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Shallow landslides susceptibility assessment by means of remotely sensed data and field survey: multi-scale analysis/monitoring of predisposing factors in a climate change context

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To my family and to my soulmate Luca

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ABSTRACT

Rainfall-induced shallow landslides are common phenomena all over the world. These phenomena affect soil of small thickness (generally less than 2.0 m) and they are usually characterized by a triggering stage and by a subsequent runout. Despite the small soil volume involved, the shallow landslides can be densely distributed across territories, resulting particularly destructive when the sliding soil portion flows like a fluid down the slope surface, reaching very high velocity of propagation. Moreover, the absence of incipient movement evidence makes very difficult the monitoring of these instability processes.

In addition, the shallow landslides occurrence are strongly influenced by many predisposing factors that differ according to the different climatic conditions, geology, geomorphology, land use characteristics, soil properties and depth, subsurface hydrology and local relief.

In the last few years, of particular interest was the role of human activity on the shallow landslides distribution. Large areas, in fact, can be changed in a short time because of anthropogenic processes, influencing the environmental factors that control landscape stability.

Moreover, the anthropogenic modifications of the landscape have not only effects on the occurrence and spatial distribution of shallow landslides but they can have important consequence also on the propagation mechanism of the sediment mobilized by the instability phenomena.

Therefore, the large numbers of variables to consider, makes difficult the application of a unique monitoring technique able to correctly assess the landslides susceptibility in different environmental contexts. In fact, different approaches were developed and different predisposing factors, in relation to the scale of analysis and the characteristics of the study area, were taken into account to analyze their influence on slope instability. This led to constantly updating and improvement of risk management strategies.

Within this framework, the main objectives of this PhD thesis were: i) the definition of a unique methodological strategy for the shallow landslide susceptibility assessment in terms of initiation area and runout; ii) a better understanding of the role of predisposition factors and especially of the anthropogenic effects on shallow landslide distribution and on the sediment fluxes process.

A data-driven approach were exploited to develop the method for the shallow landslides susceptibility assessment in terms of initiation areas. In particular, a nonlinear

regression technique, namely the Generalized Additive Models (GAM), was applied. The exploitation of this model allowed to implement an intuitive and repeatable methodology able to obtain landslide susceptibility maps of territories characterized by different environmental settings and climatic conditions. The model applied shows a good forecasting capability and a high flexibility, allowing to identify and select the most significant geomorphological, hydrological, geological and land use predisposing factors controlling shallow landslide occurrence, according to the characteristics of each investigated areas.

Concerning the runout analysis, a topography-based index, namely the index of connectivity (IC) proposed by Cavalli et al. (2013), was used to obtain maps of sediment connectivity that permit the characterization of the main sediment transfer processes. In particular, the IC application allowed to evaluate the potential connection between the sediments mobilized by shallow landslides and downstream areas.

An in-depth analysis of the predisposition factors allowed to better investigate the role of anthropogenic factors on the shallow landslides occurrence, distribution and propagation mechanism.

A multi-temporal land use change analysis allows us to evaluate the influence of these changes on the susceptibility to shallow landslides. The results show that abandoned cultivated lands that gradually recovered through natural grasses, shrubs and woods were identified as the land use change classes that were most prone to shallow landslides.

Additionally, it was noticed as the negative qualities of the agricultural maintenance practices increased the surface water runoff and consequently intensified erosion processes and instability phenomena. Moreover, different land use scenarios were realized and implemented in the GAM calculation in order to assess the influence of the land use change on the landslides occurrence. The analysis confirmed that the territories characterized by a relevant land abandonment were those where were registered the increase of medium-high and high susceptibility areas, with a consequent reduction of low susceptibility areas. Thus, this has underlined the negative influence of the reduction of maintenance activities in cultivated lands.

The role of anthropogenic effects on the sediments delivery dynamic in response to slope instability, were also evaluated. The sediment connectivity assessment was carried out, analysing three different scenarios representative of landscape modifications due to anthropogenic effects: (i) drainage system density reduction, (ii) road network variation

and (iii) land use changes. The analysis permitted to identify the instability phenomena characterised by the highest connectivity, allowing to determine those areas in which the mobilized sediment could damage the road network or cause flooding induced by aggradation or obstruction of the riverbed.
Therefore, the results obtained from the presented research activity, allow us to provide innovative tool for the improvement of spatial planning and risk management strategies. Moreover, it provides important information to understand the best land conservation strategy to be adopted in order to reduce as much as possible the occurrence of instability phenomena.

1 INTRODUCTION

1.1 State of the art

Shallow landslides are phenomena triggered by rainstorms of high-intensity and short duration or by precipitation of medium-intensity but with higher duration (Caine 1980; Giannecchini 2006; Giannecchini et al. 2016). Mostly, they occur on slopes composed of an impermeable bedrock and a shallow very permeable layer, affecting soil of small thickness (generally less than 2.0 m), originating from the weathering of the bedrock (residual) and down slope transportation (colluvial). These phenomena are characterized by a triggering stage and by a subsequent runout that can develop in different ways (Campus et al. 1998).
The rainfall-induced shallow landslides are usually characterized by the absence of incipient movement evidence and by high velocity of propagation, especially when the sliding soil portion flows like a fluid down the slope surface, reaching a velocity of more than 9 m/s (Campus et al. 1998; Montrasio and Valentino 2007). Moreover, despite the small soil volume involved, the shallow landslides can be densely distributed across territories, resulting particularly destructive when they evolve into debris flows (Hungr et al. 2001; Sidle and Ochiai 2006; Crosta et al. 2012; Hungr et al. 2014).
Because of their rapid formation and the difficulty in predicting their occurrence, shallow landslides have caused a lot of property damages to cultivation, structures and infrastructures and, sometimes human losses.
The economic and social impact of these instability phenomena are recorded all over the world: in Hong Kong (Fuchu et al., 1999), in South Korea (Park et al., 2013), in USA

(Schmidt et al., 2001; Godt et al., 2008a, 2008b, 2009; Baum et al., 2010), in many areas of Central America (Capra et al., 2003; Harp et al., 2009; Eichenberger et al., 2013). In particular, in the last years, important events occurred in many regions of Italy, namely in Piedmont Region (Sutera Sardo et al., 1996; Campus et al., 1998; Montrasio and Valentino 2007), in Tuscany (Delmonaco et al., 2003; Giannecchini et al 2012), in Campania (Cascini et al., 2000, 2003; Olivares 2001; Olivares and Picarelli, 2001), in Emilia Romagna (Emilia Romagna Region, Report 2002), in Umbria (Cardinali et al., 2006), in Southern Lombardy (Bordoni et al 2015a,b; Zizioli et al. 2013,2014), in Sicily (Mondini et al. 2011; Ardizzone et al. 2012; Melillo et al. 2016) and in Liguria (Cevasco et al 2013a, 2014).

As a result, different approaches were developed in order to guarantee a constantly updating and improvement of risk management strategies. The most effective approach in the management of the territory to prevent slope instability phenomena is the creation and use of tools for the spatial and temporal prediction of areas mostly prone to trigger landslides (Van Westen et al. 2008; Corominas et al. 2014). The evaluation of shallow landslides hazard, defined as the probability of occurrence of a potentially damaging landslides phenomenon within a given area and in a given period of time (Varnes 1984), is described by three concepts: magnitude, spatial location and time recurrence. The first refers to the intensity of the natural phenomenon which has influence on its behavior and destructive power. The second implies the ability to identify the place where the phenomenon may occur. The third refers to the temporal frequency of the event (Guzzetti et al. 1999). In particular, the quantitative hazard assessment is based on the landslide magnitude–frequency relation. Without the correct assessment of the expected annual frequency of landslide events of a given magnitude, a quantitative assessment of landslide hazard is not feasible. In this case, the problem can only be dealt with in terms of landslide susceptibility (e.g. spatial probability; Brabb 1984; Guzzetti et al. 2006; Corominas et al. 2014).

Specifically, the landslide susceptibility gives information on the proneness to landsliding on the basis of a set of relevant environmental characteristics (Corominas et al. 2014).

Therefore, the landslide susceptibility maps represent a powerful tool since they provide coherent information on areas threatened by present and potential slope instability (Baeza et al 2009). However, the frequency or the time of occurrence of the future landslides are not assessed (Fell et al. 2008). In this context, the landslide susceptibility assessment can be considered the initial step towards the landslide hazard and risk assessment and the end product in land-use planning and environmental impact assessment, as well an important tool in early warning system techniques (Corominas et al. 2014).

The use of landslide susceptibility has increased significantly during the last few decades. Different approaches were developed to assess the shallow landslides susceptibility, in terms of initiation areas and runout and different predisposing factors were taken into account to analyze their influence on slope instability according to the scale of analysis, different environmental settings (e.g. climatic conditions, geology, geomorphology, land use characteristics) and terrain conditions (e.g. soil properties and depth, subsurface hydrology, local relief) of a given area (Corominas et al 2014).

Their reliability depends mostly on the amount and quality of available data used as well as on the selection of the appropriate methodology (Baeza et al 2009).

The PhD thesis deals only with the assessment of the shallow landslide susceptibility, both in terms of initiation areas and runout, without the evaluation of the hazard.

1.1.1 The methods used for the landslides susceptibility assessment in terms of initiation areas

The procedures available for the landslide susceptibility assessment can be grouped as based on knowledge-driven, data-driven or physically based methods. The first two are commonly used in regional hazard analyses, while the last one is used in site specific studies, in which the safety factor of the slopes is determined (Baeza and Corominas 2001; Corominas et al. 2014).

The knowledge-base or heuristic methods are qualitative approaches based on field observations and direct identification, by expert geomorphologist, of those areas where the landslides have occurred and where they could occur in the future (Hansen, 1984; Casagli et al., 2004; Regmi et al., 2010). The most disadvantages of these methods are their intrinsic subjectivity.

While in contrast the physically based or deterministic methods, represent quantitative approaches based on the modelling of slope failure processes utilizing physical properties by the investigation of geomorphological and hydrological conditions. They are very objective but they require a large amount of data for a correct application, and moreover they are usually applied only to slope or little basin scale (Montgomery and Dietrich, 1994; Baum et al., 2002, 2008; Montrasio and Valentino, 2008; Rossi et al., 2013; Corominas et al, 2014). In recent studies on slopes susceptible to shallow landslides soil water content and pore water pressure data from continuous monitoring of unsaturated soils have been revealed very useful to be implemented in different kinds of stability models, such as closed form equations based on a limit equilibrium analysis (Lu and Godt, 2008, 2013), physically based models (Campbell, 1975; Montgomery and Dietrich, 1994; Iverson, 2000; Baum et al., 2002, 2008; Montrasio and Valentino, 2008), and Finite Element Models (FEM) (Cuomo and Della Sala, 2013; Springman et al., 2013).

The third class is represented by the data-driven methods. They are quantitative approaches based on James Hutton's (1726–1797) concept of uniformitarianism: "The past and the present are keys to the future" (Orme, 2002; Petschko et al 2014). Thus, the estimation of the possible future location of landslides is usually based on the conditions (e.g. local predisposing factors) of past landslides (Varnes, 1984). Specifically, in data-driven landslide susceptibility assessment methods, the combinations of factors that have triggered landslides in the past are evaluated statistically, and quantitative predictions are made for current non-landslide-affected areas with similar geological, topographical and land-cover conditions (Baeza et al 2009). The degree of susceptibility obtained by the use of these methods are expressed in terms of probability.

Some of the most important advantages of these methods are their objectivity and their easily applicability at regional scale. Moreover, they allow to manage a large amount of terrain parameters simply derived from the elaboration of Digital Elevation Model (DEM), providing automatic and fast procedures coupled with detailed results also in case of lack of exhaustive data. Three main data-driven approaches are commonly used: active learning, bivariate and multivariate statistical analysis. (Corominas et al, 2014). These are well-established models and have been used by different authors and detailed reviews and comparison of different models can be found, among others, in Guzzetti et al. (1999), Dai et al. (2002), Brenning (2005), Glade and Crozier (2005), Rossi et al. (2010) and Vorpahl et al. (2012).

Concerning the active learning methods they are represented by the artificial neural networks (ANNs). The ANNs is one group of algorithms used for machine learning and they represent computational mechanism able to acquire, represent, and compute a mapping from one multivariate space of information to another, given a set of data representing that mapping (Atkinson and Tatnall, 1997). They have many advantages compared with other statistical methods. Firstly, the ANN methods are independent of

the statistical distribution of the data and there is no need for specific statistical variables.
However, in the landslides susceptibility analyses, the most important disadvantages of these approaches is the difficulty to adequately describe the system behaviour and in particular how well the predictors represent the processes associated with landslides (Frattini et al., 2010). This is due to the complexity to interpret their internal mechanisms because of their “black box” nature (Goetz et al 2015).
In bivariate methods, each factor map is combined with the landslide distribution map, and weight values based on landslide densities are calculated for each parameter class. The weight values can be determined by means of several statistical methods such as the information value method, weights of evidence modelling, Bayesian combination rules, certainty factors and fuzzy logic. This approach is a good learning tool useful to determine which factors or combination of factors play a role in the initiation of landslides. It does not take into account the interdependence of variables, and it has to serve as a guide when exploring the dataset before multivariate statistical methods are used (Corominas et al 2014).
The multivariate approaches are the most sophisticated techniques for landslide susceptibility assessment.
In the multivariate analysis, slope failure is considered the result of interaction of several environmental factors, that can vary in space and time. In particular, in the multivariate statistical models, the landslides distribution are predicted through the estimation of the relation between the independent predisposing factors and response variables, namely information of previous landslide occurrence (e.g. landslides inventory maps) (Baeza and Corominas 2001). Multivariate analysis allows the estimation of the relative weight of each contributing factor by means of statistical procedures such as multiple regression or discriminant analysis.
An important statistical development in the last 30 years was the advance in regression analysis provided by Generalized linear model (GLM; McCullagh and Nelder, 1989) and Generalized Additive Model (GAM) (Hastie and Tibshirani, 1986, 1990). The GLM is a well established tool for landslide susceptibility modelling and represent a flexible generalization of ordinary linear regression analysis (Brenning et al. 2015).
However, linearity is unrealistic in many environmental modelling situations (Brenning et al. 2015). In the case of geomorphic processes related to landslides occurrence, this nonlinearity can be observed when an hillslope became unstable, as a consequence of

changing in multiple hydrological, geomorphological and climatic conditions, which lead to a progressive transformation and movement of slope material (Goetz et al. 2011). This nonlinearity opens up a variety of possibilities for complex behaviours that are not possible in linear system (Phillips 2002, 2006), so the use of linear approaches may limit the modelling predictive performance.

For this reason, recently, nonlinear regression techniques, such as the GAM, have been applied to landslide susceptibility modelling and hazard zonation (Brenning 2008, 2015; Jia et al. 2008; Goetz et al. 2011; Petschko et al. 2014). In particular these new researches highlighted the better predictive performance obtained with the use of the GAM rather than with the GLM method (Goetz et al. 2015). This differences was especially related to the inability of the GLM to represent non linear relationship, leading to important local bias in predicted landslide susceptibility. These confirmed the GAM ability to describe the complex nonlinear processes characterizing the relationship between the landslides occurrence and the independent predisposing factors.

1.1.2 The recent advancement to study landslides runout

The runout area of a landslides is defined as the distance travelled by the sediment produced by landslides. Landslide magnitude, propagation mechanism and path characteristics are the main factors that affect the landslide runout.

The study of the runout characteristics and propagation is fundamental for the complete understanding of the risk associated to the landslides occurrence, since the mobilized sediments from landslides often can reach downstream areas causing extensive damages.

Effectively, the sediment yield can direct both towards streams, increasing torrent load, sometimes producing flooding induced by obstruction of the riverbed due to debris. Moreover, it often can affect the road network, generally due to a lack or deficiency of surface water draining systems, blocking traffic, isolating villages and stopping activities (D’Amato Avanzi et al. 2013; Giannecchini et al 2012).

Thus, the understanding of the degree of connection between the sediments produced by instability phenomena and downstream areas of a catchment could be very useful to evaluate the probability that a local on-site effect propagates within a multiple-events feedback system.

Several methods for determining landslide runout were developed. They may be classified into rational and empirical (Hungr et al.2005).

Rational methods are based on the use of analytical or numerical models with different degrees of complexity. They can be classified as discrete (Agliardi and Crosta 2003, Dorren and Seijmonsbergen 2003, Crosta et al. 2004) or continuum-based models (Sosio et al. 2008, Pastor et al. 2009, Alonso and Pinyol 2010).

Empirical approaches are based on simplifying assumptions, and their applicability to quantitative analysis may be restricted. These methods are based on field observations and on an analysis of the relationship between morphometric parameters of the landslide (e.g. the volume), characteristics of the path (i.e. local morphology, presence of obstacles) and the distance travelled by the landslide mass. They can be classified into geomorphological, geometrical and volume-change methods (Fannin and Wise 2001, Corominas et al. 2003, Ayala et al. 2003, Jaboyedoff 2003, Jaboyedoff and Labiouse 2003, Prochaska et al. 2008).

In the recent advancements, the sediments delivery dynamics in response to slope instability phenomena are evaluated by the assessment of sediment connectivity between sediment sources, that act as site of instability within the system, and downstream areas represented mostly by streams or roads networks. The most common methods used for the sediment connectivity analysis are qualitative approach based on geomorphological and sedimentological field observations, and monitoring of sediment fluxes by means of field instrumentation (Harvey, 2001, 2002; Hooke, 2003; Becht et al., 2005; Brown et al., 2009; Mao et al., 2009; Schlunegger et al., 2009; Beel et al., 2011; Berger et al., 2011).

In addition to these methods, analogous quantitative index, based on information commonly available in a GIS environment, were defined. Borselli et al. (2008) introduced a set of tools for the assessment of connectivity using both GIS data (e.g. landuse, DTM) and field observations. In particular, the sediment connectivity index was designed to assess connectivity using only the available landscape information, independently from the event characteristics. This index of connectivity, rather than describing connectivity in the context of specific events allow to obtain connectivity map representing the potential connectivity between the different parts of a watershed.

Reid et al. (2007) proposed a modelling approach which combines the assessment of landslide generated sediment, computed using a modified version of SHALSTAB (Montgomery and Dietrich, 1994), with an index of hydrological connectivity based on a network index version of TOPMODEL (Beven and Kirkby, 1979). Schwab et al. (2009) studied the differences in sediment flux from the opposite flanks of an alpine valley related to differences in the predominant erosion processes (landsliding vs. sediment transport in channel systems). Wichmann et al. (2009) developed an integrated modelling of rockfall, slope-type debris flows and channelized debris flows to assess the sediment cascade systems resulting from the interaction of various geomorphic processes. And recently, Cavalli et al (2013, 2016) proposed a topography-based index, based on the Borselli et al. (2008) approach, to model sediment transfer path of different sediment source areas, such as landslides and areas featuring active superficial erosion, to evaluate their potential connection with the main channel network.

1.1.3 Predisposing factors: the role of anthropogenic effects on shallow landslide distribution and on the sediment fluxes process.

The occurrence and spatial distribution of shallow landslides are strongly influenced by different climatic situations and environmental settings, such as topography, morphology, hydrology, lithology, and land use conditions. In slope stability analysis, the geological characteristics can be considered constant over long periods whereas morphology, climate, and land use can be affected by major modifications seasonally or over a period of decades (Reichenbach et al. 2014). In the last few years, of particular interest was the role of land use change on slope instability, recognized throughout the world as one of the most important factors influencing the occurrence, the movement and the behaviour of shallow landslides (Glade 2003).

In particular, the vegetation cover has important effects on shallow landslide susceptibility because of its effects on the hydrological processes and mechanical structure of the soil. To date, the literature has mainly focused on the mechanical effects of vegetation in terms of providing additional mechanical root reinforcement to be used in slope stability models (Bischetti et al. 2009; Greenway 1987; Schmidt et al. 2001). The mechanical contributions, which affect the soil strength, are derived from the physical interactions of plant root systems with the slope. Two main actions are recognised. The first involves small flexible roots that mobilise their tensile strength by soil-root friction, increasing the compound matrix (soil-fibre) strength. The second involves large roots intersecting the shear surface, which mobilise a soil-root friction force instead of the entire tensile strength (Waldron 1977; Bischetti et al. 2009).

The magnitude of such effects depends on the environmental characteristics (structure and texture of the soil, and the humidity, temperature and competition between the different species) and on the genetic properties of the different species (development of root systems). The environmental characteristics, in particular, induce great spatial variability in root patterns, introducing dramatic heterogeneity in soil reinforcement across different depths, planes and locations.

Thus, understanding the main land use changes through time could be very useful to evaluate the role of vegetation cover on slopes that are prone to shallow landslides and, in particular, the effect of its modification over the time on shallow landslide susceptibility (Carone et al. 2015; Glade 2003; Reichenbach et al. 2014; Van Beek and Van Asch 2004).

Generally, changes in vegetation cover are related to a combination of natural and socio-economic processes that operate at different spatial and temporal scales and often modify shallow landslide behaviour. Of particular interest is the role of human activity on vegetation changes. In fact, large areas can be changed in a short time because of anthropogenic processes, influencing the environmental factors that control landscape stability (Glade 2003).

Moreover, changes in hillslope caused by the construction of anthropogenic structures, such as agricultural roads, forestry road networks or trial paths, often result in situations that may lead to local instabilities (Reid and Dunne, 1984; Luce and Cundy, 1994; Luce and Black, 1999; Borga et al., 2004; Gucinski et al., 2001; Tarolli et al., 2013, 2014b).

In some cases, land use changes may be also a consequence of landslide activity instead of its major cause. Some works underlined that the occurrence of environmental hazards such as landslides in farmland areas can represent an important threat to human security, leading to greater difficulty in continuing to manage the land and causing possible migration and land abandonment (Warner et al. 2010; Piguet 2013).

In Europe, particularly in the Mediterranean region, land abandonment has been one of the most specific environmental processes that caused the most important land use changes over the last century (Gerard et al. 2010). In particular, the agricultural abandonment in the Italian Alps and Apennines led to substantial increases in forest area, depending on the altitude and changes in the structural diversity of the landscape (Falcucci et al. 2007). In many case, changes in land use along steep terrains that are prone to shallow landslides, especially changes that are linked to the degradation and progressive abandonment of cultivations, had negative effects on the predisposition for landslide occurrence (Begueria 2006; Cevasco et al. 2014; Crosta et al. 2003; Galve et al. 2015; Glade 2003; Lorente et al. 2002).

For example, Lorente et al. (2002) and Begueria (2006) showed the negative effects of land degradation on landslide processes. In particular, these authors studied an extremely degraded area in the Central Pyrenees, where shifting agriculture on steep slopes and the frequent use of fire to control the expansion of thorny vegetation led to soil erosion and general land abandonment. This situation strongly contributed to shallow landslides even decades after human activities had ceased and after re-vegetation by shrubs or trees, confirming the strong influence of land degradation on the occurrence of shallow landslides. Other authors (Cevasco et al. 2014; Crosta et al. 2003; Galve et al. 2015) showed that the abandonment of cultivated plants and the lack of maintenance of human structures, such as drainage ditches and retaining walls, along the steep slopes of different Alpine and Apennines hilly areas increased erosional processes and the instability of slopes that were cultivated with vineyards and oliveyards. Moreover, other studies (Bordoni et al. 2016; Bordoni et al. 2016a) highlighted the effect of vineyards and their abandonment on shallow landslide susceptibility, demonstrating that cultivated vineyards provide greater reinforcement to soil than abandoned grapevine plants.

