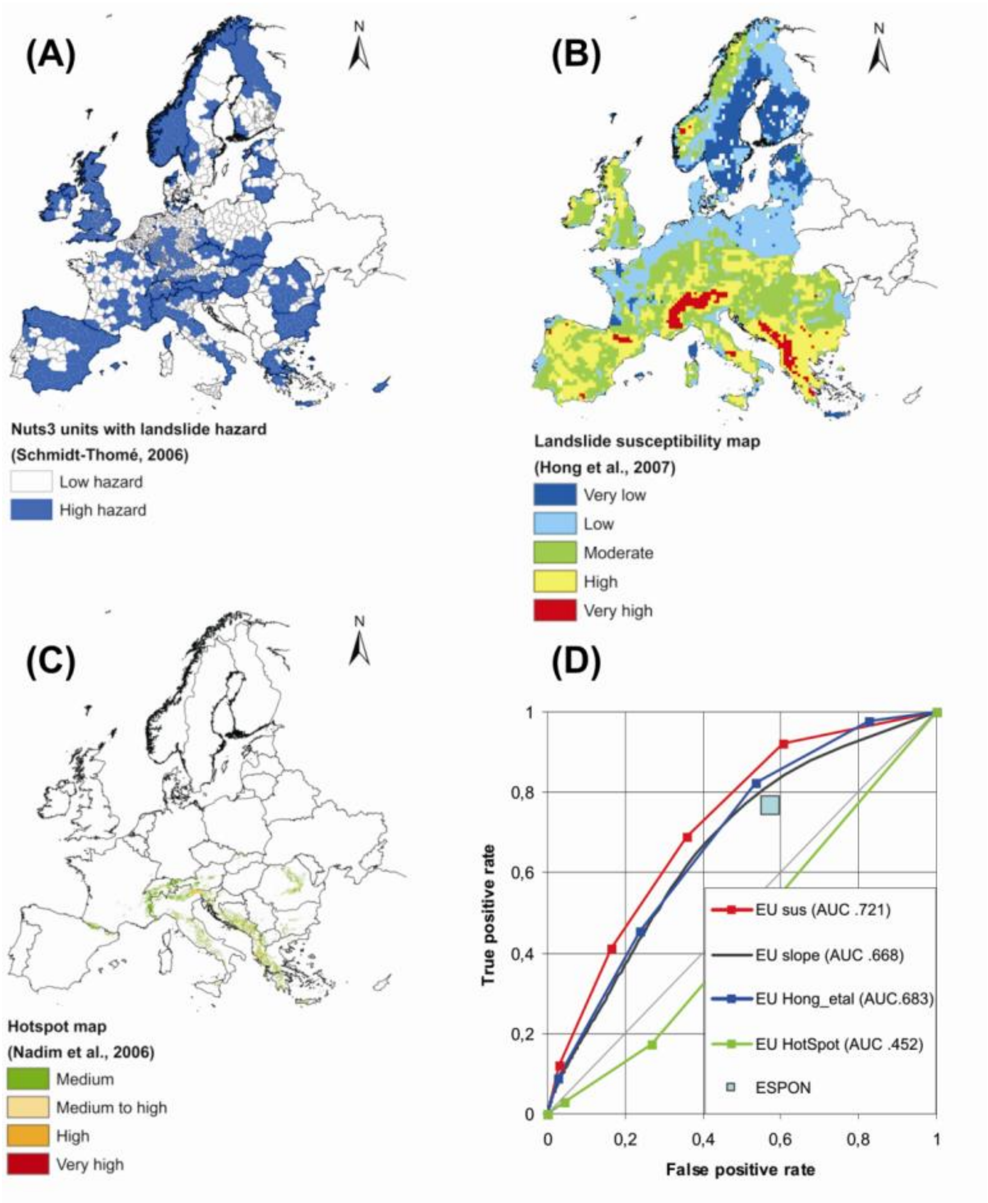

(A)
N
Nuts3 units with landslide hazard
(Schmidt-Thomé, 2006)
Low hazard
High hazard
(B)
N
Landslide susceptibility map
(Hong et al., 2007)
Very low
Low
Moderate
High
Very high
(C)
N
Hotspot map
(Nadim et al., 2006)
Medium
Medium to high
High
Very high
(D)
True positive rate
False positive rate
0
0,2
0,4
0,6
0,8
1
EU sus (AUC .721)
EU slope (AUC .668)
EU Hong_etal (AUC.683)
EU HotSpot (AUC .452)
ESPON