The anthropogenic modifications of the landscape have not only effects on the occurrence and spatial distribution of shallow landslides but they can have important consequence also on the propagation mechanism of the sediment mobilized by the instability phenomena. The human activities, due to the progressive increase of intensive farming, industrialisation and urbanization, have altered the natural landscapes by increasing roads networks and by changing topography, land use, soil properties and drainage systems density, inducing to major changes in sediment delivery dynamic along the hillslope-channel system (Tarolli et al., 2014, 2014a). This lead to important effects on earth surface processes (Brown et al. 2013a), especially in response to slope instability. In fact the modification of the magnitude and the temporal evolution of the sediment transport processes can increase the occurrence of damage due to the increased connectivity of the sediment mobilized by shallow landslides with roads, buildings or rivers.

1.2 Open questions

In the shallow landslide susceptibility assessment there is a continuous need to improve the quantitative analyses in order to provide even more effective decision-making tools for the management and mitigation of hydrogeological risk. For this reason, there are some questions still open in this context. Among these, three of them will be take into consideration.

The first one regards the methods used for the shallow landslide susceptibility assessment. As said in the section 1.1.1, a wide variety of methods for assessing landslide susceptibility have been developed and proposed during these years, as reported in several works of Soeters and Van Westen (1996), Carrara et al. (1999), Guzzetti et al. (1999), Aleotti and Chowdhury (1999), Dai et al. (2002) and recently in Corominas et al. (2014). In particular, there is a clear link between the scale of analysis and the type of method that can be used, with more statistical methods being applied at larger scales due to the increased amount of data required. However, the methodologies implemented diverge significantly from country to country, and even within the same country (Corominas et al.2010, 2014), due to the characteristics of the study area and the wide variety of climatic conditions and environmental factors that control the occurrence and the spatial distribution of shallow landslides in a given area. This makes difficult the application of a unique monitoring technique able to correctly assess the landslides susceptibility of different environmental contexts. For this reason, it is getting more necessary the definition of an objective and reproducible method able to correctly assess the landslides susceptibility of different territories despite the influence of different climatic conditions and environmental settings, in order to guarantee the comparison of the results from one location (site, region, etc.) to another.

The second important problem concern the run out analysis. The methods available for assessing landslide runout (travel distance) are applied only to some types of landslides. Effectively, these methods are usually used for the analysis of rock falls, rock avalanches (Agliardi and Crosta 2003, Dorren and Seijmonsbergen 2003, Crosta et al. 2004, Calvetti et al. 2000), debris flows and mud flows (McDougall and Hungr 2004, Pastor et al. 2009, Iverson and Denlinger 2001, Sosio et al. 2008), while, they are not so common in the shallow landslide analysis. The lack of information about the sediment transfer path mobilized by shallow landslides has made necessary the application of run out analysis also to these landslides typology in order to improve the knowledge about their propagation mechanism.

The third open question concern the parameters controlling the occurrence of shallow landslides. Specifically, the problem regards principally the lack of information about the influence of anthropogenic activities on shallow landslide distribution and on the consequent sediment transfer process. In fact, the role of human activities on landslides occurrence is still discussed controversially in literature (Glade, 2003; Krohmer and Deil, 2003; Tasser et al., 2003; Petley et al.,2007, Meusburge and Alewell, 2008). In particular, understanding and quantifying the effects of land use change on slopes instability still remains an unresolved problem (Schwarz et al., 2010). In fact, it is well known as different land use types may control the stability of slopes, and in particular, that slope stability is enhanced by vegetation in terms of mechanical and hydrological characteristics (Greenway 1987). However, some authors showed that under certain conditions the increasing of vegetation cover could have negative influence (Parsons et al., 1996; Wainwright et al., 2000; Puigdefábregas, 2005). Moreover, the anthropogenic modification of the landscape (land use and drainage system changes, presence and variation of roads network) has significant influence also on the sediment delivery dynamic, since it induce to major changes on sediment propagation mechanism. Within this framework, deepen studies about this theme are necessary to obtain more detailed information about the importance of the anthropogenic effect as predisposing factor in the shallow landslides occurrence, distribution and propagation.

1.3 The main objectives of this PhD research project

The main objectives of this PhD research project were chosen and developed starting from the open questions analysed in the section 1.2.

In particular the research is focused on two main branches.

The first branch regards the development and the implementation of a new methodology for the shallow landslide susceptibility assessment in terms of initiation area and runout, characterized by simplicity, reproducibility and predictive efficiency.

For what concern the analysis on the initiation areas the aim was the application of a nonlinear regression technique, namely the Generalized Additive Models (GAM) to perform an intuitive and repeatable methodology able:

i) to guarantee its application in different environmental contexts;

ii)to identify the most influent predisposing factors in the shallow landslide occurrence, according to the different environmental characteristics.

While, regarding the runout analysis the main purpose was the application of a topography-based index of sediment connectivity (IC), based on the Cavalli et al (2013) approach, in order:

i) to determine the potential connection between the sediment mobilized by shallow landslides and features which act as targets for transported sediment, namely the streams and roads networks;

ii) to represent the sediment delivery dynamics of shallow landslides-prone areas characterized by different degree of landscape complexity.

The second main branch, instead, was focused on the in-depth analysis of the predisposition factors and, principally, on the understanding of the role of anthropogenic factors on the shallow landslides occurrence, distribution and propagation mechanism.

In particular the main objectives within this framework were:

1) The investigation on the role of land use changes in shallow landslides occurrence and distribution, identifying the land use classes more prone to shallow landsliding.

2) The application of the GAM methodology, developed for the shallow landslides susceptibility assessment, to evaluate the influence of land use changes on shallow landslide susceptibility.

3) Development of different IC scenarios to evaluate the role of anthropogenic effect, such as land use changes and modification of drainage system and roads network, on the sediment delivery dynamics in response to shallow landslides occurrence.

2 STRUCTURE OF THE PHD THESIS

The PhD research project was developed in collaboration with the Department of Earth Sciences and Department of Civil and Industrial Engineering of University of Pisa, the Department of Earth, Environment and Life Sciences of University of Genova and the Research Institute for Geo-Hydrological Protection of National Research Council of Padova.

The PhD Thesis will be developed as follows:

In the Chapter 3 (Study areas), five shallow landslides prone-areas, used for the developed analyses, were described. In particular, their peculiar geological, geomorphological and land use characteristics, were highlighted. Moreover, the main shallow landslide events, that affected the investigated areas were presented.
In the Chapter 4 (Method), the developed methodology was described in detail, while in the Chapter 5 (Dataset), the data (remotly sensed data and geological investigations) used to carry out this research were described.
The results were presented from Chapter 6 to Chapter 10, represented by all the research papers produced during the PhD, as result of the research work carried out:

- Chapter 6:
  Persichillo M.G., Bordoni M., Meisina C., Bartelletti C., Barsanti M., Giannecchini R., D'Amato Avanzi G., Galanti Y., Cevasco A., Brandolini P., Galve J.P. Shallow landslides susceptibility assessment in different environments. Geomatics, Natural Hazard and Risk. In press.
- Chapter 7:
  Persichillo M.G., Bordoni M., Cavalli M., Crema S., Meisina C. The role of human activities on sediment connectivity of shallow landslides. Catena. Submitted.
- Chapter 8:
  Persichillo M.G., Bordoni M., Meisina C. 2017. The role of land use changes in the distribution of shallow landslides. Science of the Total Environment, 574, 924-937, DOI: 10.1016/j.scitotenv.2016.09.125.
- Chapter 9:
  Bordoni M., Persichillo M.G., Meisina C. 2016. The role of the vineyards on slope stability: a case study from an area susceptible to shallow landslides. Rend. Online Soc. Geol. It., Vol. 39, pp. 8-11, doi: 10.3301/ROL.2016.34.
- Chapter 10:
  Persichillo M.G, Bordoni M., Meisina C., Bartelletti C., Giannecchini R., D'Amato Avanzi G., Galanti Y., Cevasco A., Brandolini P., Galve J.P., Barsanti M. 2016. Shallow landslides susceptibility analysis in relation to land use scenarios. In Aversa et al. (Eds), Landslides and Engineered Slopes. Experience, Theory and Practices:

Proceedings of the 12th International Symposium on Landslides (Napoli, Italy, 12-19 June 2016). 3, 1605-1612.

The main conclusion were presented in the Chapter 11.

In the Appendix the research paper concerning a work to which I have collaborated was inserted:

- *Bordoni M., Meisina C., Vercesi A., Bischetti G.B., Chiaradia E.A., Vergani C., Chersich S., Valentino R., Bittelli M., Comolli R., Persichillo M.G., Cislaghi A. 2016. Quantifying the contribution of grapevine roots to soil mechanical reinforcement in an area susceptible to shallow landslides. Soil & Tillage Research. 163, 195-206.*

3 STUDY AREAS

To perform the analyses, five different shallow landslides prone-areas, characterized by different geographical settings and size (table 1) were selected, in order to test the applicability of the developed methodology in different environments and multi-scale contexts (from municipal to regional scale – table 1). However, all the analyses were conducted at catchment scale.

All the catchments are located in North-western Italy, in correspondence of the North-west Apennines sector: the Rio Frate, the Versa and Alta Val Tidone catchments (Oltrepo Pavese, Southern Lombardy), the Pogliaschina catchment (Vara Valley - Eastern Liguria) and the Vernazza catchment (Cinque Terre - Eastern Liguria).

In particular, the study areas were chosen according to their peculiar geology, geomorphology, land use and climatic conditions. However, the selection of the study sites was also conditioned by the availability of useful data to perform the analyses.

Concerning the geological and geomorphological settings, the Italian study sites are representative of the typical characteristics of the northern Apennines, with some areas formed principally by steep slopes and hard rocks, as the Rio Frate, the Vernazza and the Pogliaschina catchments, and others mostly characterized by clay components and gentle slope, as the Versa and Alta Val Tidone catchments.

Specifically, the Rio Frate, the Vernazza and the Pogliaschina catchments are characterized by arenaceous conglomeratic bedrock, sandstone–siltstone flysch, sandstone-claystone flysch and pelitic complex, respectively. The Versa catchment is characterised by homogeneous geology formed by flysch and slope relatively uniform with medium-low topographic gradient. The Alta Val Tidone catchment is characterised by a heterogeneous geology, altimetry and slope gradient distribution. The northern sector of this area is formed by lower altitudes and topographic gradient, and the geology in mostly composed by clay components. Whereas, the southern part has higher altitude characterized by steeper slopes and the geology is composed for the majority by calcareous formations.

The climatic conditions are also very different. Effectively, the Rio Frate, the Versa and the Alta Val Tidone catchments are areas mostly characterized by landslide-triggering rainfall with low intensity and high duration. The Vernazza and Pogliaschina catchments are sites usually affected by rainfall with very high intensity.

Table 1. The main characteristics of the investigated study areas: geology, geomorphology, land use and climatic conditions.

Study Areas	Bedrock	Size (Km^2)	Altitude (m a.s.l.)	Slope (°)	Landslides-triggering rainfall	Land use
Rio Frate	Sandstone, conglomerates	1.9	95–295 m	22°-35°	160mm/62h	Abandoned Vineyards
Val Versa	Marls, calcareous-marls, sandstones and scaly shales	38	200-600 m	15°-25°	160mm/62h	Vineyards
Lower Alta Val Tidone	Marls and shale with few areanaceous intercalation emipelagic clays.	94	300-600 m	10°-20°	68.9mm/42h	Arable areas, Woods
Upper Alta Val Tidone	Calcareous marls with interbedded emipelagic clay		600-1160 m	20°-35°		Grassland, Woods
Pogliaschina	sandstone–siltstone flysch	25	95-720 m	> 45°	538.2mm/24 h	Hard-wood (mostly chestnut), coniferous and mixed forest
Vernazza	sandstone-claystone flysch and pelitic complex	5.7	10-800 m	30°-40°	382mm/24h	Terraced areas (olive trees and vineyards) woodlands

About the land use settings, the Rio Frate and the Vernazza catchments, were characterized by an high percentage of abandoned land, previously cultivated with vineyards and terraced vineyards/olive groves. The Versa catchment, although still cultivated, experienced an important modification of agricultural practices with a pronounced transition from arable lands to vineyards.

Instead, the Alta Val Tidone is mainly characterised by semi-natural habitats with predominant presence of woodlands, grasslands and fields consisting of arable land. The Pogliaschina catchment have not undergone major land use changes over the years, in fact, it was characterized only by a slight reduction of agricultural areas replaced by woodland.

All the investigated study areas were recently affected by widespread rainfall-induced shallow landslides: on April 2009 the Rio Frate catchment, on April 2009 and March/April 2013 the Versa catchments, on January 2014 the Alta Val Tidone and on the October 2011 the Pogliaschina and the Vernazza catchments. In particular, the Rio

Frate and the Versa catchments were mainly affected by roto-traslational slides evolving into earth flow. The shallow landslides of the Alta Val Tidone were principally translational soil slides. While, the Pogliaschina and Vernazza catchments were interested by debris flows and debris avalanches.

3.1 Rio Frate catchment

Rio Frate catchment (Figure 1a) has an extension of about 1.9 km^2 and its elevation is between 95-295 m a.s.l. The slopes have medium-high gradient, which can reach values higher than 35°, and they finish in narrow little valleys, formed by creeks of limited extent, ranging between 55 to 348 m^2.

In this area the bedrock is characterised by a Mio-Pliocenic succession called as “Serie del Margine” (Vercesi and Scagni 1984). In particular, medium low-permeable arenaceous conglomeratic bedrock (Monte Arzolo Sandstones, Rocca Ticozzi Conglomerates) overlies impermeable silty-sandy marly bedrock and evaporitic chalky marls and gypsum (Sant’Agata Fossili Marls, Gessoso-Solfifera Formation). The superficial soils, derived by bedrock weathering, are mainly clayey-sandy silts and clayey-silty sands. The soil thickness ranges between a few centimetres to less than 2.0 m.

The Rio Frate catchment was interested by a significant modification of its land use in the last 60 years. Specifically, from 1954 to the present, the area was characterized by an increasing of abandoned land, previously cultivated by vineyards. The current land use is represented by vineyards (26%) and woodlands (44%), mostly derived from the abandonment of past vineyards especially after the 1980s.

This area was affected by an high number of shallow landslides during the event occurred in 27-28 April 2009 (Zizioli et al. 2013). The shallow landslides were triggered in consequence of an extreme rainfall event characterized by 160 mm of cumulated rain in 62 h (20% of the yearly average amount of 1921–1979 period, 25% of the yearly average amount of 2004–2013 period) with a maximum intensity of 22 mm/h (from 18:00 to 19:00 UTC) on 27th April (Zizioli et al., 2013).

245 shallow landslides were recorded. They were characterized by an average length of about 35 m and their area of extension varied from a minimum of 13 m^2 to a maximum of 6289 m^2, with an average of about 473 m^2. The slide surface depth was included between 0.90 m and 1 m.

The shallow landslides recorded during these events were classified according to Cruden and Varnes (1996) classification. Most of them were classified as roto-translational slides evolving into flows, with width/length ratio > 1.

3.2 Versa catchment

Versa catchment (Figure 1b) covers an area of about 38 km^2, with altitude ranging between 128 and 662 m a.s.l. The slopes have a low-medium gradient, with values commonly ranging between 15 and 25°. The area is characterized by a bedrock of age ranging from Cretaceous to Miocene. It has a predominant clayey-marley component, constituted by flysch deposits (Ranzano Sandstones, Monte Piano Marls, Val Luretta Formation). Above the bedrock, soils have especially a clayey texture and their thickness can reach values higher than 3-4 m.

According to these characteristics, this area was previously affected by deep-seated complex landslides (rotational and translational slides that were associated with earth flows) whose sliding surfaces could reach depths greater than 10 m. These types of landslides were located on sandstones that were interbedded with clays, marls, calcareous marls, and scaly shales. In some cases, deep-seated and large translational slides that included bedrock, which consisted of marls and shales with few arenaceous intercalations, were registered (Meisina et al. 2006).

The catchment was also affected by shallow landslides between 2009 and 2013. 196 shallow landslides were triggered during the event of 27-28 April 2009. The triggering event was the same occurred in the Rio Frate catchment (160 mm of cumulated rain in 62 h). The shallow landslides were characterized by an average length of 48.5 m and they reached an area of extension included between 6 m^2 and 8098 m^2 , with an average extension of 491 m^2. Whereas, 193 shallow landslides were recorded during the event of March/April 2013. They were triggered by an high cumulated rainfall amount (till 227.8 mm measured in Canevino rain gauge, equal to 28.5% of the annual average amount; Zizioli et al., 2014).

In this case, the shallow landslides were characterized by an average length of 56 m and an area of extension included between 7 m^2 and 14612 m^2, with an average extension of approximately 1155 m^2. Both in 2009 and 2013 the slide surface depth varied between 0.90 m and 1 m and the shallow landslides recorded were classified as roto-translational slides evolving into flows, with width/length ratio > 1, according to Cruden and Varnes (1996) classification.

3.3 Alta Val Tidone catchment

The Alta Val Tidone catchment (Figure 1c) covers an area of 94 km^2. Its elevation ranges between 300 and 1160 m a.s.l. According to its altimetry and the slope gradient distribution, this area can be subdivided into the Lower Alta Val Tidone, which is located in the northern part of the catchment, and the Upper Alta Val Tidone, which is located in the southern sector. The Lower Alta Val Tidone ranges between 300 and 600 m a.s.l. and is characterised by slope of 10°-20°. The Upper Alta Val Tidone has a higher altitude between 600 and 1160 m a.s.l. and steeper slopes with a gradient of 20°-35°.

The two zones in the Alta Val Tidone catchment exhibit different lithological conditions. The Lower Alta Val Tidone contains a predominance of marls and shale with few arenaceous intercalations, hemipelagic clays (varicoloured clay) and sandstones and limestones in a clay matrix. Silty and/or clayey soils that formed from weathering and down-slope transportation cover the argillaceous bedrock, and the soil thickness can reach values higher than 4 m. The Upper Alta Val Tidone mainly consists of calcareous marls with interbedded hemipelagic clay (Ghiselli et al. 1994) and is covered by silty sand soil with thickness less than 0.20 m.

As in the Versa catchment, rotational and translational slides that were associated with earth flows (complex landslides) and involved calcareous marls with interbedded clays have been registered. Moreover, very large rotational and translational slides were distinguished in the southern part of the study area in relation with calcareous marls with interbedded hemipelagic clay (Meisina et al. 2006).

The study area was also affected by shallow landslide phenomena over the last 7 years (2009-2016). In particular, the most significant event occurred during 18-20 January 2014 and it was triggered by an intense rainfall event characterized by 68.9 mm in 42 h. 90 shallow landslides were recorded. They were, principally, translational soil slides and they were characterized by an average length of 56 m and an area of extension included between 159 m^2 and 8949 m^2, with an average extension of approximately 1305 m^2.

These shallow landslides are especially concentrated in the Lower Alta Val Tidone, corresponding to slopes with bedrock that consists of sandstones that are interbedded with clay and sandstones and limestones in a clay matrix. A few landslides were also located along slopes with bedrock that consists of calcareous marls with interbedded clay but is characterised by very high soil thickness (3-4 m from ground level). The actual land use in this area is different from that in the other two sites. This territory is mostly covered by woods (44%) and by arable lands (29%) in the Lower Alta Val Tidone. The other two land use classes within the catchment are uncultivated areas (11%) and grasslands (8%).

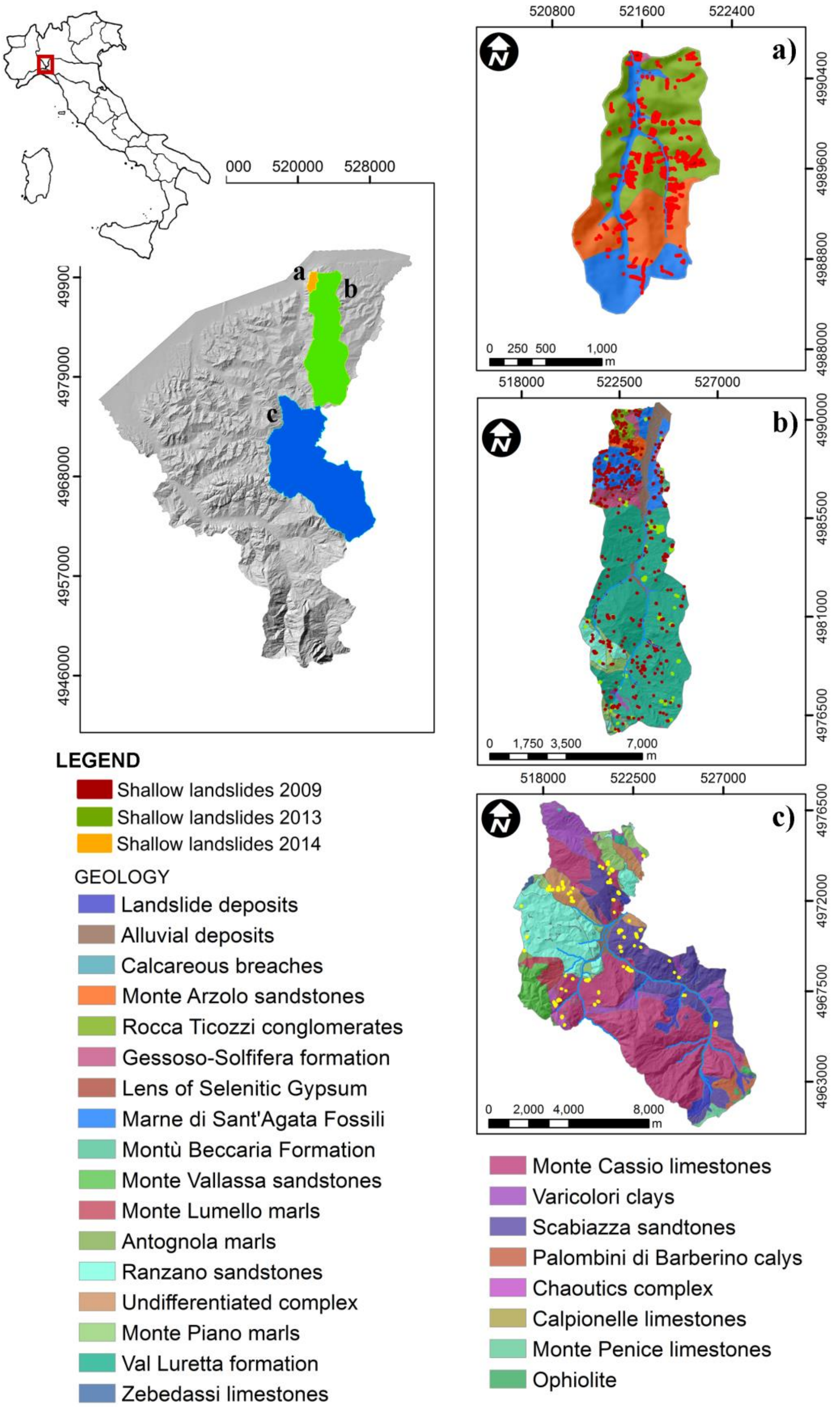

Figure 1**.** Geological maps: **a)** Rio Frate catchment; **b)** Versa catchment; **c)** Alta Val Tidone catchment.

3.4 Pogliaschina catchment

The Pogliaschina catchment is located in the Northern Apennines in the Vara Valley (Figure 2a). It is 25 km^2 wide and has a maximum altitude of about 720 m a.s.l., while the valley bottom is about 95–100 m a.s.l. The slope are characterized by high gradient, since they can reach values higher than 45°. The bedrock is mainly composed of medium and coarse quartz-feldspathic sandstone turbidite (Macigno Fm.; Tuscan Nappe Unit) and quartz-feldspathic greywacke sandstone-siltstone turbidite (Arenarie di Monte Gottero Fm.; Gottero Unit) and is covered by a soil thickness ranging from 0.5 to 1.5 m. From a tectonic point of view, Vara Valley occupies a depression separated from La Spezia Dorsal to the west and from M. Picchiara-M. Cornoviglio Dorsal to the east, that originated from the combination of two main tectonic phases associated with the Northern Apennine chain formation (Raggi 1985).

Vegetation is mainly represented by woodland, characterized by hardwood (mostly chestnut trees), coniferous (principally maritime pines) and mixed hardwood and coniferous forests (93% of the whole basin). Vineyards, olive groves and other plantations occupy about 6% of area (D’Amato Avanzi et al. 2014). This agricultural areas, from 1960, have been affected by a small reduction (9%) and further substituted by scrublands and shrubbery.

On 25 October 2011, a total rainfall of 538.2 mm in 24 h was recorded by the Brugnato rain gauge, with a rainfall intensity of 143.4 mm/h (from 13:00 to 14:00 UTC) and up to 108,1 mm/h in 6 h (from 9:00 to 15:00 UTC; D’Amato et al. 2014). A total of 658 shallow landslide were mapped, 569 of which were classified as complex, translational debris slide-flow (Cruden and Varnes 1996). They were usually superficial (0.3-1.5 m thick), linear (width/length ratio 0.03-0.5) and involved mostly coarse-grained soil and sometimes portions of fractured bedrock. 89 landslides were classified as roto-traslational slides (Cruden and Varnes 1996), with a small size and a width/length ratio > 1 (Bartelletti et al. 2015). The landslides area characterized by a minimum area of 50 m^2 and a maximum area of 18502 m^2 , with an average of about 1190 m^2. The average length of the landslides was approximately 95 m and their slide surface was localized at depth of about 1-2 m.

3.5 Vernazza catchment

The Vernazza catchment (Eastern Liguria, La Spezia province) is located along the Tyrrhenian side of the northern Apennines (Figure 2b). It is part of the Cinque Terre area, which was declared World Heritage Site by Unesco and included in the Cinque Terre National Park.

The bedrock is mainly composed of a sandstone-claystone flysch (Macigno Fm., upper Oligocene– lower Miocene?, Tuscan Nappe) and a pelitic complex (Canetolo Shales and Limestones, Canetolo Unit), which are part of a wide overturned antiform megafold whose axes strikes 150°N (Regione Liguria 2006).

It shows typical geomorphological features characteristic for most of the Ligurian coastal catchments: small area (about 5.7 km^2), very steep slopes due to the proximity of mountains to the sea and short streams, often controlled by tectonics (Cevasco 2007), with considerable erosive power and capacity to transport sediment because of their steep profiles. The Vernazza catchment has an altitude included between 10 m and 800 m a.s.l. and more than 50% of the terrain gradient ranges between 30°and 40°.

Unusual land use conditions characterise the slopes within the Vernazza catchment (Cevasco et al. 2013a; 2014).

Approximately 50% of these slopes, located in the middle and lower parts of the catchment, were terraced during the past millennium for vineyards and olive groves. Currently, only approximately 20% of the terraced areas are still cultivated, leading to increasing geomorphological instability in the last decades (Terranova et al. 2006; Brandolini, in press). In abandoned terracing, the dry stone walls retaining the terraces are in poor condition because of lack of maintenance. However, due to their old age, also the dry stone walls retaining terraced areas still cultivated do not guarantee the drainage of surface water. The upper part of the basin is characterised by woods and scrub lands. Due to reworking of debris covers for terracing, the soil thickness is greater on agricultural terraces (up to 2.5 m) than on woodlands (up to 1.5 m).

Whilst large rock landslides and rock failures are widespread on the coast of Liguria (Brandolini et al. 2007; Cevasco 2007; Carobene and Cevasco 2011; De Vita et al. 2012, Corradi et al. 2013), within the Vernazza catchment, due to its morphological features, shallow phenomena triggered by rainfall are prevalent (Cevasco et al. 2013a). In particular, on 25 October 2011, high-intensity rainfall affected the Cinque Terre area, triggering more than 500 rainfall-induced shallow landslides in the Vernazza catchment.

A total rainfall of 382 mm was recorded in 24 hours along the coast by the Monterosso rain gauge located 3 km northwest of Vernazza. At Monterosso, rainfall intensities of 90 mm/h, 195 mm/3 h and 350 mm/6 h were recorded between 9:00 and 15:00 UTC (A.R.P.A.L.-C.F.M.I.-P.C. 2012; Cevasco et al 2014).

A total of 473 landslides were mapped. They were characterized by an average length of about 74 m. Moreover, their extent is ranging between 6 m^2 and 6307 m^2, with an average value of 322 m^2.

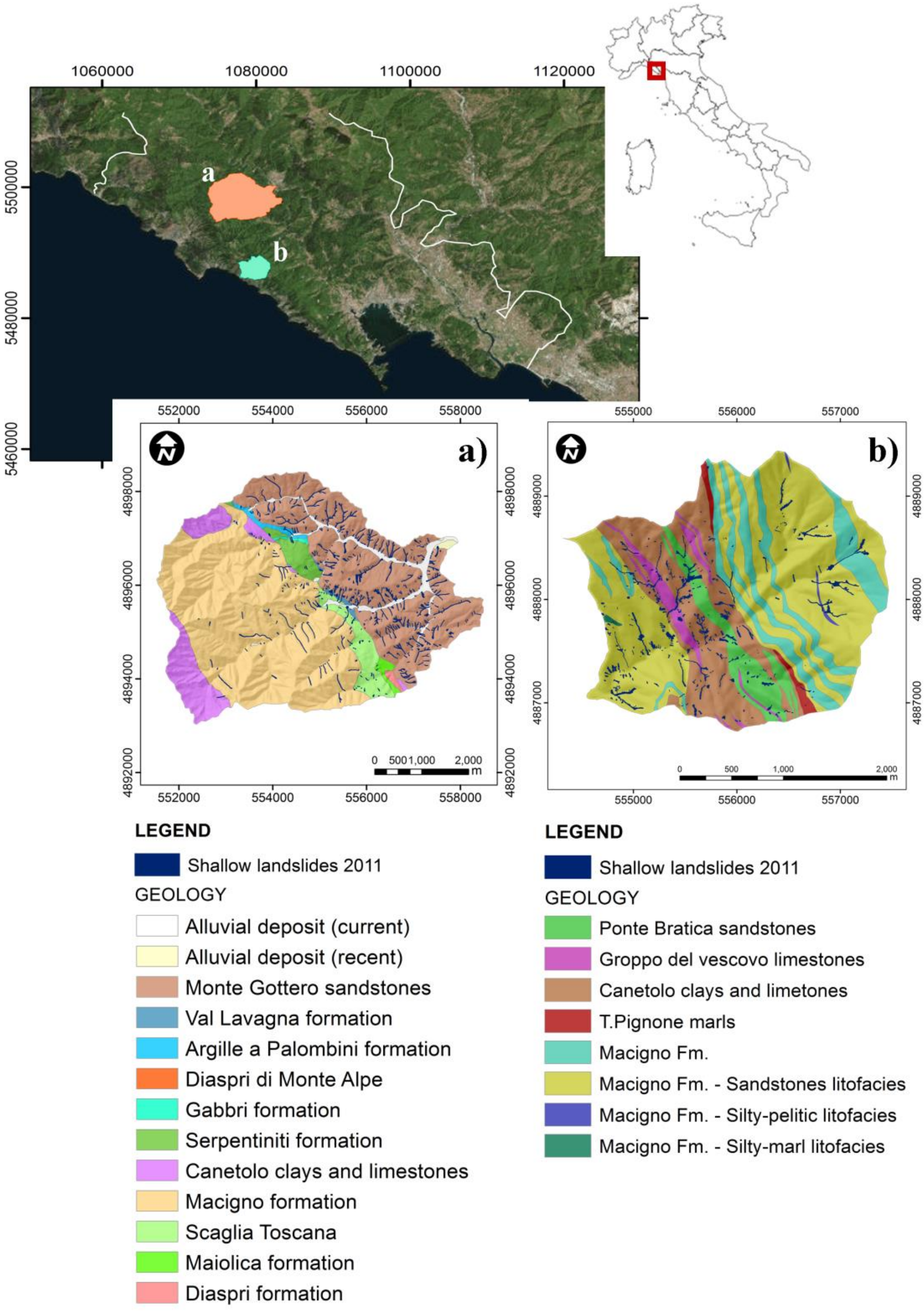

Figure 2. Geological maps: **a)** Pogliaschina catchment; **b)** Vernazza catchment.

The slide surface depth varies according to the location of the landslides and the characteristics of the soil. In fact, the failure of eluvial and colluvial soils are located at a depth up to 1.5 m on woodland while the failure of artificially reworked deposits are located at a depth up to 2.5 m on terraced slopes (Cevasco et al. 2013b, 2014). The shallow landslides recorded were classified following the landslides classifications of Cruden and Varnes (1996) and Hungr et al. (2001). Most of the landslide phenomena that occurred on 25 October 2011 were classified as debris avalanches (Cevasco et al. 2014).

4 METHOD

The developed methodology can be subdivided into two phases (Figure 3):

(1) Development of methodological strategy for shallow landslides susceptibility assessment in terms of initiation areas and runout;
(2) Analysis of the role of anthropogenic effects as predisposing factors of shallow landslides.

During the first phase, the shallow landslide susceptibility analysis related to the initiation area was performed by the implementation of a nonlinear regression technique, called Generalized Additive Model (GAM). The GAM methodology, described in the subparagraph 4.1.1, was applied to four study sites: the Rio Frate, the Versa, the Pogliaschina and the Vernazza catchments. The areas were chosen according to their different geological, geomorphological and land use settings, in order to test the reproducibility, the flexibility and predictive efficiency of the method in different environmental contexts.
Concern the runout analysis, a Topography-based index of sediment connectivity (IC), based on the Cavalli et al. (2013) approach, was applied. The method was tested only in the Rio Frate and the Versa catchments since only in this areas LIDAR DTMs and orthophotos, necessary for the analysis, were available.
During the second phase, three aspects were examined. At first, a multi-temporal land use change analysis were carried out to understand the role of land use changes on the shallow landslides distribution. Only, the Rio Frate, the Versa and the Alta Val Tidone

catchment were used as study areas since only for these sites was available the time series of land use maps required to perform the multi-temporal change detection.
Thereafter, land use scenarios were realized to model, by means of the GAM methodology, the shallow landslide susceptibility in response to land use changes. In this case, the study areas used for the analysis were the Rio Frate, the Versa, the Pogliaschina and the Vernazza.
Finally, the IC was evaluated analysing different scenarios developed to understand the influence of the anthropogenic factors on the sediments delivery dynamic in response to shallow landslides occurrence.

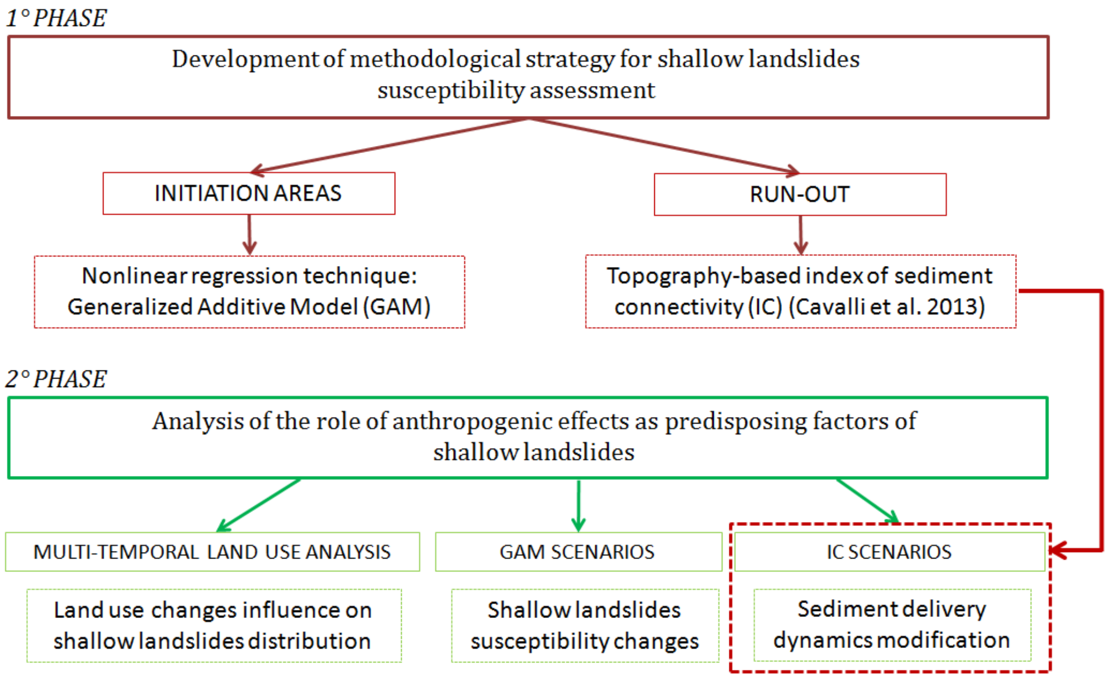

Figure 3. Schematization of the developed methodology

4.1 First phase

4.1.1 Initiation areas

The methodology, applied for the shallow landslide susceptibility assessment in terms of initiation areas, is based on the application of a multiple regression model based on GAM (Hastie and Tibshirani 1990).
The procedure for the data analysis is made of two parts (Figure 4):

1) Pre-processing of input data in order to extract a list of predictive variables
2) Statistical implementation of GAM

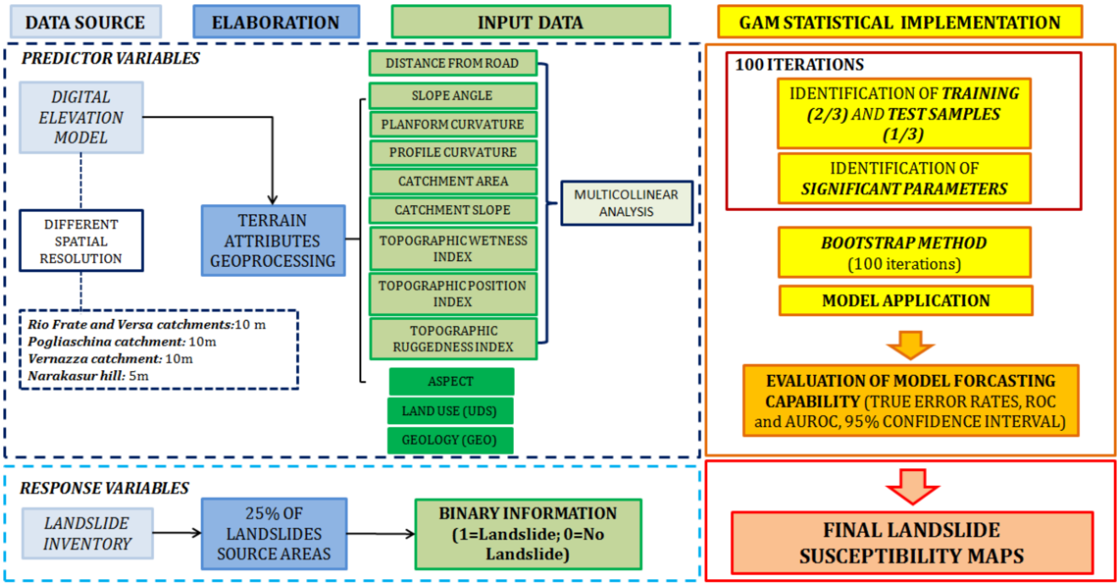

Figure 4. GAM methodology scheme

1) Pre-processing of input data

The Predictors Variables:

During the pre-processing phase, 12 predictors variables were identified, according to their influence on shallow landslide mechanisms.

Nine different terrain attributes, representing morphological and hydrological parameters, were extracted by DEMs (digital elevation models) at resolution of 10 meters, through a set of tools implemented in SAGA GIS (System for Automated Geoscientific Analyses). All DEMs were antecedent to the shallow landslide events.

The geomorphic and hydrological attributes derived from DEM are the following (table 1): Slope (SL), Aspect (ASP), that was transformed from continuous into categorical variable to avoid the presence of No Data in correspondence of flat areas, Planform curvature (PLA), Profile curvature (PRO), Catchment area (CA), Catchment slope (CS), Topographic wetness index (TWI), Topographic position index (TPI), Terrain ruggedness index (TRI). This parameters were selected according to their capacity to outline destabilizing factors (Montgomery and Dietrich 1994; Brenning 2008). In particular, their geophysical controls on slope stability represent their crucial role in several processes such as subsurface flow convergence, increased soil saturation and shear strength reduction (Goetz et al. 2011).

In addition to the DEM-derived terrain attributes, the Euclidean distance from roads (RD) was calculated by using the streets network shapefiles available for each study areas. Also the land use (LU) and the geology (GEO) were considered as predictors variables They were derived by means of GIS analyses from specific thematic maps. In particular, for what concern the LU, in the Rio Frate and the Versa catchments the LU maps from DUSAF of 2007 (Lombardy Region) were used; in the Pogliaschina catchment the LU map of 2009 (Liguria Region) was utilized; in the Vernazza catchment a LU map of 2011 was expressly prepared through air photo-analysis and field surveys (Cevasco et al. 2013a). In all the cases analysed, the evaluation of GEO was carried out considering the different geological formations as reported on the available geological maps.

The Response Variables:

The shallow landslides inventories were used as response variables. All landslide inventories consist of polygons which delimit the whole landslide perimeter. A semi-automatic method, already used in Galve et al. (2015), was implemented to extract each landslide source areas. In particular, this procedure allowed to define the source areas by selecting the 25% of the pixels with the highest elevation in each landslides. The extracted landslide source areas were applied in GAM as the binary response variable, assigning 0 or 1 in case of landslide absence or presence, respectively.

The source areas automatically extracted were compared with those selected manually by visual interpretation of orthophotos. This analysis was useful to assess the uncertainty of the automatic procedure. The difference obtained is due to the transformation from vector data to raster format at 10 m resolution. This leads to an overestimation and underestimation of about 10 m due to the raster resolution used.

2) Statistical implementation of GAM

The second phase of the developed methodology (Figure 4) is referred to the implementation of the Generalized Additive Model (GAM, Hastie and Tibshirani 1990). The GAM represents a semi-parametric extension of the generalized linear model (GLM). Its basic assumption is to replace the linear function used in a GLM, with an empirically fitted smooth function, in order to find the more likely functional form to fit the data (Hastie and Tibshirani 1990; Brenning 2008; Goetz et al. 2011). Specifically, it uses a link function to establish the relationship between the mean of the response variables and a sum of a group of smooth functions of independent variables, as shown in the equation 1 below (Jia et al. 2008):

$$g(\mu) = \sum_{i=1}^{n} f_i(x_i) \tag{1}$$

Where $g(\mu)$ is the link function and the $f_i(x)$ are smooth function (typically splines).
The GAM allows the combination of linear and nonlinear smoothing functions and the application of different modelling policies according to the characteristics of the predictor factors. This permit to better describe the complex relationship between independents and response variables (Petschko et al 2014).
The implementation of the GAM was provided by means of R software and the *R package 'gam'* (Hastie 2013).
The procedure adopted can be subdivided in the following steps:

(1) Multicollinear analysis to evaluate the dependence between the predictors variables and to avoid the violation of the basic assumptions of multiple regression models;
(2) Selection of the most significant parameters for the better description of the shallow landslides occurrence by using minimization of Akaike Information Criterion (AIC) and 100-fold bootstrap procedure of random selection of train and test data set to evaluate the model accuracy;
(3) Evaluation of model forecasting capabilities and shallow landslides maps extraction.

The first step in the GAM implementation was the application of a multi-collinear analysis. This procedure is fundamental, since the multi-collinearity represent a critical point in the application of multivariate analysis. Multicollinearity is an undesirable situation that occurs when the predictors variables (in this case landslides predisposing factors) are highly linearly related. Thus, the identification of this dependency is necessary to reduce redundancy and to improve numerical stability in the subsequent analyses (Farrar and Glauber 1967). This analysis was performed with the function *Colldiag*, available in the R package "*perturb*". This is an implementation of the regression collinearity diagnostic procedures found in Belsley et al. (1980). The procedure calculate the condition indexes of the matrix of the independent variables. The condition index greater than 30 or higher (as suggest by Belsley et al. 1980), indicates collinearity problems. All variables with large condition indexes were deeply investigated to provide further information useful to identify the source of these problems. In particular, the variance decomposition proportions associated with each condition index was computed. If large condition index (> 30) is associated with two or more variables with large variance decomposition proportions (equal or greater than 50%, as suggested by Belsley et al. 1980), these variables may cause collinearity problems. These predictors were excluded from the analyses in order to reduce collinearity.

In the second step, an equal number of non-landslide pixels has been appended to the landslide database to avoid an over-estimation of non-landslide areas, according to a general method described in Dai and Lee (2002); Ayalew and Yamagashi (2005); Duman et al. (2006) and Mathew et al. (2009). Thus, the entire database, consisting of all landslide pixels and the same number of randomly selected non landslide pixels, was subdivided into 2 subsets: the training and the test sets. The training set, representing 2/3 of the dataset, was used to build the GAM fitting the samples, while the test dataset, including 1/3 of the dataset, was used to estimate the model accuracy. The process of training and test random selection was repeated in a 100-fold bootstrap procedure. Then, the 100 fits have been used to extend the prediction to the whole areas in order to obtain a distribution of landslide probability for each pixel. The mean values of each bootstrap distribution of 100 probability values have been used to compute the landslide susceptibility maps. The 95 confidence interval of probabilities gives information about the reliability of the prediction.

In particular, the GAM is built using a stepwise variable selection. Starting from null model, each variable can be entered as linear (untransformed), nonlinear (non parametrically transformed predictor of two equivalent degrees of freedom), or not included in the model. The minimization of Akaike Informaton Criterion (AIC) is used as selection criterion (Brenning 2008; Guisan et al. 2010; Goetz et al. 2011). For instance, it may introduce some predictor variables as linear functions, while other ones as non linear smooth functions, well representing complicated relations between the variables, and providing high flexibility (Jia et al. 2008).

The process of training and data sets random selection was repeated in a 100-fold bootstrap procedure. This method allow to identify the most frequent predictors variables.

The parameters whose frequency was more than 80% in the bootstrap extraction were identified as the most influent and used to build the model. Among the selected predictors, the linear and non-linear were identified. The discrimination was based on the higher percentage of selection obtained. The selected parameters were used to build the model for the landslide occurrence prediction in all study area.

In the third step, the initially predictive accuracy was evaluated through a repeated holdout method for regression with a binary response, slightly modified with respect to the standard procedure (Maindonald and Braun 2010). Holdout method is the simplest kind of cross validation technique, allowing easy computational processes (McLachlan 1992; Molinaro et al. 2005). Specifically, the repeated holdout is a k-fold repetition of holdout method, which consists of a random subsampling of different training and test set, in proportion of 2/3 for testing and 1/3 for test. The repeated holdout method provides an estimate of the true error rate (accuracy) for each iteration. Unlike the standard holdout method separates the entire dataset into training and test sets, these two sets were the ones for the bootstrap model selection. The true error rates of the 100 different iterations were calculated in all training and test sets. The results were averaged to yield an overall accuracy and compared.

Another measure of the predictive performance was evaluated through the Receiver-Operating Characteristic (ROC) curve (Hosmer and Lemeshow 2000;). In particular, the area under the ROC curve (AUROC) was compute to evaluate the model ability to discriminate landslide and non-landslide location.

The ROC is calculated by plotting the sensitivity of a model (proportion of true positives) to the specificity (1-specificity, or false positives rate; Hosmer and Lemeshow 2000; Petschko et al. 2014). The AUROC (area under ROC) can takes values from 0.5 (no discrimination) to 1.0 (perfect discrimination; Brenning 2005;);

Specifically, the mean value of the 100 AUROC samples obtained from the 100-fold bootstrap procedure was calculated. Also the bootstrap 95% confidence bands of ROC and bootstrap 95% confidence AUROC were obtained.