Figure 5

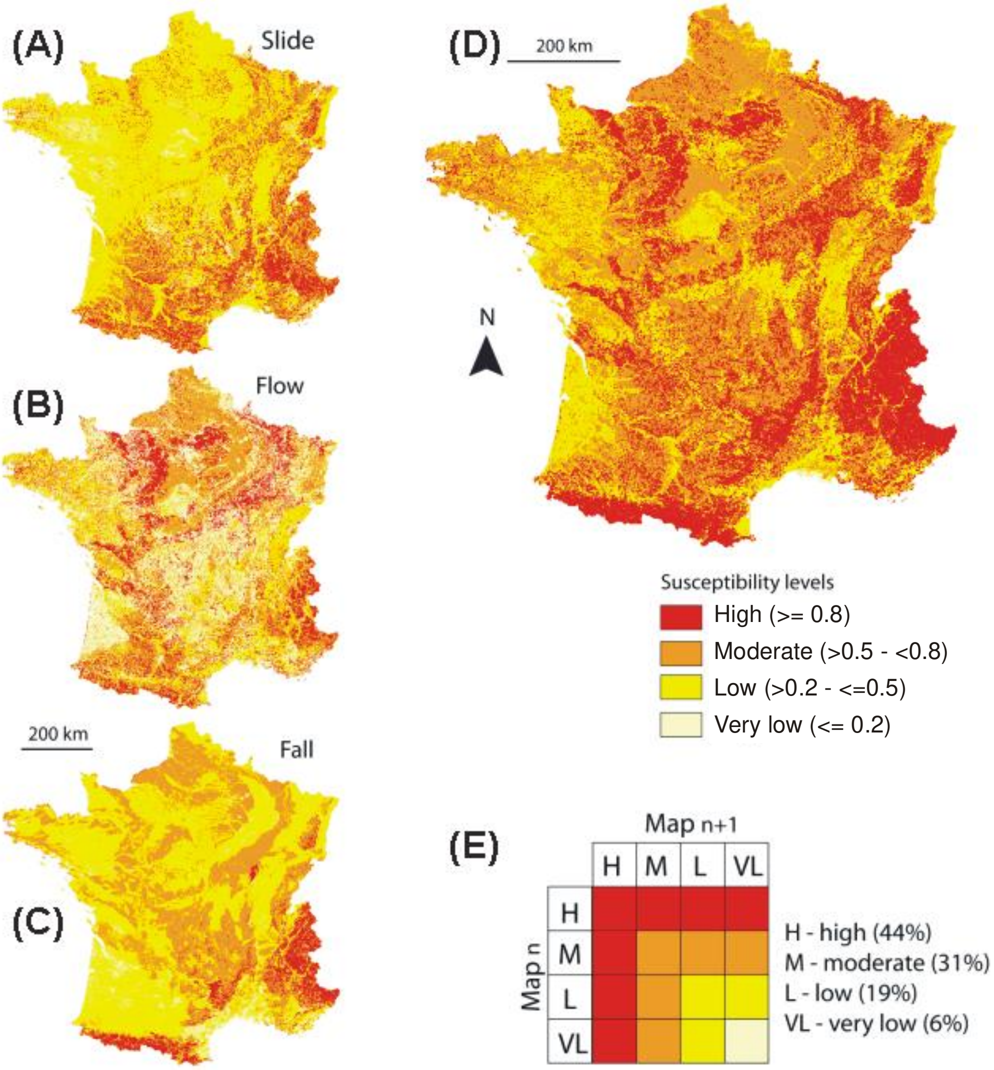

(A)
Slide
(B)
Flow
200 km
Fall
(C)
(D)
200 km
N
Susceptibility levels
🟥 High (>= 0.8)
🟧 Moderate (>0.5 - <0.8)
🟨 Low (>0.2 - <=0.5)
⬜ Very low (<= 0.2)
(E)
Map n+1
H
M
L
VL
Map n
H
M
L
VL
H - high (44%)
M - moderate (31%)
L - low (19%)
VL - very low (6%)