In the last step, the model forecasting capability was assessed and the shallow landslides susceptibility maps were extracted by extending the prediction of the model to all the study areas. The landslide probability and the bootstrap confidence interval were estimated for each pixels.

The final shallow landslides susceptibility maps were computed using the means of the landslides probability values, which represent an estimated conditional mean value of the landslide probability (Hosmer and Lemeshow 2000). A prediction uncertainty is associated to each estimated probability by computing the boostrap 95% confidence intervals.

The probability values were subdivided into 4 intervals in the susceptibility map: $0 \leq p \leq 0.25$, $0.25 < p \leq 0.50$, $0.50 < p \leq 0.75$, $0.75 < p \leq 1$.
This classification method considers the equal probability interval of 0.25 for each susceptibility class. A value of 0.5 represents the same probability of occurrence or not of landslide. The ranges $0 \leq p \leq 0.25$, $0.25 < p \leq 0.50$, $0.50 < p \leq 0.75$ and $0.75 < p \leq 1$ indicate a low, medium-low, medium-high and high probability of landslide occurrence, respectively.

4.1.2 Runout

The runout was analysed by means of a topography-based index of sediment connectivity (IC), following the Cavalli et al. (2013) approach.
The IC allow to represent the potential connection between different parts of the catchment and aims, in particular, at evaluating the potential connection between hillslopes and features which act as targets or storage areas (sinks) for transported sediment (channels, basin outlet, lake, roads networks).
The original IC was developed by Borselli et al (2008), who defined the IC as:

$$IC = log_{10} \frac{D_{up}}{D_{dn}} \tag{2}$$

where D_{up} and D_{dn} are the upslope and downslope components of connectivity respectively (Figure 5).
The D_{up} represent the potential for downward routing of the sediment produced upslope and it depend on the upslope catchment area, mean slope and terrain roughness. It is estimated as follows:

$$D_{up} = \overline{W}\overline{S}\sqrt{A} \tag{3}$$

Where $\overline{W}$ is the average weighting factor of the upslope contributing area to model the impedance to runoff and sediment fluxes due to properties of the local land use and soil surface. $\bar{S}$ is the average slope gradient of the upslope contributing area (m/m) and A is the upslope contributing area (m^2).
The D_{dn} takes into account the flow path length that a particle has to travel to arrive to the nearest target or sink and it depend on path length, terrain roughness and gradient along the downslope path. It can be expressed as:

$$D_{dn} = \sum_i \frac{d_i}{W_i S_i} \tag{4}$$

where d_i is the length of the flow path along the i^th cell according to the steepest downslope direction (m), W_i and S_i are the weighting factor and the slope gradient of the i^th cell, respectively. It's worth noting that d_i can assume two values: cell size (l) in the case of cardinal direction and l√2 in the case of diagonal direction.

IC is defined in the range of [-∞, +∞], with connectivity increasing for larger IC values.

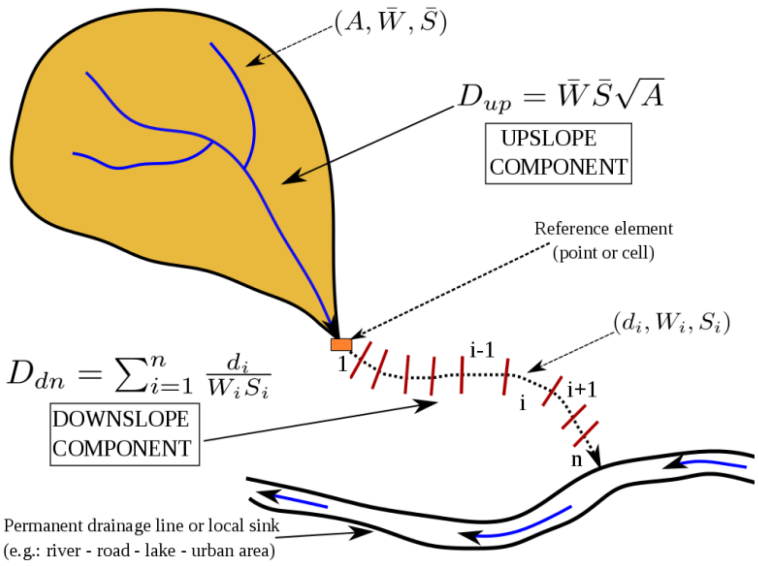

Figure 5 Definition of upslope and downslope component of the index of connectivity (IC). (From Borselli et al. 2008)

Starting to the original IC, Cavalli et al (2013) decided to introduce some refinement of the implemented IC to adapt the mode to its use with High Resolution- Digital Terrain Models (HR-DTMs). Details on the main changes introduced in the IC calculation can be found in Cavalli et al. (2013).

The IC was computed through the stand-alone application SedInConnect 2.1 (Crema et al., 2015 – Figure 6).

The input/output requirements, showed in the Figure 6, are the following:

1. Input DTM raster;
2. Target features. They must be polygon shapefiles;
3. DTM to compute weighting factor derived from the Roughness Index as in Cavalli et al. (2013), or to choose any other weighting factor without flag this option;

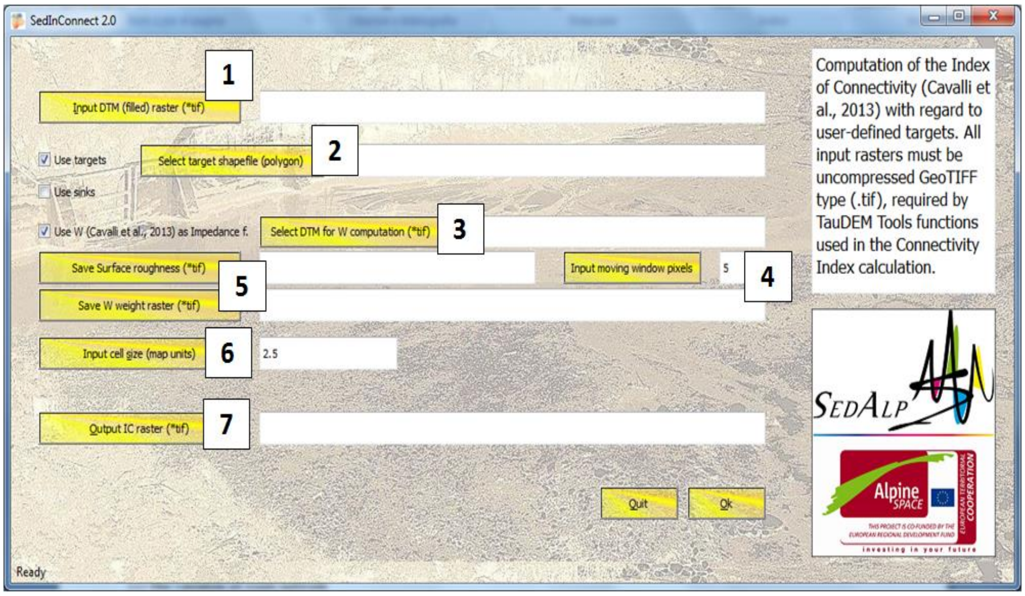

Figure 6. Input/output requirements in the stand-alone application SedInConnect 2.1

4. the number of pixel that define the size of the moving window to consider while smoothing the original DTM and for the computation of the standard deviation of residual topography. Required to calculate the surface roughness as proposed by Cavalli et al. (2008);
5. Saving of surface roughness and the weight raster;
6. DTM cell size (in map units);
7. Output Connectivity Index map.

4.2 Second phase

4.2.1 Multi-temporal land use change analysis

The method is made by three main analyses:

1. A multi-temporal analysis to obtain historical profile of the main land use changes, especially regarding the land abandonment phenomena and agricultural practices modification, occurred from 1954 to 2012 in the study areas investigated.
2. Application of Frequency Ratio Method (FRM - Lee and Talib 2005) to analyse the land use change influence on the shallow landslide occurrence and to identify the land use change classes more prone to shallow landsliding.

3. Detailed analysis on the effect of vineyards on shallow landslides susceptibility, by considering the effect of their abandonment on soil root reinforcement of steep slopes.

LAND USE CHANGE DETECTION

Change detection analysis was exploited to investigate the main modification from 1954 to 2012 and to quantify the percentage of changed area in the three different study areas (i.e. the Rio Frate, the Versa and the Alta Val Tidone catchments).
The change detection analysis comprises of a wide range of methods used to describe and quantify differences in the state of an object or matter or phenomenon by observing it at different times (Singh 1989). In this case, with this technique, the total area and proportion of land use occupation throughout the years were analysed, using all the available land use maps. Hereafter, different periods were chosen to provide information about the transition rates between the main land use classes. Specifically, the land use variation rates were calculated between the years where significant modifications on land use occurred, to highlight the principal variation trends that characterised the three study areas in the investigated time span (1954-2012).

FREQUENCY RATIO ANALYSIS

Shallow landslides distribution on each land use type was obtained superimposing the position of landslides' source areas to the land use maps. For each landslides database, the available land use map of a period immediately before the considered shallow landslide event was considered. According to this, the shallow landslides of 2009 event, occurred in the Rio Frate and the Versa catchments, were compared with the land use maps of 2007. Instead, for the shallow landslides events of 2013 and 2014, occurred in the Versa catchment and Alta Val Tidone catchment respectively, the land use map of 2012 was used.
For quantifying the land use change influence on the landslides occurrence in each study area, the FRM (Lee and Talib 2005; Regmi et al. 2010) was applied. FRM is based on the observed relationships between distribution of landslides and a landslide-related factor, in this case the land use change, to reveal the correlation between landslide locations and this factor in the study area (Lee and Talib 2005; Karim et al. 2011). The Frequency ratio (Fr) is calculated by the ratio of the percentage of the landslides in each

category of land use change to the percentage of each land use change classes. It is represented by the following equation (equation 5):

$$Fr = \frac{AF_{lu(i)}/A_{lu(i)}}{\sum AF_{tot} \,/\, \sum A_{tot}} \tag{5}$$

Where:

$AF_{lu(i)}$= area occupied by the shallow landslides within the land use change classes considered *(i)*

$A_{lu(i)}$ = total area occupied by the land use change classes considered *(i)*

$\sum AF_{tot}$ = total area occupied by the shallow landslide in the entire catchment

$\sum A_{tot}$ = total area of the entire catchment

If the value of Fr is higher than 1, the density of landslides in a particular land use change category is higher than the density for the entire map, while if the value is lower than 1, the density of landslides in that category is lower than the density for the entire map (Regmi et al. 2010). Then, the land use change class having the highest value of Fr can be considered more susceptible to landslide occurrence, while those having the lowest values have minor role in landslide occurrence. Considering the Fr, which allows for taking into account also the area occupied in a region by a single land use change type, it can convey in a better way the effective influence of a land use change on shallow landslide occurrence.

For each study area, the distribution of shallow landslides were compared with the most significant identified land use change occurred in the study area immediately before the landslides triggering event. As for the quantification of the land use influence on shallow landslide occurrence, the used databases in Fr analysis were: the database of 2009 shallow landslides event for Rio Frate catchment, the databases of 2009 and 2013 shallow landslides events for Versa catchment, the database of 2014 shallow landslides event for Alta Val Tidone catchment.

ROOT REINFORCEMENT ASSESSMENT

For the performance of this analysis only the areas characterized by the highest phenomena of vineyards' abandonment were considered, in order to understand the effect of vineyards on shallow landslides susceptibility, by considering the effect of their abandonment on soil root reinforcement of steep slopes. In particular the hilly area, located between the Versa River and the Rio Frate Creek, were selected.

The method applied is based on the Bordoni et al (2016a) approach.

Root reinforcement (c_{rtot}) was assessed, for cultivated and abandoned vineyards and woodlands on each test slope where a shallow landslide had occurred. The required variables are amount of roots in the considered soil profile and root tensile strength. Possible pullout strength of large roots (diameters higher than 10 mm), was not considered, because large roots do not act in root reinforcement due to their stiffness (Bischetti et al., 2009). A trench pit was excavated in each site to collect grapevine root samples for mechanical properties measurement and to estimate root density, in terms of Root Area Ratio (RAR, the ratio between the area occupied by roots and the sample area). Root density was measured through the root-wall technique (Bischetti et al. 2009) by analyzing the images acquired along the depth in a frame of known size (0.3x0.3 m).

Grapevine roots mechanical properties were measured through laboratory tensile tests on sampled roots, obtaining a power law relationship between the tensile force at failure (f) that represents the root mechanical behaviour. Force-diameter (f/d) relationship and root density were used to estimate root reinforcement (c_{rtot}) by means of the Fiber Bundle Model (FBM; Pollen and Simon, 2005) at a particular depth in the soil profile.

c_{rtot} was assessed also through a back analysis procedure. The failure sites were assumed to have a factor of safety of the slope, F_s , equal to 1 and then the contribution of plants in terms of c_{rtot} at depth of the sliding surface was evaluated. c_{rtot} was assumed to have the same geotechnical behavior as the soil cohesion (Schwarz et al. 2010). Back analysis was carried out using GeoSlope software (Version 8.13; Geoslope 2012) based on the limit-equilibrium method. For each studied slope, the profile was created and the soil stratigraphic profile was inserted. Under the soil profile, the lower boundary condition is represented by a bedrock which cannot be affected by the landslide. Along the slope, a perched water table rising up from the soil-bedrock contact was included in the model. According to Bordoni et al. (2015a), this hydrological scenario represents the most likely conditions in the slopes that trigger shallow landslides in the study area. The measured soil geotechnical properties of the studied slopes, such as unit weight (mean value for the entire soil profile), friction angle and effective cohesion were included as input parameters. According to these boundary conditions, the software calculates the slope F_s along the most unstable part of the slope at the depth where the shallow landslides sliding surface developed.

4.2.2 GAM scenarios

The methodology applied for the shallow landslide susceptibility assessment was performed by the application of the GAM (Hastie and Tibshirani, 1986, 1990).
The procedure adopted is composed of the following steps:

i. Application of the GAM and selection of the most significant parameters for the better description of the shallow landslides occurrence;
ii. Identification of the areas where the land use parameter is more significant;
iii. Assessment of shallow landslides susceptibility in relation to future land use change scenarios.

The application of the GAM methodology allowed characterizing the predisposition of each investigated territory to shallow landslide occurrence, and in particular the role of the land use on the shallow landslides susceptibility.
The study areas, where the land use was identified as the most significant predisposing factor, were used to perform a multi-temporal land use change analysis. This permitted to highlight the main land use change occurred, and to realized land use scenarios according to the main modification observed. The GAM was, then, performed again with the application of land use scenarios as predictor variables, in order to understand how land use changes can affect the landslide susceptibility during time.

4.2.3 IC scenarios

The IC was evaluated analysing different scenarios developed to understand the influence of the anthropogenic factors on the sediments delivery dynamic in response to shallow landslides occurrence (Figure 7).
In particular, three scenarios were take into consideration:

(1) The evolution of drainage system density
(2) The variation of roads network
(3) The multi-temporal land use change

In the first scenario four different drainage networks, characterized by a decrease of drainage density, were used as targets in the IC calculation in order to evaluate the sediment connectivity change according to the drainage density variation.

Instead, the second IC scenario involved the use as target of 4 road networks in order to evaluate the influence of the gradual evolution of the road network on the sediment connectivity.
Finally, in the third scenario, Overland Flow Manning's n Roughness Values (adapted from COE, HEC-1 Manual , 1990 and the COE , Technical Engineering Design Guide, No 19, 1997) were used as weight factor (W) to model the impedance to sediment fluxes process replacing the index of residual topographic roughness (RI) used by the Cavalli et al. (2013) approach.

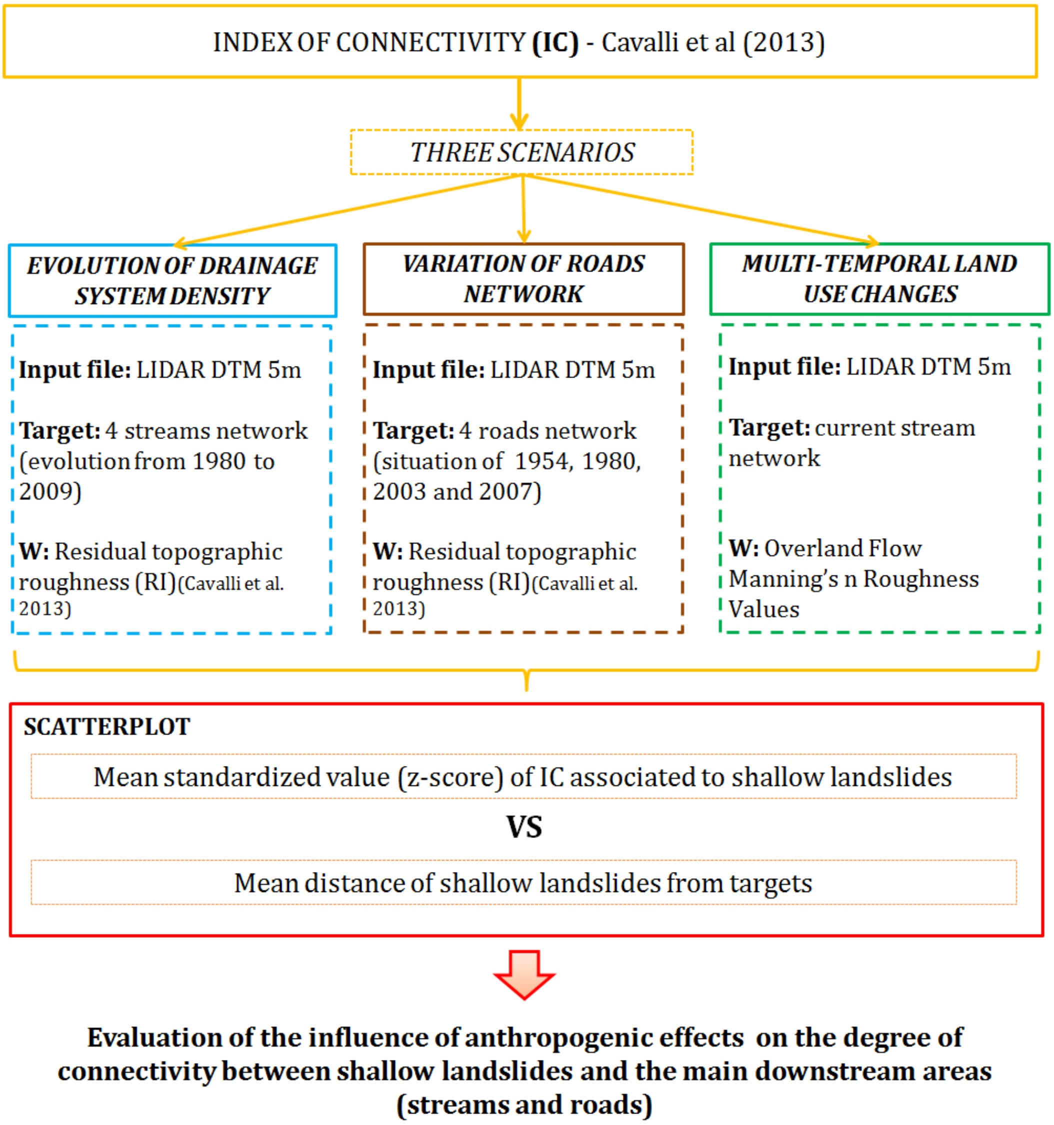

Figure 7. Scheme of the sediment connectivity analysis performed

After the extraction of the IC maps for each scenarios developed, the mean standardized value (z-score) of IC was associated to each individual shallow landslides, and compared with their mean distance from the downstream areas of each different

scenario. This analysis were performed taking into consideration the different extension and typology of the shallow landslides.
Finally, the variation of degree of connectivity between the sediment mobilized by the shallow landslides and the main downstream areas were evaluated, allowing to understand the influence of anthropogenic effects on the sediment delivery dynamics.

5 DATASET

To carry out this research were used remotely sensed data and field survey. In particular, the dataset is composed by the following data:

- Digital Elevation Models (DEMs) and LIDAR Digital Terrain Model (DTM)
- Orthophotos
- Land use and geology maps
- Shallow landslide inventories

5.1 DEMs, LIDAR DTM and orthophotos

Concerning the DEMs, for the Rio Frate, the Versa and Alta Val Tidone catchments DEMs at 10m were used. In addition, only for the first two catchments LIDAR DTM at 5m were available. The DEMs at 10 m were obtained by the Regional Technical Map (original scale 1:10000 ed. 1980-1994). Instead, the LIDAR DTM at 5m were made available by Ministry of the Environment and for Protection of the Land and Sea, following the realization of the Piano Straordinario di Telerilevamento Ambientale (Extraordinary Plan of Environmental Remote Sensing' - PST-A).
Only DEMs at 10 m were provided for the Pogliaschina and the Vernazza catchments. The DEM of Pogliaschina derived from the Regional Technical Map (original scale 1:5000 II ed. Regional Topography 3D/DB, 2007) with at 5-meter resolution resampled at 10 meters. The DEM of Vernazza catchment was realized using LiDAR data acquired in 2008 and 2010 by the Ministry for Environment, Land and Sea (Ministero dell'Ambiente e della Tutela del Territorio e del Mare, MATTM), within the framework of the 'Extraordinary Plan of Environmental Remote Sensing' (PST-A).
Detailed analysis on the sediment connectivity and the land use changes, in the Rio Frate and the Versa catchments, also necessitated the use of orthophotos. In particular, orthophotos of 1954, 1980, 2000, 2003, 2007, 2009 were utilized. The orthophotos of 1954 were acquired by "Gruppo Aereo Italiano" (Italian Aerial Group), with a

resolution of 0.5 m. Those of 1980, 2000, 2003 and 2007 were acquired by Lombardy Region, with a resolution ranging between 0.5 and 1.0 m. While, the orthophotos of 2009 were acquired by Ditta Rossi s.r.l. (Brescia, Italy) with a resolution of 0.15 m, after the shallow landslides event of 27-28 April 2009. The latter were also used for the comparison of the results with the field observations.

5.2 Land use and geology maps

For the Rio Frate, the Versa and the Alta Val Tidone catchments multi-temporal land use maps of 1954, 1980, 2000, 2007 and 2012 were available. These data are part of a tool for land use analysis and monitoring, which was developed for the Lombardy Region within the CORINE LAND COVER European Programme. In particular, the land use maps were provided by the Lombardy Region and shared as part of the Infrastructure for Spatial Information in Lombardy (IIT) via the Geoportal (http:// www.cartografia.regione.lombardia.it/geoportale). In particular, the map of 1954 is a historical land use map realized by the use of aerial photographs acquired by "Gruppo Aereo Italiano" (Italian Aerial Group), with a resolution of 0.5 m. The land use map of 1980 was obtained by digitization of land use cartography derived from photo interpretation at the scale 1: 50000 of TEM flight (Lombardia 1980-82, scale 1:20.000). The land use maps of 2000, 2007 and 2012 are included in the geographic database DUSAF (Destinazione d’Uso dei Suoli Agricoli e forestali - Intended Use of Soils Agricultural and Forestry), which was created in 2000-2001 as part of a project by the Directorates General of Territory, Urban Planning and Agriculture of Lombardy Region and realized by the Regional Agency for Development of Agriculture and Forestry (ERSAF) with the collaboration of the Regional Environmental Protection Agency of Lombardy (ARPA). The maps from 2000 were obtained from the photo interpretation of aerial images from 1998-1999 (Flight IT2000, built by Blom CGR - 1 m pixels). The land use maps from 2007 were realized by using colour and infrared orthophotos from IT2007 (made by Blom CGR - pixels 50 cm).

The map from 2012 was obtained by photo-interpretation of aerial photos realized by Agency for Disbursement in Agriculture (AGEA).

Moreover, detailed land use maps of 1954, 1980 and 2009 were realized, in the Rio Frate catchment, by the visual interpretation of the orthophotos of 1954, 1980 and 2009, in order to obtain information also on the main agricultural practices of the area.

The land use maps available for the Pogliaschina catchment were those of 1960, 2000 and 2012, while for the Vernazza were available the land use maps of 1960, 2009 and 2011. The land use map of 1960 is part of the “Carta dell’utilizzazione del suolo d’Italia” at scale 1:200000 realized by CNR and the Italian Touring Club during the period 1956-60. The land use maps of 2000 (scale 1:25000) was realized by photo-interpretation of aerial photos at scale 1:13000, while the maps of 2009 and 2012 (scale 1.10000) were realized by photo-interpretation of remote sensing images at high resolution (QuickBird 2004-2007, WORD VIEW2 2012 - http://old.regione.liguria.it/). Whereas, the land use map of 2011, available for the Vernazza catchment, it was expressly prepared through analysis of high-resolution aerial photographs and field surveys (Cevasco et al. 2013a). The air photo analysis was carried out on digital georeferenced orthophotos provided by Liguria Regional Administration, taken by the Air Service of Remote Sensing and Monitoring of Civil Protection of Friuli Venezia Giulia Regional Administration (11 November 2011 flight; ground resolution of 3 cm to 50 cm, depending on altitude).

Concerning the geological maps, for the Rio Frate, the Versa and the Alta Val Tidone catchments, they were realized by the Department of Earth and Environmental Sciences of University of Pavia by means of field surveys. The geological map of the Pogliaschina catchment (scale 1: 10000) was born from the union of the surveys carried out by Abbate et al. (1969, 2005), Bortolotti et al. (2011), Puccinelli et al. (2015a).The geological map of Vernazza catchment derives from the CARG project (original scale 1: 25,000 – Regione Liguria, 2006).

5.3 Shallow landslides inventories

Regarding the shallow landslides inventories, in the Rio Frate, the Versa and the Alta Val Tidone catchments, they are referred to the event occurred in the 2009 (Rio Frate and Versa catchments), 2013 (Versa catchment) and 2014 (Alta Val Tidone catchment). Post-event colour aerial photographs at a resolution of 0.15 m (photo scale of 1:12000), which were obtained from an aero-photogrammetric survey that was performed by the company Rossi s.r.l., were used to map existing landslides from the 2009 event (Zizioli et al. 2013). The shallow landslides that occurred in 2013 were recorded by means of Pleiades satellite images. PLEIADES triplets from an evaluation program that was organized by AIRBUS Defence & Space (PUG 47 / P.I. Claudia Meisina UNIPavia) were used in a stereo analyst environment to investigate the post-event status and detect the shallow landslides' location by visual interpretation (Zizioli et al. 2014). Google Earth images were also used alongside field surveys for the shallow landslides from 2014 to analyse areas that were not covered by aerial reliefs.

The shallow landslides recorded were subdivided according to their typology. In particular, five typologies were identified, according to the Cruden and Varnes (1996) classification: a) Incipient translational slides: where fractures are present but the displaced mass has limited movement with little internal deformation; b) Translational soil slides where the mass has moved, the failure surface is completely exposed and the collapsed materials break into different blocks; b2) Roto-translational slides: generally develop in the presence of a road cut; c) Complex landslides which start as shallow roto-translational failures and then evolve into earth-flows due to the large amount of water and the fabric loss of collapsed materials; d) Disintegrating soil slips: similar to type c) but in which the accumulation zone is not recognizable because the collapsed materials are completely dispersed along the slope and at its toe.

In the Vernazza and Poglischina catchments the landslide inventories correspond to the event of 25 October 2011. The inventories were obtained by means of the analysis of post-event aerial photographs, digital georeferenced ortophotos (both provided by Liguria Regional Administration) and detailed field surveys. The aerial photos belonged to BLOM C.G.R.S 28 October 2011 flight while the orthophotos (with a ground resolution of 3 to 50 cm, depending on altitude) belonged to a flight taken by the Air Service of Remote Sensing and Monitoring of Civil Protection of Friuli Venezia Giulia Regional Administration on 28 November 2011. For what concern the Vernazza catchment, we referred to the inventory available from Cevasco et al. (2013). In the Pogliaschina catchment, the Google Earth images were also used in order to analyse areas not covered by aerial reliefs. In the Vernazza catchment most of the landslide phenomena occurred were classified as debris avalanches, while in the Pogliaschina catchment the they were classified as complex, translational debris slide-flow (Cruden and Varnes 1996; Hungr et al. 2001).

6 Shallow landslides susceptibility assessment in different environments

The following research paper was accepted for publication in the Geomatics, Natural Hazard and Risk Journal.

Shallow landslides susceptibility assessment in different environments

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ABSTRACT

The spatial distribution of shallow landslides is strongly influenced by different climatic conditions and environmental settings. This makes difficult the application of a unique monitoring technique able to correctly assess the landslides susceptibility in different environmental contexts.

In this work a unique methodological strategy, based on the statistical implementation of the Generalized Additive Model (GAM), was performed. In particular, the methodology applied allowed to investigate the predisposition to shallow landslides of four sites with different geological, geomorphological and land use characteristics: the Rio Frate and the Versa catchments (Southern Lombardy), the Vernazza catchment (Eastern Liguria) and the Pogliaschina catchment (Eastern Liguria).

A good predictive overall accuracy was underlined by AUROC measures, with values ranging from 0.76 and 0.82, and by the mean accuracy reached by the model (70-75%).

Moreover, the method showed an high flexibility, allowing to identify the most influent predisposing factors in the shallow landslide occurrence, according to the different

environmental characteristics of the investigated areas. In particular, detailed susceptibility maps were obtained, allowing the identification of the most shallow landslides prone-areas. Therefore, their integrated use with the landslide-triggering rainfall thresholds, may provide an innovative tool useful for the improvement of spatial planning and early warning systems.

Keywords: Shallow landslide susceptibility, Generalized additive methods, cross validation and bootstrap techniques, Eastern Liguria, Southern Lombardy

1 Introduction

Shallow landslides are phenomena triggered by rainfall events with short duration and high intensity or with long duration and medium-low intensity (Caine 1980; Giannecchini et al 2006, 2016). These phenomena affect soil of small thickness (generally less than 2.0 m), originating from the weathering of the bedrock (residual) and down slope transportation (colluvial). The rainfall-induced shallow landslides are usually characterized by the absence of incipient movement evidence and by high velocity of propagation, especially when the sliding soil portion flows like a fluid down the slope surface, reaching a velocity of more than 9 m/s (Campus et al. 1998; Montrasio and Valentino 2007). Moreover, despite the small soil volume involved, the shallow landslides can be densely distributed across territories, resulting particularly destructive when they evolve into debris flows (Hungr et al. 2001; Sidle and Ochiai 2006; Crosta et al. 2012; Hungr et al. 2014).

Due to the absence of warning signs from unstable landslide-prone areas, shallow landslides result very difficult to monitor. As a result, the most effective approach in the management of the territory to prevent such phenomena is the creation and use of tools for the spatial and temporal prediction of areas mostly prone to trigger landslides (Van Westen et al. 2008; Corominas et al. 2014). The evaluation of shallow landslides hazard, defined as the probability of occurrence of a potentially damaging landslides phenomenon within a given area and in a given period of time (Varnes 1984), is described by three concepts: magnitude, spatial location and time recurrence. The first refers to the intensity of the natural phenomenon which has influence on its behavior and destructive power. The second implies the ability to identify the place where the phenomenon may occur. The third refers to the temporal frequency of the event (Guzzetti et al. 1999). In particular, the quantitative hazard assessment is based on the landslide magnitude–frequency relation. Without the correct assessment of the expected annual frequency of landslide events of a given magnitude, a quantitative assessment of landslide hazard is not feasible. In this case, the problem can only be dealt with in terms of landslide susceptibility (e.g. spatial probability; Brabb 1984; Guzzetti et al. 2006; Corominas et al. 2014).

The landslide susceptibility gives information on the proneness to landsliding, in terms of initiation areas, on the basis of a set of relevant environmental characteristics. In particular, the main data layers required for landslide susceptibility are landslide inventory data, predisposing and triggering factors (Soeters and van Westen1996; Van Westen et al. 2008; Corominas et al. 2014). Of these, the landslide inventory is the most important, as it gives insight in the location of past landslide occurrences, as well as their failure mechanisms.

Therefore, the landslide susceptibility maps represent a powerful tool since they provide coherent information on potentially unstable slopes. However, the frequency or the time of occurrence of the future landslides are not assessed (Fell et al. 2008). In this context, the landslide susceptibility assessment can be considered the initial step towards the landslide hazard and risk assessment and the end product in land-use planning and environmental impact assessment, as well an important tool in early warning system techniques (Corominas et al. 2014).

The procedures available for the landslide susceptibility assessment can be grouped as based on knowledge-driven, data-driven or physically base methods. The first two are commonly used in regional hazard analyses, while the last one is used in site specific studies, in which the safety factor of the slopes is determined (Baeza and Corominas 2001; Corominas et al. 2014). For what concern the data-driven methods, they are quantitative approaches based on the principle that the landslides are most likely to occur under similar ground conditions of previous events (Varnes 1984).

Some of the most important advantages of these methods are their objectivity and their easily applicability at regional scale. Moreover, they allow to manage a large amount of predisposing factors simply derived from the elaboration of Digital Elevation Model (DEM), providing automatic and fast procedures coupled with detailed results also in case of lack of exhaustive data.

Among the data-driven approaches (Dai and Lee 2002; Chen and Wang 2007), multivariate analysis is one of the most sophisticated techniques for landslide susceptibility assessment.

In the multivariate analysis, slope failure is considered the result of interaction of several environmental factors, that can vary in space and time. In particular, in the multivariate statistical models, the landslides distribution are predicted through the estimation of the relation between the independent predisposing factors and response variables, namely information of previous landslide occurrence (e.g. landslides inventory maps) (Baeza and Corominas 2001). Multivariate analysis allows the estimation of the relative weight of each contributing factor by means of statistical procedures such as multiple regression or discriminant analysis.

An important statistical improvement was the advance in regression analysis, provided by Generalized linear model (GLM) and Generalized Additive Model (GAM, Hastie and Tibshirani

1990). The GLM is a well established tool for landslide susceptibility modelling and represent a flexible generalization of ordinary linear regression analysis (Brenning et al. 2015).

However, linearity is unrealistic in many environmental modelling situations (Brenning et al. 2015). In the case of geomorphic processes related to landslides occurrence, this nonlinearity can be observed when an hillslope became unstable, as a consequence of changing in multiple hydrological, geomorphological and climatic conditions, which lead to a progressive transformation and movement of slope material (Goetz et al. 2011). This nonlinearity opens up a variety of possibilities for complex behaviours that are not possible in linear system (Phillips 2002, 2006), so the use of linear approaches may limit the modelling predictive performance.

For this reason, recently, nonlinear regression techniques, such as the GAM, have been applied to landslide susceptibility modelling and hazard zonation (Brenning 2008, 2015; Jia et al. 2008; Goetz et al. 2011; Petschko et al. 2014). In particular these new researches highlighted the better predictive performance obtained with the use of the GAM rather than with the GLM method (Goetz et al. 2015). This differences was especially related to the inability of the GLM to represent non linear relationship, leading to important local bias in predicted landslide susceptibility. These confirmed the GAM ability to describe the complex nonlinear processes characterizing the relationship between the landslides occurrence and the independent predisposing factors.

Starting from these important advancements, the aim of this research was:

(1) to develop a unique methodology strategy, based on the use of the GAM, characterized by simplicity, reproducibility and predictive efficiency in order to guarantee its application in different environmental contexts;

(2) to identify the most influent predisposing factors in the shallow landslide occurrence, according to the different environmental characteristics.

The performed methodology provided also the use of the 25% upper part of landslides as initiation area, allowing the implementation of an automatic approach for the source area extraction, developed by Galve et al. (2015), by the simple use of landslide polygons and the digital elevation model (DEM).

In particular, the GAM methodology was applied to four study sites, which recently were affected by widespread rainfall-induced shallow landslides: the Rio Frate and the Versa catchments (Oltrepo Pavese, Southern Lombardy), the Pogliaschina catchment (Vara Valley - Eastern Liguria) and the Vernazza catchment (Cinque Terre - Eastern Liguria). These four sites are characterized by different geological, geomorphological and land use settings.

2 Study areas

In order to develop a unique methodology strategy and applicable to different geographical settings, four shallow landslides prone-areas, characterized by different geology, geomorphology and land use, were selected.

The areas under investigation are localized in the northwestern Apennines sector and they are (Figure 1): the Rio Frate (1.9 km^2) and the Versa (38 km^2) catchments, situated in the Oltrepò Pavese (southern Lombardy); the Pogliaschina catchment (25 km^2) located in the Vara Valley

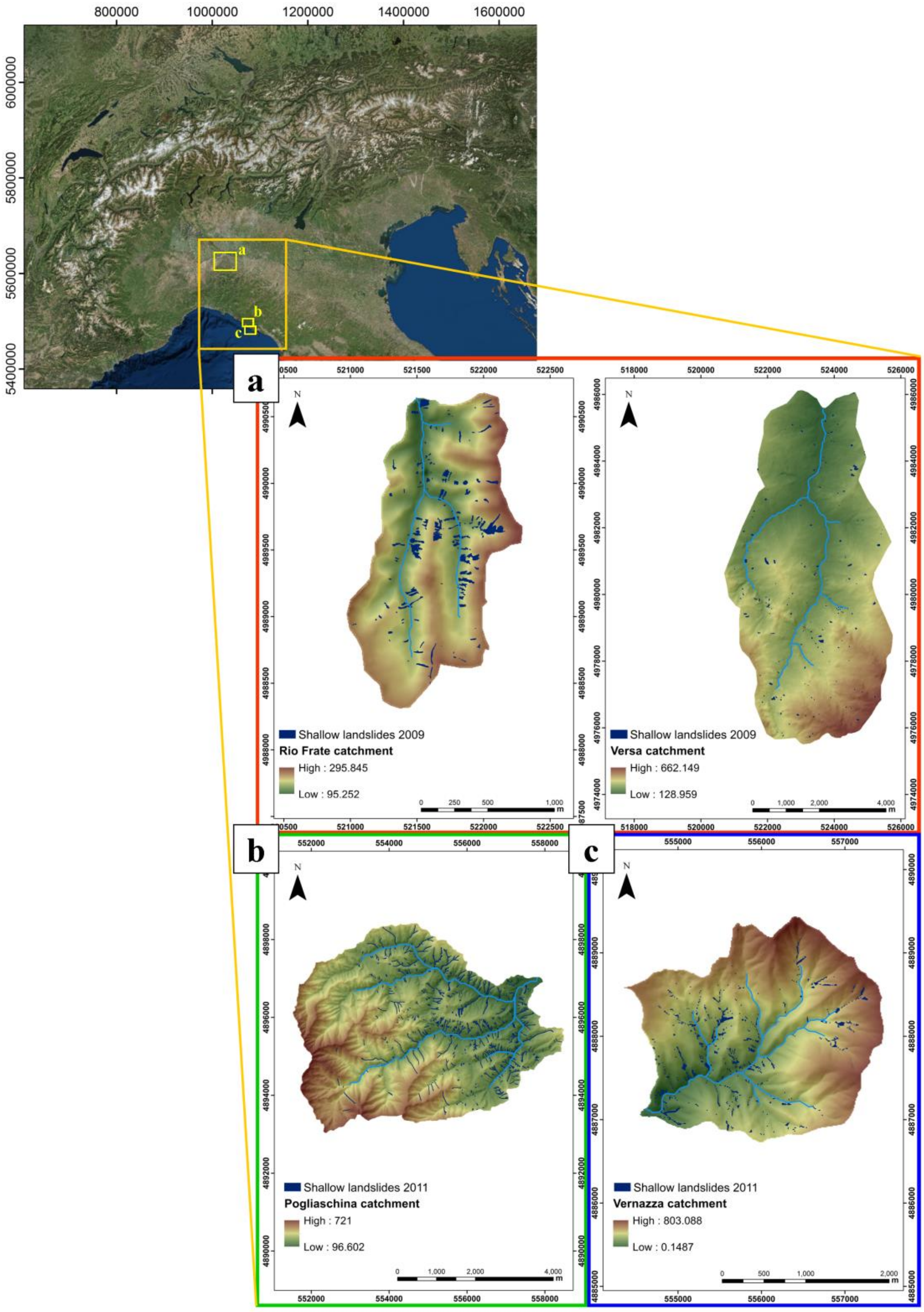

Figure 1. *a)* Upper left the Rio Frate catchment; Upper right the Versa catchment; *b)* Pogliaschina catchment; *c)* Vernazza catchment.

(Eastern Liguria); the Vernazza catchment (5.7 km^2) located along the Tyrrhenian side of Eastern Liguria.

Specifically, the Rio Frate, the Vernazza and the Pogliaschina catchments are characterized by very steep slopes and hard rock units, namely arenaceous conglomeratic bedrock, sandstone–siltstone flysch, sandstone-claystone flysch and pelitic complex, respectively. They were interested by different shallow landslides typologies. In particular, the Rio Frate catchment was mostly affected by roto-traslational slides evolving into earth flow, while the Pogliaschina and Vernazza catchments have been completely affected by complex, translational debris slide-flow and debris avalanches. Concerning the land use, the Rio Frate and the Vernazza catchments were characterized by a high percentage of abandoned land, previously cultivated with vineyards and terraced vineyards/olive groves respectively, while the Pogliaschina was characterized by a slight reduction of agricultural areas replaced by woodland.

Instead, the Versa catchment is mostly formed by flysch with clay component, slope relatively uniform with medium-low topographic gradient, and characterized by intensively cultivated areas, especially vineyards. This area was mainly affected by roto-translational slides that evolve into earth flow as in the Rio Frate catchment.

The four study catchments were recently affected by widespread of rainfall-induced shallow landslides: on 27-28 April 2009 the Rio Frate and Versa catchments and on the 25 October 2011 the Vernazza and Pogliaschina catchments. All shallow landslides used in the landslide susceptibility assessment belong to the landslide inventories associated to these specific triggering events.

2.1 Rio Frate catchment

Rio Frate catchment (Figure *2a*) has an extension of about 1.9 km^2 and its elevation is between 95-295 m a.s.l. The slopes have medium-high gradient, which can reach values higher than 35°, and they finish in narrow little valleys, formed by creeks of limited extent, ranging between 55 to 348 m^2.

In this area the bedrock is characterised by a Mio-Pliocenic succession called as "Serie del Margine" (Vercesi and Scagni 1984). In particular, medium low-permeable arenaceous conglomeratic bedrock (Monte Arzolo Sandstones, Rocca Ticozzi Conglomerates) overlies impermeable silty-sandy marly bedrock and evaporitic chalky marls and gypsum (Sant'Agata Fossili Marls, Gessoso-Solfifera Formation). The superficial soils, derived by bedrock weathering, are mainly clayey-sandy silts and clayey-silty sands. The soil thickness ranges between a few centimetres to less than 2.0 m.

The Rio Frate catchment was interested by a significant modification of its land use in the last 60 years. Specifically, from 1954 to the present, the area was characterized by an increasing of abandoned land, previously cultivated by vineyards. The current land use is represented by vineyards (26%) and woodlands (44%), mostly derived from the abandonment of past vineyards especially after the 1980s.

This area was affected by an high number of shallow landslides during the event occurred in 27-28 April 2009 (Zizioli et al. 2013). The shallow landslides were triggered in consequence of a rainfall event characterized by 160 mm of cumulated rainfall in 62 h (20% of the mean annual rainfall of 1921–1979 period, 25% of the yearly average amount of 2004–2013 period) with a maximum intensity of 22 mm/h (from 18:00 to 19:00 UTC) on 27th April (Zizioli et al., 2013).

In particular, 245 shallow landslides were recorded. They were characterized by an average length of about 35 m and their area of extension varied from a minimum of 13 m^2 to a maximum of 6289 m^2, with an average of about 473 m^2. The slide surface depth was included between 0.90 m and 1 m (table 1).

The shallow landslides recorded during these events were classified according to Cruden and Varnes (1996) classification. Most of them were classified as roto-translational slides evolving into flows, with width/length ratio > 1.

2.2 Versa catchment

Versa catchment (Figure *2b*) covers an area of about 38 km^2, with altitude ranging between 128 and 662 m a.s.l. The slopes have a low-medium gradient, with values commonly ranging between 15 and 25°. The area is characterized by a bedrock of age ranging from Cretaceous to Miocene. It has a predominant clayey-marley component, constituted by flysch deposits (Ranzano Sandstones, Monte Piano Marls, Val Luretta Formation). Above the bedrock, soils have especially a clayey texture and their thickness can reach values higher than 3-4 m.

In the Versa catchment an important modification of agricultural practices occurred after 1954: sowed areas were substituted by vineyards, representing now the most widespread cultural practice (65%).

196 shallow landslides were triggered during the event of 27-28 April 2009. The triggering event was the same occurred in the Rio Frate catchment (160 mm of cumulated rain in 62 h). The shallow landslides were characterized by an average length of 48 m and they reached an area of extension included between 6 m^2 and 8098 m^2 , with an average extension of 491 m^2. The slide surface depth varied between 0.90 m and 1 m (table 1). Also in this case, the shallow landslides recorded were classified according to Cruden and Varnes (1996) classification and most of them were classified as roto-translational slides evolving into flows, with width/length ratio > 1.

2.3 Pogliaschina catchment

The Pogliaschina catchment is located in the Northern Apennines in the Vara Valley (figure 1). It is 25 km^2 wide and has a maximum altitude of about 720 m a.s.l., while the valley bottom is about 95–100 m a.s.l. The slope are characterized by high gradient, since they can reach values higher than 45°. The bedrock is mainly composed of medium and coarse quartz-feldspathic sandstone turbidite (Macigno Fm.; Tuscan *Nappe* Unit) and quartz-feldspathic greywacke sandstone-siltstone turbidite (Arenarie di Monte Gottero Fm.; Gottero Unit) and is covered by a soil thickness ranging from 0.5 to 1.5 m. From a tectonic point of view, Vara Valley occupies a depression separated from La Spezia Dorsal to the west and from M. Picchiara-M. Cornoviglio Dorsal to the east, that originated from the combination of two main tectonic phases associated with the Northern Apennine chain formation (Raggi 1985; figure *2c*).
Vegetation is mainly represented by woodland, characterized by hardwood (mostly chestnut trees), coniferous (principally maritime pines) and mixed hardwood and coniferous forests (93% of the whole basin). Vineyards, olive groves and other plantations occupy about 6% of area (D'Amato Avanzi et al. 2014). This agricultural areas, from 1960, have been affected by a small reduction (9%) and further substituted by scrublands and shrubbery.
On 25 October 2011, a total rainfall of 538.2 mm in 24 h was recorded by the Brugnato rain gauge, with a rainfall intensity of 143.4 mm/h (from 13:00 to 14:00 UTC) and up to 108,1 mm/h in 6 h (from 9:00 to 15:00 UTC; D'Amato et al. 2014). A total of 658 shallow landslide were mapped, 569 of which were classified as complex, translational debris slide-flow (Cruden and Varnes 1996). They were usually superficial (0.3-1.5 m thick), linear (width/length ratio 0.03-0.5) and involved mostly coarse-grained soil and sometimes portions of fractured bedrock. 89 landslides were classified as roto-traslational slides (Cruden and Varnes 1996), with a small size and a width/length ratio > 1 (Bartelletti et al. 2015). The landslides area characterized by a minimum area of 50 m^2 and a maximum area of 18502 m^2 , with an average of about 1190 m^2. The average length of the landslides was approximately 95 m and their slide surface was localized at depth of about 1-2 m (table 1).