Figure 6

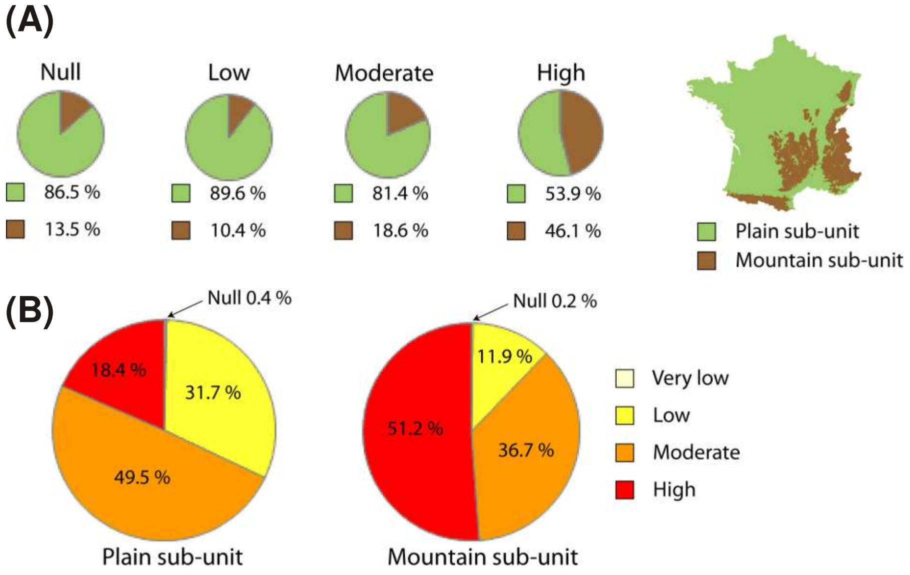

(A)
Null
Low
Moderate
High
🟩 86.5 %
🟫 13.5 %
🟩 89.6 %
🟫 10.4 %
🟩 81.4 %
🟫 18.6 %
🟩 53.9 %
🟫 46.1 %
🟩 Plain sub-unit
🟫 Mountain sub-unit
(B)
Null 0.4 %
18.4 %
31.7 %
49.5 %
Plain sub-unit
Null 0.2 %
11.9 %
51.2 %
36.7 %
Mountain sub-unit
☐ Very low
🟨 Low
🟧 Moderate
🟥 High

Figure 7

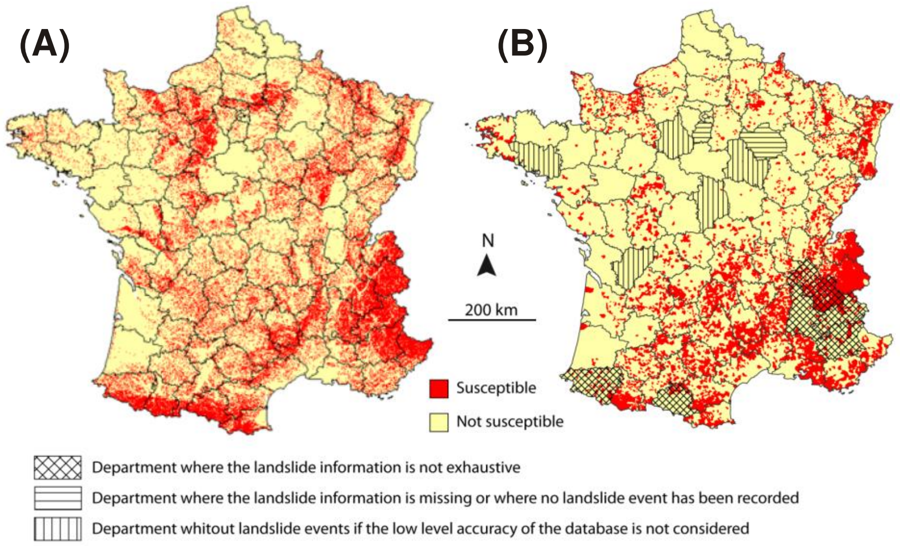
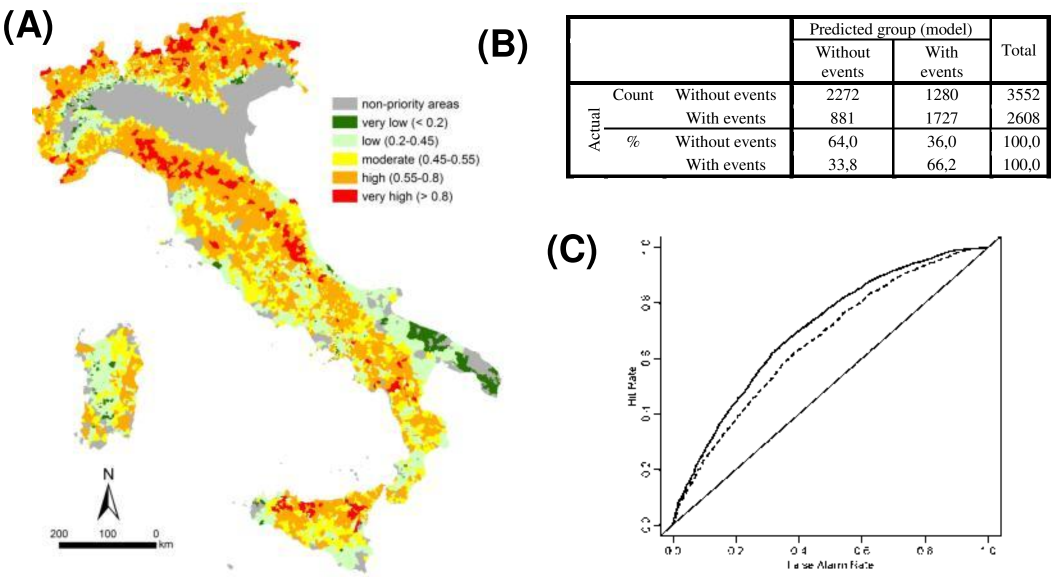

(A)
(B)
N
200 km
Susceptible
Not susceptible
Department where the landslide information is not exhaustive
Department where the landslide information is missing or where no landslide event has been recorded
Department whitout landslide events if the low level accuracy of the database is not considered

Figure 8



			Predicted group (model)		Total
			Without events	With events	
Actual	Count	Without events	2272	1280	3552
		With events	881	1727	2608
	%	Without events	64,0	36,0	100,0
		With events	33,8	66,2	100,0

Figure 9