2.4 Vernazza catchment

The Vernazza catchment (Eastern Liguria, La Spezia province) is located along the Tyrrhenian side of the northern Apennines (figure 1). It is part of the Cinque Terre area, which was declared World Heritage Site by Unesco and included in the Cinque Terre National Park.
The bedrock is mainly composed of a sandstone-claystone flysch (Macigno Fm., upper Oligocene– lower Miocene?, Tuscan Nappe) and a pelitic complex (Canetolo Shales and Limestones, Canetolo Unit), which are part of a wide overturned antiform megafold whose axes strikes 150°N (Regione Liguria 2006; figure *2d*).

It shows typical geomorphological features characteristic for most of the Ligurian coastal catchments: small area (about 5.7 km^2), very steep slopes due to the proximity of mountains to the sea and short streams, often controlled by tectonics (Cevasco 2007), with considerable erosive power and capacity to transport sediment because of their steep profiles. More than 50% of the terrain gradient ranges between 30°and 40°.

Unusual land use conditions characterise the slopes within the Vernazza catchment (Cevasco et al. 2013a; 2014). Approximately 50% of these slopes, located in the middle and lower parts of the catchment, were terraced during the past millennium for vineyards and olive groves. Currently, only approximately 20% of the terraced areas are still cultivated, leading to increasing geomorphological instability in the last decades (Terranova et al. 2006; Brandolini, in press). In abandoned terracing, the dry stone walls retaining the terraces are in poor condition because of lack of maintenance. However, due to their old age, also the dry stone walls retaining terraced areas still cultivated do not guarantee the drainage of surface water. The upper part of the basin is characterised by woods and scrub lands. Due to reworking of debris covers for terracing, the soil thickness is greater on agricultural terraces (up to 2.5 m) than on woodlands (up to 1.5 m).

Whilst large rock landslides and rock failures are widespread on the coast of Liguria (Brandolini et al. 2007; Cevasco 2007; Carobene and Cevasco 2011; De Vita et al. 2012, Corradi et al. 2013), within the Vernazza catchment, due to its morphological features, shallow phenomena triggered by rainfall are prevalent (Cevasco et al. 2013a). In particular, on 25 October 2011, high-intensity rainfall affected the Cinque Terre area, triggering more than 500 rainfall-induced shallow landslides in the Vernazza catchment. A total rainfall of 382 mm was recorded in 24 hours along the coast by the Monterosso rain gauge located 3 km northwest of Vernazza. At Monterosso, rainfall intensities of 90 mm/h, 195 mm/3 h and 350 mm/6 h were recorded between 9:00 and 15:00 UTC (A.R.P.A.L.-C.F.M.I.-P.C. 2012; Cevasco et al 2014).

A total of 473 landslides were mapped. They were characterized by an average length of about 74 m. Moreover, their extent is ranging between 6 m^2 and 6307 m^2, with an average value of 322 m^2 (table 1). The slide surface depth varies according to the location of the landslides and the characteristics of the soil. In fact, the failure of eluvial and colluvial soils are located at a depth up to 1.5 m on woodland while the failure of artificially reworked deposits are located at a depth up to 2.5 m on terraced slopes (table 1; Cevasco et al. 2013b, 2014). The shallow landslides recorded were classified following the landslides classifications of Cruden and Varnes (1996) and Hungr et al. (2001). Most of the landslide phenomena that occurred on 25 October 2011 were classified as debris avalanches (Cevasco et al. 2014).

Table 1. The main morphometric characteristics of the landslide inventories of each study areas.

Catchment	N° landslides	Min Area (m^2)	Max Area (m^2)	Average Area (m^2)	Avarage Length (m)	Slide surface depth (m)
Rio Frate	245	13	6289	473	35	0.90-1
Versa	196	6	8098	491	48	0.90-1
Pogliaschina	658	50	18502	1190	95	1-2
Vernazza	473	5.5	6307	322	74	1.5 (on woodlands) 2.5 (on terraced slopes)

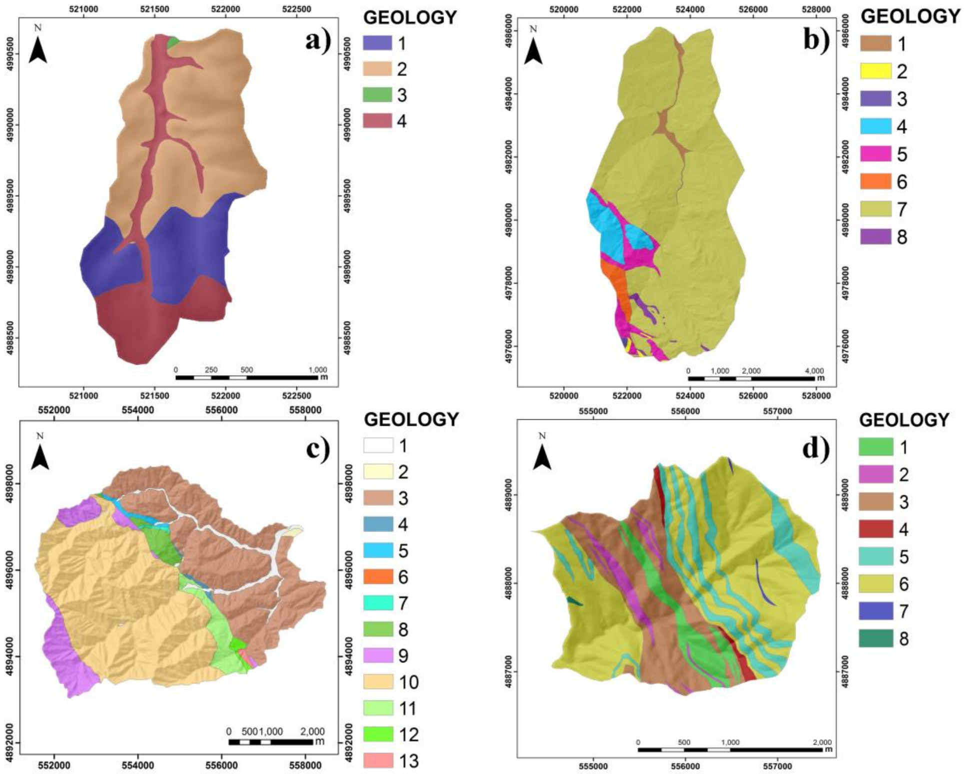

Figure 2. Geology maps: **a)** Rio Frate catchment: *1. Monte Arzolo Sandstones; 2. Rocca Ticozzi conglomerates; 3. Gessoso-Solfifera Fm.; 4. Sant'Agata Fossili marls;* ***b)*** Versa catchment: *1. Alluvial deposits; 2. Ranzano sandstones; 3. Ranzano sandstones (arenaceous lithofaces); 4. Ranzano sandstones (marly lithofaces); 5. Monte Piano marls; 6. Val Luretta Fm. (arenaceous lithofaces); 7. Val Luretta Fm. (calcareous lithofaces); 8. Varicolori clays;* **c)** Pogliaschina catchment: *1. Alluvial deposits (current); 2. Alluvial deposits (recent); 3. Monte Gottero sandstones Fm.; 4. Val Lavagna Fm.; 5. Argille a Palombini Fm; 6. Diaspri di Monte Alpe Fm.; 7. Gabbri Fm.; 8. Serpentiniti Fm.; 9. Canetolo clays and limestones; 10. Macigno Fm.; 11. Scaglia Toscana Fm.; 12. Maiolica Fm.; 13. Diaspri Fm.;* **d)** Vernazza catchment: *1. Ponte Bratica sandstones; 2. Groppo del Vescovo limestones; 3. Canetolo clays and limestones; 4. T. Pignone marls; 5. Macigno Fm.; 6. Macigno Fm. (sandstones lithofaces); 7. Macigno Fm. (silty-pelitic lithofaces); 8. Macigno Fm. (silty-marl lithofaces).*

3 Method

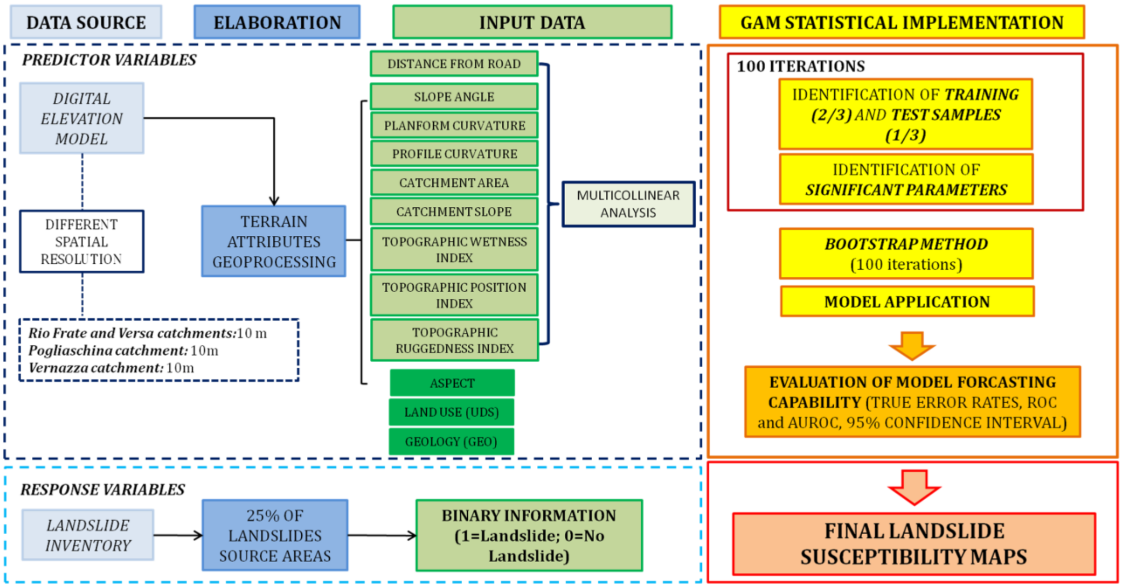

Figure 3. GAM methodology scheme.

The methodology, applied for the shallow landslide susceptibility assessment, is based on the application of a multiple regression model based on GAM (Hastie and Tibshirani 1990).
The procedure for the data analysis is made of two phases (figure 3):

1) Pre-processing of input data in order to extract a list of predictive variables
2) Statistical implementation of GAM

3.1 Pre-processing of input data

3.1.1 The predictors variables. During the pre-processing phase, 12 predictors variables were identified, according to their influence on shallow landslide mechanisms (table 2).
Nine different predisposing factors, representing morphological and hydrological parameters, were extracted by DEMs (digital elevation models) at resolution of 10 meters, through a set of tools implemented in SAGA GIS (System for Automated Geoscientific Analyses). All DEMs were antecedent to the shallow landslide events. The DEMs of the Rio Frate and the Versa catchments were obtained by the Regional Technical Map (original scale 1:10000 ed. 1980-1994). The DEM of Pogliaschina derived from the Regional Technical Map (original scale 1:5000 II ed. Regional Topography 3D/DB, 2007) with at 5-meter resolution resampled at 10 meters. The DEM of Vernazza catchment was realized using LiDAR data acquired in 2008 and 2010 by the Ministry for Environment, Land and Sea (Ministero dell'Ambiente e della Tutela del Territorio e del Mare, MATTM), within the framework of the 'Extraordinary Plan of Environmental Remote Sensing' (PST-A).

The geomorphic and hydrological attributes derived from DEM are the following (table 2): Slope (SL), Aspect (ASP), Planform curvature (PLA), Profile curvature (PRO), Catchment area (CA), Catchment slope (CS), Topographic wetness index (TWI), Topographic position index (TPI), Terrain ruggedness index (TRI). These parameters were selected according to their capacity to outline destabilizing factors (Montgomery and Dietrich 1994; Brenning 2008). In particular, their geophysical controls on slope stability represent their crucial role in several processes such as subsurface flow convergence, increased soil saturation and shear strength reduction (Goetz et al. 2011).

In addition to the DEM-derived predisposing factors, also the Euclidean distance from roads (RD), was calculated by using the streets network shapefiles available for each study areas. This variable was selected as predisposing factor since the shallow landslides inventories were composed also by landslides developed in correspondence of road. Land use (LU) and Geology (GEO) were also considered as predictors, according to their influence on shallow landslides mechanisms and spatial distribution (table. 2).

SL, ASP, PLA and PRO were calculated based on local polynomial approximations, according to Zevenbergen and Thorne (1987). SL is one of the most important factor, as it strongly controls the shear forces acting on hillslopes and the water distribution (Baeza et al. 2009; Catani et al. 2013). ASP can play a key role in landslide susceptibility, as it may have influence on the exposition of the terrain to different amounts of rainfall and solar radiation, thus conditioning the local temperature and evaporation and, consequently, the soil moisture and the vegetation growth (Van Westen et al. 2008; Demir et al. 2013). ASP was transformed from continuous into categorical variable to avoid the presence of No Data in correspondence of flat areas. PLA and PRO represent the topographic influence of local morphology on slope hydrology and soil erosion and deposition. In particular, PLA is the curvature of the surface perpendicular to the direction of the maximum slope which controls the convergence and divergence of topography and the sub-surface water flow. While PRO is the curvature of surface parallel to the direction of the maximum slope, which characterizes the near-surface acceleration or deceleration of flow down the slope, influencing the potential erosion or deposition rate and, consequently, the soil depth. (Dai et al. 2002; Goetz et al. 2011). CA and CS were derived using the multiple-flow-direction algorithm (Quinn et al. 1991). CA was then transformed to the natural logarithm in order to reduce skewness and used as proxy for soil moisture and soil depth (Brenning et al. 2015). The CS is another important factor which influences the intensity of the destabilizing forces upslope (Brenning et al. 2015).

TWI highlights the tendency of water to accumulate at any point in the drainage basin and the tendency of the water to move along a slope by the action of the gravitational forces, so that it can be easy correlated to the soil moisture content and the groundwater conditions (Seibert et al. 2007).

Table 2. Explanatory variables used in GAM analysis and their influences on shallow landslides triggering.

Variable	**Data source**	**Influence on shallow landslide mechanisms**
Slope (SL)	DEM	Affects the magnitude of the downslope driving forces and water distribution (Baeza et al., 2009; Catani et al 2013)
Aspect (ASP)	DEM	Having influences on solar radiation intensity, which controls the local temperature and evaporation and therefore soil moisture (Van Westen et al., 2008; Demir et al., 2013)
Planform curvature (PLA)	DEM	Divergent or convergent curvature: Influences on the water run-off concentration (Dai et al., 2002; Goetz et al 2011)
Profile curvature (PRO)	DEM	Concave or convex curvature: Influences on near-surface acceleration or deceleration of flow ; potential erosion or deposition rate (Dai et al., 2002; Goetz et al 2011)
Catchment area (CA)	DEM	Proxy for soil moisture and soil depth (Brenning et al., 2015)
Catchment slope (CS)	DEM	Influences on the intensity of the destabilizing forces upslope (Brenning et al., 2015)
Topographic wetness index (TWI)	DEM	Influences on the soil moisture content and the groundwater conditions (Seibert et al., 2007)
Topographic position index (TPI)	DEM	Proxy on the effects of the location of a point on a landscape to the shallow landslides occurrence (Weiss 2001)
Terrain ruggedness index (TRI)	DEM	Proxy to quantify the landscape heterogeneities (Riley et al., 1999)
Distance from roads (RD)	DEM	Influence on changing of hillslope geometry and hydrology (Devkota et al., 2013; Demir et al., 2013)
Land use (LU)	Land use database	Mechanical and hydrological effects of different vegetation types on slope stability (Tasser et al., 2003; Pereira et al., 2012)
Geology (GEO)	Geological database	Influence on the weathering of the bedrock and the resulting soils (Dai and Lee, 2002; Catani et al., 2005, 2013; Costanzo et al., 2012)

TPI provides a simple proxy to study the effects of the location of objects on a landscape. In the case of landslides, this allows to understand their localization in relation to the slope elevation. It was calculated by comparing the elevation of a cell to the mean elevation of the surrounding pixels in a ring buffer of around 1000 m radius (Weiss 2001). TRI, calculated as the sum of the change in altitude between a cell of the grid and its eight neighboring cells (Riley et al. 1999), was used to quantify the landscape heterogeneities, which could have effects on the localizations of shallow landslides triggering area.

RD was calculated by using the streets network shapefiles available for each study areas. This parameter has been successfully used in landslide susceptibility assessments as landslide predisposing factor (Devkota et al. 2013; Demir et al. 2013). Effectively, the construction of roads, which sometimes implies road cuts or fills and culverts, can lead to anthropogenic modification of the hillslope profile or drainage system.

LU and GEO were derived by means of GIS analyses from specific thematic maps. LU was used to consider the mechanical and hydrological effects of different vegetation types as well as the influence of terracing on slope stability (Tasser et al. 2003; Pereira et al. 2012). GEO allowed to represent the geomechanical and hydraulic properties of the bedrock and it influences the characteristics of the soil coverage (Dai and Lee 2002; Catani et al. 2005, 2013; Costanzo et al. 2012). In this case, the evaluation of GEO was carried out considering the different geological formations as reported on the available geological maps.In particular, for what concern the LU, in the Rio Frate and the Versa catchments the LU maps from DUSAF of 2007 (Lombardy Region) were used. This map was realized using color and infrared orthophotos IT2007 (made by Blom CGR - pixels 50cm). In the Pogliaschina catchment the LU map of 2012 (scale 1.10000) was utilized (Regione Liguria 2013). In the Vernazza catchment a detailed LU map was expressly prepared through analysis of high-resolution aerial photographs and field surveys (Cevasco et al. 2013a). The air photo analysis was carried out on digital georeferenced orthophotos provided by Liguria Regional Administration, taken by the Air Service of Remote Sensing and Monitoring of Civil Protection of Friuli Venezia Giulia Regional Administration (11 November 2011 flight; ground resolution of 3 cm to 50 cm, depending on altitude). Concerning the GEO variable, the geological maps of the Rio Frate and Versa catchments were realized by the Department of Earth and Environmental Sciences of University of Pavia by means of field surveys. The geological map of the Pogliaschina catchment (scale 1: 10000) was born from the union of the surveys carried out by Abbate et al. (2005), Bortolotti et al. (2011), Puccinelli et al. (2015).The geological map of Vernazza catchment derives from the CARG project (original scale 1: 25,000 – Regione Liguria, 2006).

3.1.2 The response variables. Detailed landslides inventory maps were prepared for all the study areas. In the Rio Frate and the Versa catchments, the inventory maps are referred to the shallow landslides event occurred on the on 27-28 April 2009. Post-event colour aerial photographs (18 May 2009) at resolution of 15 cm (photo scale of 1:12000), were examined. Detailed field surveys were also conducted to detect slope failures and to study landslide elements (e.g., scarp and body). Aerial photo interpretation, coupled with field surveys, allowed detecting about 245 shallow landslides in the Rio Frate catchment and about 196 shallow landslides in the Versa catchment.

In the Vernazza and Poglischina catchments the landslide inventories correspond to the event of 25 October 2011. The inventories were obtained by means of the analysis of post-event aerial photographs, digital georeferenced ortophotos (both provided by Liguria Regional Administration) and detailed field surveys. The aerial photos belonged to BLOM C.G.R.S 28 October 2011 flight while the orthophotos were the same used for LU map (taken by the Air Service of Remote Sensing and Monitoring of Civil Protection of Friuli Venezia Giulia Regional Administration on 28 November 2011). For what concern the Vernazza catchment, we referred to the inventory available from Cevasco et al. (2013a). In the Pogliaschina catchment, the Google Earth images were also used in order to analyse areas not covered by aerial reliefs.

All landslide inventories consist of polygons which delimit the whole landslide perimeter. A semi-automatic method, already used in Galve et al. (2015), was implemented to extract each landslide source areas. In particular, this procedure allowed to define the source areas by selecting the 25% of the pixels with the highest elevation in each landslides (figure 4*a*). The extracted landslide source areas were applied in GAM as the binary response variable, assigning 0 or 1 in case of landslide absence or presence, respectively.

The source areas automatically extracted were compared with those selected manually by visual interpretation of orthophotos. This analysis was useful to assess the uncertainty of the automatic procedure. The difference obtained is due to the transformation from vector data to raster format at 10 m resolution. This leads to an overestimation and underestimation of about 10 m due to the raster resolution used (figure 4*b*).

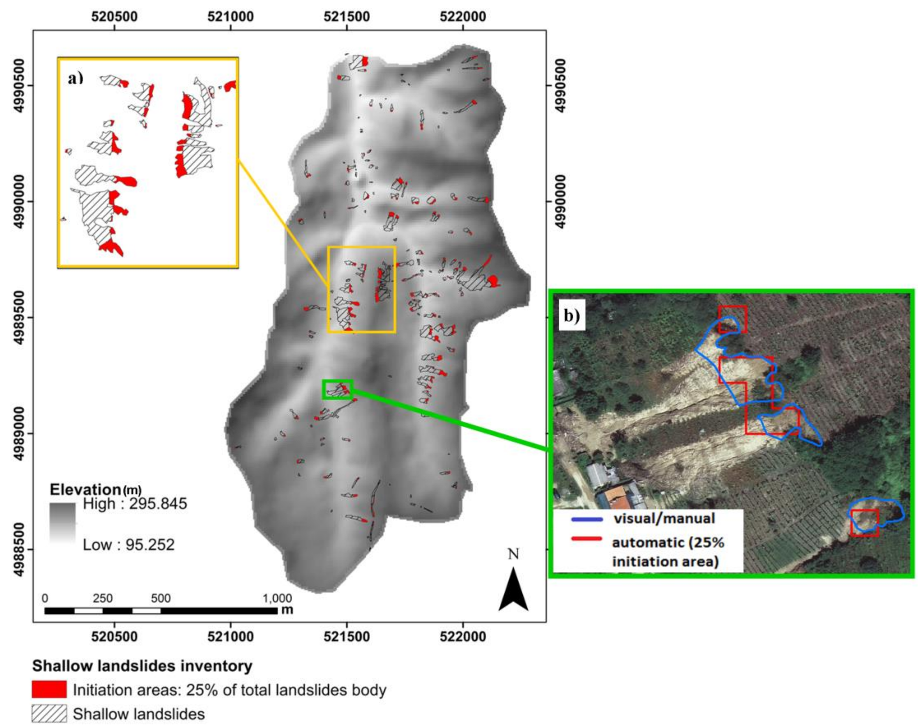

Figure 4. Source areas extracted for the shallow landslides event of 27-28 April 2009 in the Rio Frate catchment: *a)* example of 25% of total landslides body defined; *b)* comparison between the source areas automatically extracted in raster format and those selected manually by visual interpretation of orthophotos

3.2 Statistical implementation of GAM

The second phase of the developed methodology (figure 5) is referred to the implementation of the Generalized Additive Model (GAM, Hastie and Tibshirani 1990).

The GAM represents a semi-parametric extension of the generalized linear model (GLM). Its basic assumption is to replace the linear function used in a GLM, with an empirically fitted smooth function, in order to find the more likely functional form to fit the data (Hastie and Tibshirani 1990; Brenning 2008; Goetz et al. 2011). Specifically, it uses a link function to establish the relationship between the mean of the response variables and a sum of a group of smooth functions of independent variables, as shown in the equation 1 below (Jia et al. 2008):

$$g(\mu) = \sum_{i=1}^{n} f_i(x_i) \tag{1}$$

Where *g(μ)* is the link function and the $f_i(x)$ are smooth function (typically splines).

The GAM allows the combination of linear and nonlinear smoothing functions and the application of different modelling policies according to the characteristics of the predictor factors. This permit to better describe the complex relationship between independents and response variables (Petschko et al 2014).

The implementation of the GAM was provided by means of R software and the *R package 'gam'* (Hastie 2013).

The procedure adopted can be subdivided in the following steps:

(4) Multicollinear analysis to evaluate the dependence between the predictors variables and to avoid the violation of the basic assumptions of multiple regression models;

(5) Selection of the most significant parameters for the better description of the shallow landslides occurrence by using minimization of Akaike Information Criterion (AIC) and 100-fold bootstrap procedure of random selection of train and test data set to evaluate the model accuracy;

(6) Evaluation of model forecasting capabilities and shallow landslides maps extraction.

The first step in the GAM implementation was the application of a multi-collinear analysis. This procedure is fundamental, since the multi-collinearity represent a critical point in the application of multivariate analysis. Multicollinearity is an undesirable situation that occurs when the predictors variables (in this case landslides predisposing factors) are highly linearly related. Thus, the identification of this dependency is necessary to reduce redundancy and to improve numerical stability in the subsequent analyses (Farrar and Glauber 1967). This analysis was performed with the function *Colldiag*, available in the R package "*perturb*". This is an implementation of the regression collinearity diagnostic procedures found in Belsley et al. (1980). The procedure calculates the condition indexes of the matrix of the independent variables. The condition index greater than 30 or higher (as suggest by Belsley et al. 1980), indicates collinearity problems. All variables with large condition indexes were deeply investigated to provide further information useful to identify the source of these problems. In particular, the variance decomposition proportions associated with each condition index was computed. If large condition index (> 30) is associated with two or more variables with large variance decomposition proportions (equal or greater than 50%, as suggested by Belsley et al. 1980), these variables may cause collinearity problems. These predictors were excluded from the analyses in order to reduce collinearity.

In the second step, an equal number of non-landslide pixels has been appended to the landslide database to avoid an over-estimation of non-landslide areas, according to a general method described in Dai and Lee (2002); Ayalew and Yamagashi (2005); Duman et al. (2006) and Mathew et al. (2009). Thus, the entire database, consisting of all landslide pixels and the same number of randomly selected non landslide pixels, was subdivided into 2 subsets: the training and the test sets. The training set, representing 2/3 of the dataset, was used to build the GAM fitting the samples, while the test dataset, including 1/3 of the dataset, was used to estimate the model accuracy. The process of training and test random selection was repeated in a 100-fold bootstrap procedure. Then, the 100 fits have been used to extend the prediction to the whole areas in order to obtain a distribution of landslide probability for each pixel. The mean values of each bootstrap distribution of 100 probability values have been used to compute the landslide susceptibility maps. The 95 confidence interval of probabilities gives information about the reliability of the prediction.

In particular, the GAM is built using a stepwise variable selection. Starting from null model, each variable can be entered as linear (untransformed), nonlinear (non parametrically transformed predictor of two equivalent degrees of freedom), or not included in the model. The minimization of Akaike Informaton Criterion (AIC) is used as selection criterion (Brenning 2008; Guisan et al. 2010; Goetz et al. 2011). For instance, it may introduce some predictor variables as linear functions, while other ones as non linear smooth functions, well representing complicated relations between the variables, and providing high flexibility (Jia et al. 2008).

The process of training and data sets random selection was repeated in a 100-fold bootstrap procedure. This method allows to identify the most frequent predictors variables.

The parameters whose frequency was more than 80% in the bootstrap extraction were identified as the most influent and used to build the model. Among the selected predictors, the linear and non-linear were identified. The discrimination was based on the higher percentage of selection obtained. The selected parameters were used to build the model for the landslide occurrence prediction in all study area.

In the third step, the initially predictive accuracy was evaluated through a repeated holdout method for regression with a binary response, slightly modified with respect to the standard procedure (Maindonald and Braun 2010). Holdout method is the simplest kind of cross validation technique, allowing easy computational processes (McLachlan 1992; Molinaro et al. 2005). Specifically, the repeated holdout is a k-fold repetition of holdout method, which consists of a random subsampling of different training and test set, in proportion of 2/3 for testing and 1/3 for test. The repeated holdout method provides an estimate of the accuracy for each iteration. Unlike the standard holdout method separates the entire dataset into training and test sets, these two sets were the ones for the bootstrap model selection. The accuracy of the 100 different iterations were calculated in all training and test sets. The results were averaged to yield an overall accuracy and compared.

Another measure of the predictive performance was evaluated through the Receiver-Operating Characteristic (ROC) curve (Hosmer and Lemeshow 2000;). In particular, the area under the ROC curve (AUROC) was compute to evaluate the model ability to discriminate landslide and non-landslide location.

The ROC is calculated by plotting the sensitivity of a model (proportion of true positives) to the specificity (1-specificity, or false positives rate; Hosmer and Lemeshow 2000; Petschko et al. 2014). The AUROC (area under ROC) can takes values from 0.5 (no discrimination) to 1.0 (perfect discrimination; Brenning 2005).

Specifically, the mean value of the 100 AUROC samples obtained from the 100-fold bootstrap procedure was calculated. Also the bootstrap 95% confidence bands of ROC and bootstrap 95% confidence AUROC were obtained.

In the last step, the model forecasting capability was assessed and the shallow landslides susceptibility maps were extracted by extending the prediction of the model to all the study areas. The landslide probability and the bootstrap confidence interval were estimated for each pixels.

The final shallow landslides susceptibility maps were computed using the means of the landslides probability values, which represent an estimated conditional mean value of the landslide probability (Hosmer and Lemeshow 2000). A prediction uncertainty is associated to each estimated probability by computing the boostrap 95% confidence intervals.

The probability values were subdivided into 4 intervals in the susceptibility map: $0 \leq p \leq 0.25$, $0.25 < p \leq 0.50$, $0.50 < p \leq 0.75$, $0.75 < p \leq 1$.

This classification method considers the equal probability interval of 0.25 for each susceptibility class. A value of 0.5 represents the same probability of occurrence or not of landslide. The ranges $0 \leq p \leq 0.25$, $0.25 < p \leq 0.50$, $0.50 < p \leq 0.75$ and $0.75 < p \leq 1$ indicate a low, medium-low, medium-high and high probability of landslide occurrence, respectively.

4 Results

4.1 Collinearity analysis selection and identification of the significant explanatory variables

The collinearity test allows to exclude correlated variables from input data. In the Rio Frate, the Versa and the Pogliaschina catchments TRI and TWI were the parameters that caused collinearity problems. While, in the Vernazza catchment in addition to the last two parameters, also the CA was excluded. In order to reduce the collinearity and to improve numerical stability in the subsequent analyses, it was necessary to eliminate them from the successive elaborations.

The frequency of predictive variables selected by the 100-fold bootstrap procedure was calculated. The most significant variables were those selected by 80 % times (table 3).

In the Rio Frate catchment only SL (100) and ASP (87) were considered. The PRO and LU reached an high percentage (78 and 63 respectively), but under threshold of selection. In the Versa catchment, in addition to the SL (96) and ASP (80), also the CS (90) and LU (92) were taken into consideration.

In the Vernazza catchment the most influent predisposing factors are TPI, LU and GEO, with a frequency selection of 100, and ASP, that reached a frequency of 98. In the Pogliaschina catchment, the majority of the parameters reached a frequency of selection ranging between 99 and 100. In particular, the significant explanatory variables were: GEO, LU, SL, ASP, PLA and TPI.

PRO, CA and RD have never been selected as relevant explanatory variables in all the study areas, as they never reached a frequency of selection greater than 80% in the 100-fold bootstrap procedure.

Table 3. Absolute frequencies of explanatory variables (both linear and non linear) selected by 100-fold bootstrap procedure. NA: "not available" indicates parameters discarded by the multicollinear analysis. In bold red were highlighted the explanatory variables selected by 100-fold bootstrap procedure with an absolute frequency greater or equal than 80. SL: Slope; TPI: Topographic position index; PLA: Planform curvature; PRO: Profile curvature; CS: Catchment slope; CA: Catchment area; RD: Distance from roads; ASP: Aspect; LU: Land use; GEO: Geology.

Catchments	**SL**	**TPI**	**PLA**	**PRO**	**CS**	**CA**	**RD**	**ASP**	**LU**	**GEO**
Rio Frate	**100**	37	59	78	59	12	12	**87**	63	13
Versa	**96**	41	62	64	**90**	45	18	**80**	**92**	72
Pogliaschina	**100**	**100**	**100**	72	**99**	49	9	**99**	**100**	**100**
Vernazza	17	**100**	31	69	63	NA	3	**98**	**100**	**100**

The selected continuous explanatory variables were distinguished into linear or nonlinear. The discrimination was based on the higher percentage of selection obtained (table 4).

In the Rio Frate and the Vernazza catchments the parameters selected resulted all linear. Whereas, in the Versa and the Pogliaschina catchments only the categorical variables (ASP, LU and GEO) were defined as linear. The other continuous explanatory variables were all chosen as non-linear.

Table 4. Absolute frequencies of linear and non-linear selection for continuous explanatory variables. Each cell is split diagonally in two parts: in the right upper part and in left lower part are shown the frequencies of linear and non-linear choice of explanatory variables, respectively; The numbers highlighted in bold and italics are refer to the linear or non-linear type of explanatory variables that were chosen to build the model. NA: "not available" indicates parameters discarded by model (selection frequency lower than 80).

CHOICE OF LINEAR AND NON-LINEARCONTINUOUS EXPLANATORY VARIABLES				
EXPLANATORY / *CATCHMENTS*	***SL***	***TPI***	***PLA***	***CS***
Rio Frate	***52*** / 48	NA	NA	NA
Versa	30 / ***66***	NA	NA	43 / ***47***
Pogliaschina	19 / ***81***	28 / ***68***	**33** / ***72***	49 / ***50***
Vernazza	NA	***75*** / 25	NA	NA

4.2 Assessment of the predictive model performance.

The GAM performance was characterized by a good predictive capability, as demonstrated by the accuracy and AUROC values of the 100 different iterations. For each areas, both the mean and standard deviation of accuracy were computed in the training and test sets. They resulted very similar, with an absolute differences ranging between 0.01-0.1 (table 5).

A good predictive overall accuracy was also obtained by AUROC measure, with values ranging from 0.76 and 0.82. The extreme of 95% bootstrap confidence bands of AUROC were shown in table 5. It is possible to notice a small fluctuation of values. The best result was obtained in the Pogliaschina catchment case.

As showed in Table 6, very narrow 95% bootstrap confidence intervals of AUROC were obtained. Their maximum amplitude was about 0.03 in the Rio Frate, the Versa and the Pogliaschina catchment, while in the Vernazza catchment it was equal to 0.02. These results confirmed that ROC (figure 5) and AUROC variability of all 100 iterations was low in each study areas.

To investigate the reliability of landslide probability associated to each pixel, the 95% bootstrap confidence intervals of landslide probability were computed. The amplitude characterized each study areas is showed in Figure 8. By analyzing the maps (figure 6), it was possible to notice that the spatial variability of landslide probability is generally low in a large region of all catchments. The highest variability was observed in the Versa and the Pogliaschina catchments, where bootstrap confidence intervals amplitude of landslides probability reached values equal to 1 (figure 6*b*,6*c*). Respect to Versa, in the Pogliaschina catchment the high variability was represented by smaller and concentrated areas. On the contrary, Rio Frate and Vernazza catchments showed lower variability with a larger fluctuation of middle values belonging to bootstrap confidence intervals amplitude (figure 6*a*,6*d*). The overall results highlight that landslide probability associated to a large fraction of pixel is reliable.

Table 5. Mean and standard deviation of accuracy computed in the training and test sets.

Catchment	Mean Accuracy on training sets	Mean Accuracy on test sets	Standard deviation of accuracy on training sets	Standard deviation of accuracy on test sets
Rio Frate	0.70	0.68	0.03	0.03
Versa	0.74	0.70	0.02	0.03
Pogliaschina	0.75	0.74	0.01	0.01
Vernazza	0.72	0.70	0.01	0.02

Table 6. Mean AUROC values obtained averaging output of 100 iterations for each study area and 95% bootstrap confidence intervals of AUROC.

Catchment	MEAN AUROC	95 % CONFIDENCE INTERVAL OF AUROC
Rio Frate	0.77	0.75-0.78
Versa	0.76	0.74-0.77
Pogliaschina	0.82	0.82-0.85
Vernazza	0.76	0.74-0.77

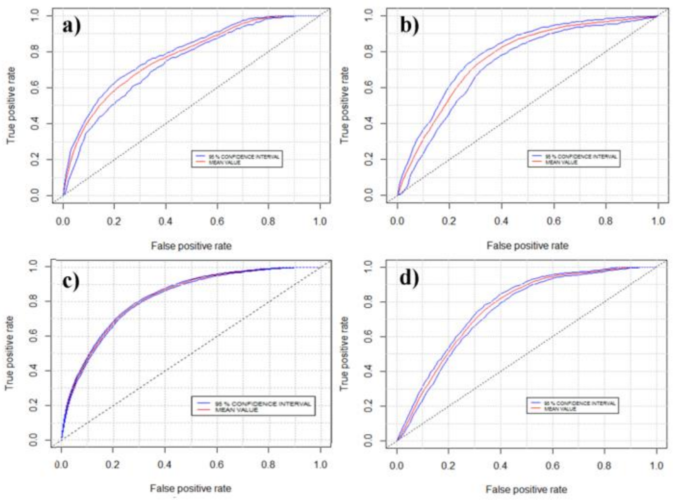

Figure 5. 95% bootstrap confidence bands of ROC: *a)* Rio Frate catchment; *b)* Versa catchment; *c)* Pogliaschina catchment; *d)* Vernazza catchment.

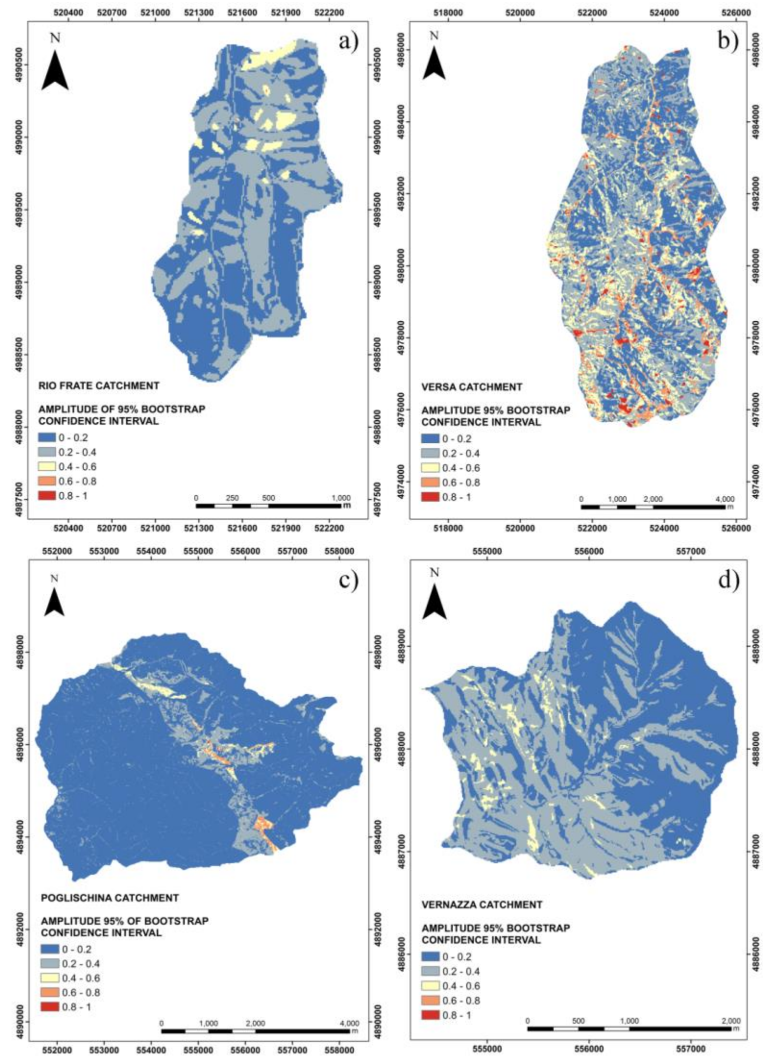

Figure 6. Maps of amplitude of 95% bootstrap confidence intervals of landslide probability: *a)* Rio Frate catchment; *b)* Versa catchment; *c)* Pogliaschina catchment; *d)* Vernazza catchment.

4.3 Shallow landslides susceptibility maps extraction

The shallow landslide susceptibility maps extracted by GAM model are shown in figure 7.

In the Rio Frate catchment, 62 % of the territory covers low and medium-low shallow susceptibility classes, while the remaining 38% falls into medium-high and high shallow susceptibility classes. (figure 7*a*). The highest shallow landslides susceptibility is localized in correspondence to very steep slopes (range between 24- 36°) and to East and South-West/West facing slopes.

In the Versa catchment, 66% of the area is classified with low and medium-low susceptibility, whereas the other 34% with medium-high and high (figure 7*b*). By comparing the shallow landslide susceptibility map with the more frequent parameters, it is possible to observed that the highest susceptibility is located in correspondence to areas with slope and catchment slopes comprised between 18- 27°.

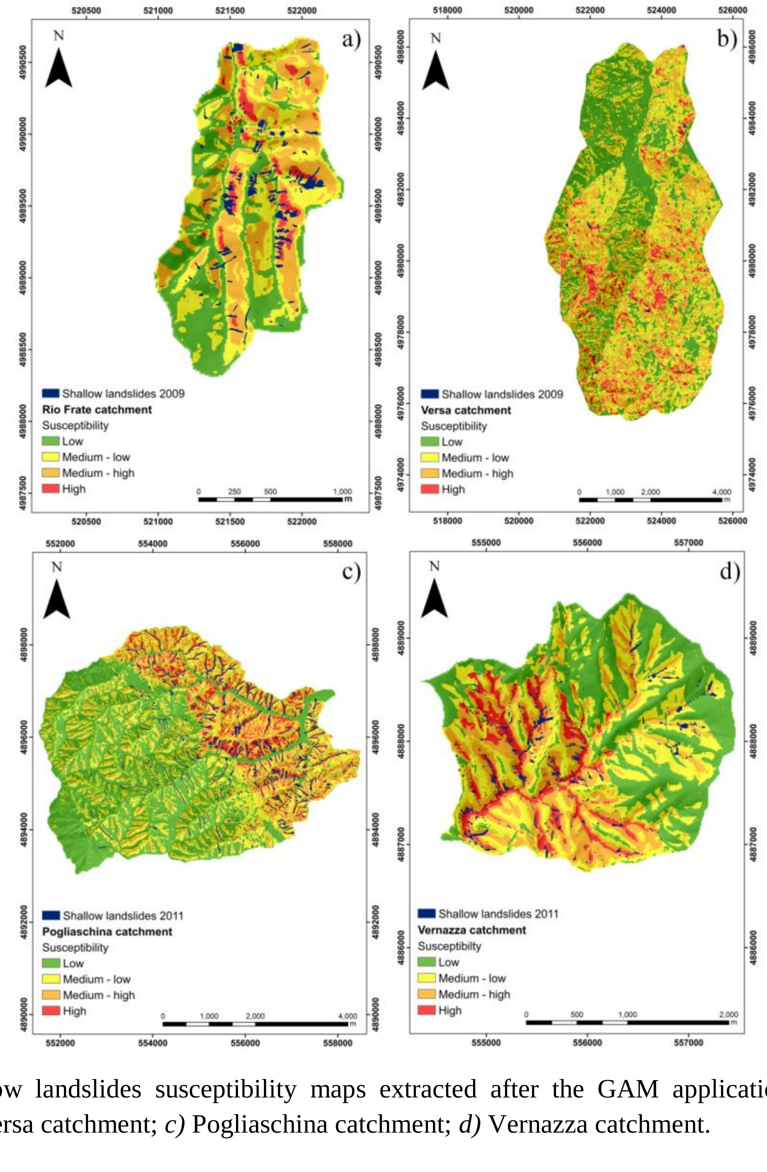

Figure 7. Shallow landslides susceptibility maps extracted after the GAM application: *a)* Rio Frate catchment; *b)* Versa catchment; *c)* Pogliaschina catchment; *d)* Vernazza catchment.

As in the Rio Frate catchment case, slope towards South-West/West are more susceptible to landsliding. In addition to the other geomorphological parameters, also the land use is very influent in the slopes instability. In particular, cultivated areas (e.g. vineyards) cover the highest shallow landslide classes.

In the Pogliaschina catchment, a lower extension percentage (27.7 %) of medium-high and high landslide susceptibility classes was obtained. Otherwise, 72.3 % of territory fall into low and medium low landslide susceptibility classes (figure 7*c*). It was found that concave slope, South-East and South facing slopes and arenaceus Formations were more susceptible to landslide.

In the Vernazza catchment, 36% of the territory is located in medium-high and high shallow landslide susceptibility classes, whereas the remaining 64% has a low and medium-low probability of instability (figure 7*d*). In this site, the land use is the most influent parameter in landsliding. By comparing the areas with high values of susceptibility and the land use map, it was possible to observe that slopes more prone to instability are situated in correspondence to terraced vineyard and especially abandoned terraced areas are particularly susceptible.

5 Discussion

This work is aimed to develop and test the capability of a comprehensive data-driven methodology, based on GAM statistical technique, in order to assess the shallow landslides susceptibility of areas with different geological, geomorphological and environmental features.

In literature, data-driven methodology have been often applied in single areas, without investigating the predictive powerful of method in heterogeneous contexts (Guzzetti et al. 2006; Goetz et al. 2011; Galve et al. 2015). In this work, an innovative method for the evaluation of shallow landslide susceptibility of four different study areas was developed. This methodological strategy was able to identify the main geomorphological, hydrological, geological and land use parameters controlling shallow landslide occurrence, according to the characteristics of each investigated areas. .

The investigation of the most important predisposing factors could lead to improve the knowledge about mechanisms which regulate landslide occurrence. To this purpose, the collinearity analysis and 100-fold bootstrap techniques were found to be objective tools to select the most influential parameters.

Moreover, instead of using a single initiation point located in the upper part of landslide as response variable, the introduction in the model of the landslide source area (25 % of the total landslide area) by means of an automatic procedure allowed to better characterize the detachment area. In addition, it allowed to reduce the spatial data quality degradation derived from the transformation from vectors to raster. The degradation is in connection with pixel size resolution, which could lead to a wrong characterization of shallow landslide initiation zone. At the size resolution of 10 meters, a single initiation point could almost entirely include portion of area outside landslide perimeter during the process of conversion from vector to raster. Anyway, at this size resolution, also using 25 % of the total landslide area revealed some problems. In case of landslide of reduced dimension, an overestimation of landslide initiation area occurred, wrongly including part of the accumulation area. Fortunately, small size landslides were few.

As regards the model accuracy, the good forecasting capability of GAM was confirmed by high values of accuracy.

Nevertheless, the worst results were obtained in the Rio Frate catchment. In this case the GAM wasn't completely able to identify roto-translational slides developed in correspondence of road cut scarps. This is due to the spatial resolution of data source used for the analysis. In fact, working with a cell size of 10 m the model is not able to obtain enough detail at the building scale. Moreover, the model did not take into account the RD parameter during the processing, failing to represent all the terrain conditions that may affect landslide occurrence. This lack of information could lead to a misleading analysis of those areas where local peculiar factors may have given a contribute to slope instability (figure 8).

In the Rio Frate catchment case, the parameter that mostly contribute to generate shallow instability was slope. It was selected 100 times in the bootstrap repetitions. By analysing the landslide-slope class distribution, it was notice that the majority of shallow landslides occurred on very steep slope, which can reach values higher than 35°. Also in the Versa catchment the most susceptible areas were located in correspondence of steep slope, in particular with slope angle higher than 17°. In addition, it was interesting to notice that the most susceptible slopes are exposed toward South-West/West. As observed by other authors (Van Westen et al. 2008; Demir et al. 2013), the slope direction reflects differences in rainfall amount, solar radiation and soil moisture conditions , which could favor differently the landslide triggering.

In the Versa catchment, in addition to the geomorphological parameters, also the cultural practices, related to the land use, were influent in shallow landslides occurrence. In particular, the vineyards were the land use class most affected by the highest probability to landsliding. This fact was confirmed by the landslide inventory related to the 27-28 April 2009, where the majority of shallow landslides were located within cultivated areas (mostly vineyards; 55%).

In the Vernazza catchment, land use played an important role on shallow landslide susceptibility.

As already observed by Cevasco et al. (2014) and Galve et al. (2015), the shallow landslides susceptibility tends to increase in abandoned terraces (with poor vegetation cover) and thus also for terraces which have been abandoned for a long time (with dense vegetation cover). The lowest values of susceptibility were found in wood and scrub land. This fact highlights that the increase of susceptibility is predominant in correspondence of areas characterized by land abandonment. Effectively, in the Vernazza catchment, from 1960 to 2011, strongly modification of agricultural practices occurred.

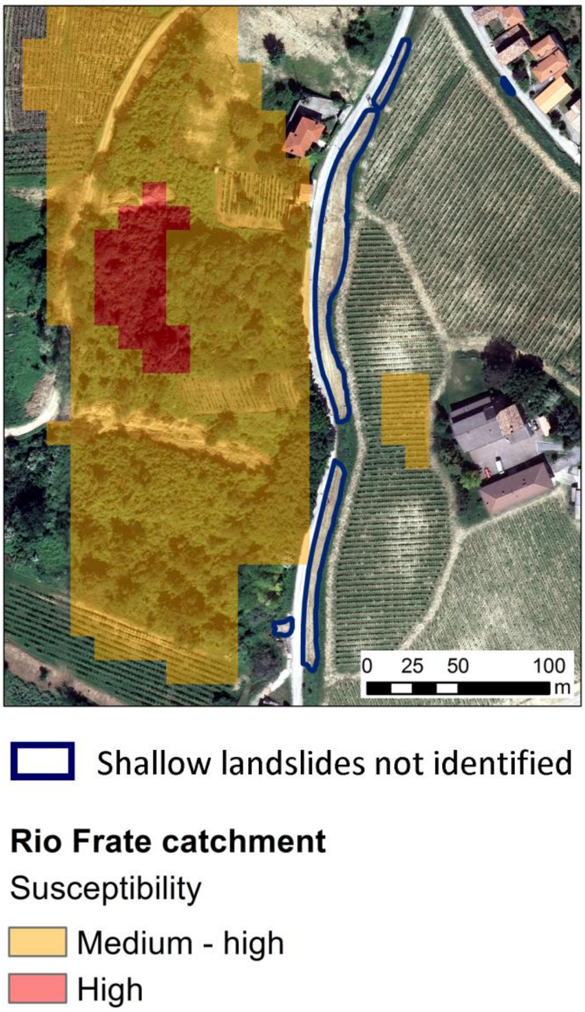

Figure 8. Example of areas within Rio Frate catchment where the model has not correctly predicted the presence of roto-translational slides developed in the road cut scarps. The aerial photograph of the area was taken by Ditta Rossi s.r.l. (Brescia, Italy) on May 18th 2009.

An high percentage of terraced areas, especially cultivated with vineyards and olive groves were abandoned. On 25 October 2011, most of the landslides occurred in correspondence of abandoned terraces. This probably attributable to the fact that the lack of maintenance of the dry-stone walls could be a primary factor favouring instability phenomena (Cevasco et al. 2013a; Galve et al. 2015).

In the Pogliaschina catchment, despite the land use resulted important during the GAM application, the influence of geomorphological parameters and the geology on the GAM predictive performance is high. Slope and planform curvature are the most relevant parameters. As regard the geology, the highest susceptibility was identified in correspondence of arenaceus rock formations.

6 Conclusion

The proposed methodology, developed by means of a nonlinear regression technique (GAM), lead to assess the shallow landslide susceptibility in different environmental contexts. In particular, it was able to characterise the predisposition to shallow landslide of four territories with different geological, geomorphological, land use characteristics and shallow landslides typologies.

Moreover, the use of initiation area represented by 25% of the total landslide area as response variable instead of a single point, seems to reduce the time consuming of computational analyses and the spatial data quality degradation caused by data transformations from vector to raster. Moreover, it enabled to guarantee the correct investigation of the detachment area.

In this work, the use of landslide inventories referred only to a single event has represented the major limitation. In absence of multi-temporal landslide databases, we randomly partitioned the entire dataset into two parts (testing and test subsets) within a 100-fold bootstrap procedure. The model accuracy was carried out for each bootstrap sample comparing results of train subset and test subset (landslide pixels not used to fit the model).

Despite this limit, the GAM performance was characterized by a good forecasting capability, as demonstrated by the accuracy and AUROC values of the 100 different iterations. In particular, a good predictive overall accuracy was underlined by AUROC measure, with values ranging from 0.76 and 0.82 with the mean accuracy reached by the model, ranging between 70-75%.

In conclusion, the novelty of this work is to present a processing chain characterized by simplicity, reproducibility and predictive efficiency in the assessment of landslides susceptibility of different territories, despite the influence of different climatic conditions and environmental settings. In particular, this methodology allowed to identify the main geomorphological, hydrological, geological and land use predisposing factors controlling shallow landslide occurrence, according to the characteristics of each investigated areas. The selection of the most significant parameters provided a better description of the shallow landslides occurrence and distribution.

Moreover, the utilization of input data simply derived from DEM allow to obtain good level of accuracy and predictive efficiency also in case of lack of exhaustive information. This could permit the use of this methodology also in contexts where is difficult to obtain effective monitoring tools.

In particular, in the future development, the presented methodology will be applied also in monsoon-influenced areas where, despite the high vulnerability that characterizes these areas, there are still lack of comprehensive study about the landslide susceptibility assessment. This will permit to deeply assess the flexibility and repeatability of the developed processing chain, comparing the results with those obtained from the study areas analysed in this research and characterized by climatic, geological and geomorphological conditions completely different from tropical areas.

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7 The role of human activities on sediment connectivity of shallow landslides

The following research paper was submitted to Catena journal

The role of human activities on sediment connectivity of shallow landslides

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ABSTRACT

Sediment connectivity within a catchment depends largely from the morphological complexity of the catchment and the effects of anthropogenic modification of the landscape. Understanding the relationship between sediment connectivity and spatio-temporal landscape changes provides a valuable tool to evaluate the probability for a local on-site effect to propagate within a multiple-events feedback system. In particular, the analysis of the spatial distribution of sediment connectivity and its temporal evolution can be useful for the characterization of sites of instability within the system.

In this context, the main aim of the present research is to apply a geomorphometric approach to evaluate the role of anthropogenic effects on the sediments delivery dynamic, in response to slope instability. The sediment connectivity assessment was carried out, analysing three different scenarios representative of landscape modifications due to anthropogenic effects: (i) drainage system density reduction, (ii) road network variation and (iii) land use changes. Moreover, shallow landslide inventories were used to identify sediment source areas and to evaluate the sediments supply from these sources to the main channels network and roads.

Two catchments with different size and morphological setting were analysed: the Rio Frate and Versa catchments (Oltrepo Pavese, Northern Apennines, Italy). The two areas were affected by important anthropogenic effects, especially regarding the land use changes, drainage system and road network modification. Moreover, several shallow landslides, which represents the main sediment source typology in the catchments, were triggered especially in the period from 2009 to 2013.

The performed analysis allowed to obtain maps of sediment connectivity that permit the characterization of the main sediment transfer processes variation as a result of landscape modification due to human activities. In particular, the effects of these modifications on the degree of connectivity between shallow landslides and roads and streams, were demonstrated. In addition, the instability phenomena characterised by the highest connectivity were identified, allowing to determine those areas where the mobilized sediment from shallow landslides can potentially reach roads and stream network, causing extensive damages.
The geomorphometric characterization of slope instability phenomena by means of sediment connectivity was particularly effective in order to provide useful information for the improvement of risk management strategies of shallow landslides prone-areas.

Keywords: Sediment connectivity, index of connectivity, anthropogenic effects, landscape modification, shallow landslides

1 Introduction

The spatial characterization of the sediments dynamics throughout the landscape and in particular the estimation of the degree of linkage between sediment sources and downstream areas (i.e., sediment connectivity) is a key element to define sediment transfer paths.
Sediment connectivity can vary both in space and time (Bracken et al. 2015; Heckmann and Schwanghart 2013) and the main factors affecting sediment delivery dynamic are:
(i) the morphological complexity of the catchment, such as relief, stream network density, catchment shape and soil surface irregularity (terrain roughness) (e.g. Baartman et al. 2013; Borselli et al. 2008; Cavalli et al. 2013).
(ii) the spatial organization of vegetation (Cammeraat 2002; Foerster et al. 2014).
Regarding landscape complexity, this can be low on local scale but very high at hillslope and catchment scale. For example, with increasing catchment size, floodplains substitute slopes that represent the direct source of sediment to the downstream areas and this affect the overall sediment export from the basin (De Vente and Poesen, 2005). For what concerns vegetation, it plays an important role due to its influence on surface roughness and local sediment retention capacity, contributing to increase the decoupling between upstream and downstream areas (Borselli et al 2008; Puigdefabregas et al., 1999). The role of vegetation affecting sediment connectivity can change according to anthropic and natural pressure, such as season and climate changes or land use and management practice modifications (López-Vicente et al. 2016).
Over the years, several methods for the analysis of sediment connectivity have been developed. The most common are qualitative approaches based on geomorphological and sedimentological field observations, and monitoring of sediment fluxes by means of field instrumentation (Becht

et al. 2005; Beel et al. 2011; Berger et al. 2011; Brown et al. 2009; Harvey 2001, 2002; Hooke 2003; Mao et al. 2009; Schlunegger et al. 2009).

In addition to these methods, analogous quantitative indexes, based on information commonly available in a GIS environment, were defined. Borselli et al. (2008) introduced a set of tools for the assessment of connectivity using both GIS data (e.g. Digital Elevation Model (DEM) and landuse map) and field observations. In particular, the sediment connectivity index was designed to assess connectivity using only a DEM and the available landscape information, independently from the event characteristics. This index of connectivity, rather than describing connectivity in the context of specific events allow to obtain connectivity map representing the potential connection between the different parts of a watershed.

Sediment connectivity was used also to investigate geomorphic processes. In particular, the spatial characterization of the sediment delivery distribution was performed to characterise sediment sources that act as sites of instability within the system (Cavalli et al., 2016; Marchi and Dalla Fontana, 2005; Surian et al., n.d.; Tiranti et al., 2016). The assessment of the degree of connectivity of sediment source areas is of upmost importance since it can indicate the probability that a local on-site effect propagates within a multiple-events feedback system (Borselli et al 2008). Reid et al. (2007) proposed a modelling approach which combines the assessment of landslide generated sediment, computed using a modified version of SHALSTAB (Montgomery and Dietrich, 1994), with an index of hydrological connectivity based on a network index version of TOPMODEL (Beven and Kirkby, 1979). Schwab et al. (2009) studied the differences in sediment flux from the opposite flanks of an alpine valley related to differences in the predominant erosion processes (landsliding vs. sediment transport in channel systems). Wichmann et al. (2009) developed an integrated modelling of rockfall, slope-type debris flows and channelized debris flows to assess the sediment cascade systems resulting from the interaction of various geomorphic processes. (Heckmann and Schwanghart, 2013) proposed a network analysis approach to analyse sediment cascades and assess connectivity using graph theory. Recently, Cavalli et al (2013; 2016) proposed a new version of the topography-based index developed by Borselli et al. (2008) to model sediment transfer pathways and to evaluate the potential connection of sediment source areas with the main channel network and the catchment outlet in mountain catchments.

Effectively, the mobilized sediments from site of instability often can reach downstream areas causing extensive damages. The sediment can reach streams, increasing bed load and sometimes producing flooding induced by aggradation of the riverbed or obstructing anthropic structure (e.g. bridges). Moreover, it often can affect the road network, generally due to a lack or deficiency of surface water draining systems, blocking traffic, isolating villages and stopping activities (D’Amato Avanzi et al. 2013; Giannecchini et al 2012). In addition, the magnitude and the temporal evolution of the sediment connectivity can be strongly influenced by the anthropogenic modification of the landscape (land use and drainage system changes, presence and variation of roads network) (Tarolli and Sofia, 2016). Human activities, in fact, act as direct disturbance of surface morphology (Ellis et al., 2006; Ellis, 2011; Vanacker et al., 2014). The progressive increase of urbanization has altered the natural landscape by changing topography, vegetation cover and soil properties, inducing to major changes in sediment retention and export along the hillslope-channel system (Tarolli et al., 2014a,b).

Within this framework, the aims of this research are:

i) The assessment of the sediment connectivity to evaluate the potential connection between site of instability, such as shallow landslides, and downstream areas of a catchment.

ii) The investigation of the role of anthropogenic effects on the sediments spatial distribution and mobilization in response to slope instability.

In particular, the sediment connectivity was evaluated analysing three different scenarios representative of landscape modification due to anthropogenic effects: the reduction of drainage system density, the variation of roads network and the land use changes. Moreover, shallow landslide inventories were used to identify sediment source area and to evaluate the sediments supply to the channel network and roads in response to slope instability.

2 Study areas

The analysis has been applied in two catchments with different size and morphological setting, both located in Oltrepo Pavese, in correspondence of the northern termination of the Apennines (Figure 1): the Rio Frate (1.9 km^2) and the Versa catchments (38.2 km^2).

The Rio Frate catchment has an elevation that ranges between 95-295 m a.s.l. It is a catchment with typical characteristics of Pede-Apennine margin of Oltrepo Pavese. Its morphological structure, in fact, is closely related to both the lithological nature of the outcropping rocks and the tectonic and neotectonic activities affecting the Apennine margin. In particular, the neotectonic activity is underlined by morphological evidence, such as altimetric irregularities of ridge lines, the development of channel network and the presence of breaks in the continuity of the slopes (Vercesi and Scagni, 1984).

The Versa catchment, characterized by elevation that are included between 128 and 662 m a.s.l, presents another different but typical morphological structure of Oltrepo Pavese. It is characterised by relatively uniform slopes with medium-low topographic gradient. Moreover, the hydrographic network in this catchment is well developed and characterised by a relatively mature stage of development (Mancuso et al. 1996).

The geology of these sites are represented by sedimentary formations. Specifically, in the Rio Frate catchment (Figure 1a), the bedrock is characterised by a Mio-Pliocenic succession called as “Serie del Margine”. In the Rio Frate catchment, medium low-permeable arenaceous conglomeratic bedrock (Monte Arzolo Sandstones, Rocca Ticozzi Conglomerates) overlies impermeable silty-sandy marly bedrock and evaporitic chalky marls and gypsum (Sant'Agata Fossili Marls, Gessoso-Solfifera Formation). The superficial soils, derived by bedrock weathering, are mainly clayey-sandy silts and clayey-silty sands. Soil thickness ranges between a few centimetres to less than 2.0 m.

The Versa catchment (Figure 1b) is characterised by an older bedrock compared to the Rio Frate catchment, the bedrock age ranges from Cretaceous to Miocene. It is composed especially by marls, calcareous-marls, sandstones and scaly shales, in some cases with few arenaceous intercalation. Soils above the bedrock present a clayey texture and their thickness can reach values higher than 3-4 m.

The differences in terms of soil texture have effects also on the geomorphological setting of the study area. The Rio Frate catchment is characterised by the presence of slopes with medium-high gradient, which can exceed 35°, and narrow little valleys formed by creeks of limited extension. In the Versa catchment the slopes have a low-medium gradient, with values commonly between 15 and 25°.

With regard to the land use the two study sites present rather different characteristics as well. The Rio Frate catchment in particular has been affected by significant variations both in landscape and land use. A high percentage of land abandonment characterised the area. Starting from the 1954, the area was occupied almost totally (75%) by Vineyards, which started to decrease since 1980 in response to important modifications to agricultural land management. In particular, the conversion from manual to mechanical cultural practices complicated the maintenance of vineyards, especially for those ones located in correspondence of very steep slope (> 25), mainly due to the lack of safety measure during the performance of maintenance practices by means of agricultural equipments. The current cultivated vineyards belong to a historical and valuable wine quality, called “Buttafuoco dell'Oltrepò Pavese”. This is one of the most important Controlled Designation of Origin zone of the entire Oltrepo Pavese area.

In the Versa catchment instead, an important modification of agricultural practices occurred after 1954: sowed areas were substituted by vineyards, which are now the most widespread cultural practice (65%). Now it is the most developed economic centre, especially thanks to the large valuable production of wine with Protected Designation of Origin. The land use changes, affecting the two study areas, were realized principally to achieve a greater efficiency in the mechanization of the agricultural management practices and to increase the economic quality of the areas. However, they led to a reduction of the maintenance activities concerning the water regulation. In particular, from 1980 on, these catchments were interested by a drastic reduction of the drainage system density. This brought to a worsening of the effects produced by the lack of water regulation, such as the increasing of the surface water runoff and the consequent intensification of erosion processes.

Moreover, human activities led to an increasing of the urbanization especially concerning road network density, as a way to reach easily the cultivated fields by means of agricultural equipments.

Both the study areas were recently affected by a relevant number of shallow landslides, triggered on 27-28 April 2009 (Rio Frate and Versa catchments) and March and April 2013 (Versa catchment). In particular, 245 shallow landslides were recorded in the Rio Frate catchment during the event occurred in 2009 (Zizioli et al., 2013).

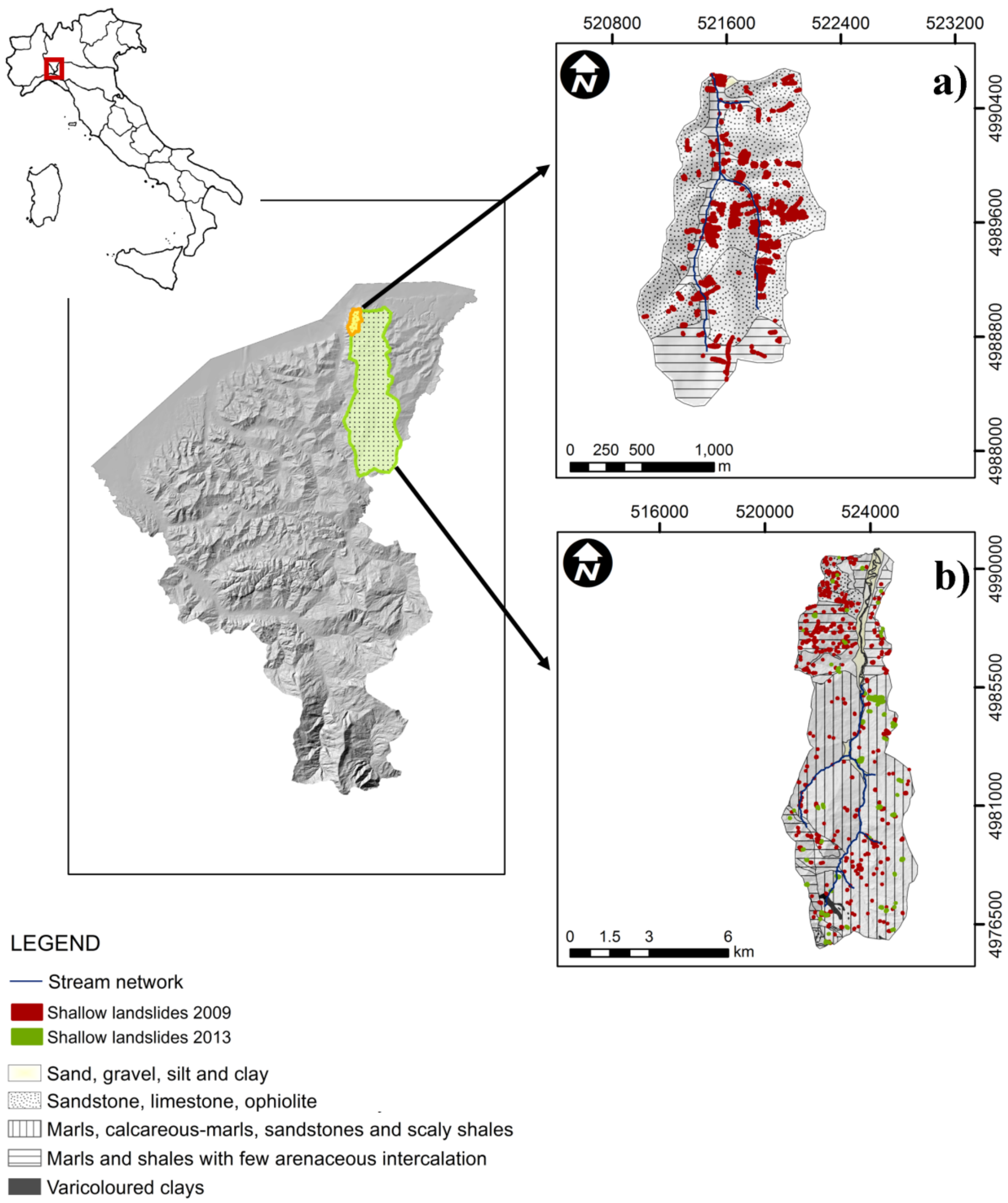

Figure 1. Lithology of the study areas: a) Rio Frate catchment; b) Versa catchment

They were characterized by an average length of about 35 m and their area of extension varied from a minimum of 13 m^2 to a maximum of 6289 m^2, with an average of about 473 m^2.

In the Versa catchment, 196 shallow landslides were recorded during the event of 2009. The shallow landslides were characterized by an average length of 48.5 m and they reached an area of extension included between 5.7 m^2 and 8098.1 m^2 , with an average extension of 491.5 m^2.

Whereas, 193 shallow landslides were recorded during the event of March/April 2013 (Zizioli et al. 2014). In this case, the shallow landslides were characterised by an average length of 56.2 m and an area of extension included between 7.5 m^2 and 14612.1 m^2, with an average extension of approximately 1155 m^2.

Both in 2009 and 2013 the slide surface depth varied between 0.90 m and 1 m and the shallow landslides recorded were classified as roto-translational slides evolving into flows, with width/length ratio > 1, according to Cruden and Varnes (1996) classification.

3 Materials and method

3.1 Sediment connectivity assessment

The assessment of connectivity was carried out by means of a topography-based index of sediment connectivity (IC), following the Cavalli et al. (2013) approach.

IC intends to represent the potential connection between different parts of the catchment and aims, in particular, at evaluating the potential connection between hillslopes and features which act as targets or storage areas (sinks) for transported sediment (e.g, channels, basin outlet, lake, roads network).

IC was originally defined by Borselli et al (2008), as:

$$IC = log_{10} \frac{D_{up}}{D_{dn}} \tag{1}$$

where D_{up} and D_{dn} are the upslope and downslope components of connectivity respectively. D_{up} represent the potential for downward routing of the sediment produced upslope and it depends on the upslope catchment area, mean slope and terrain roughness. D_{dn} takes into account the flow path length that a particle has to travel to arrive to the nearest target or sink and it depends on path length, terrain roughness and gradient along the downslope path. IC is defined in the range of [-∞, +∞], with connectivity increasing for larger IC values.

Starting from the original IC, Cavalli et al (2013) decided to introduce some refinement to the implemented IC to adapt the index to its usage with high-resolution Digital Terrain Models (DTMs). Details on the main changes introduced in the IC calculation can be found in Cavalli et al. (2013) and Cavalli et al. (2015).

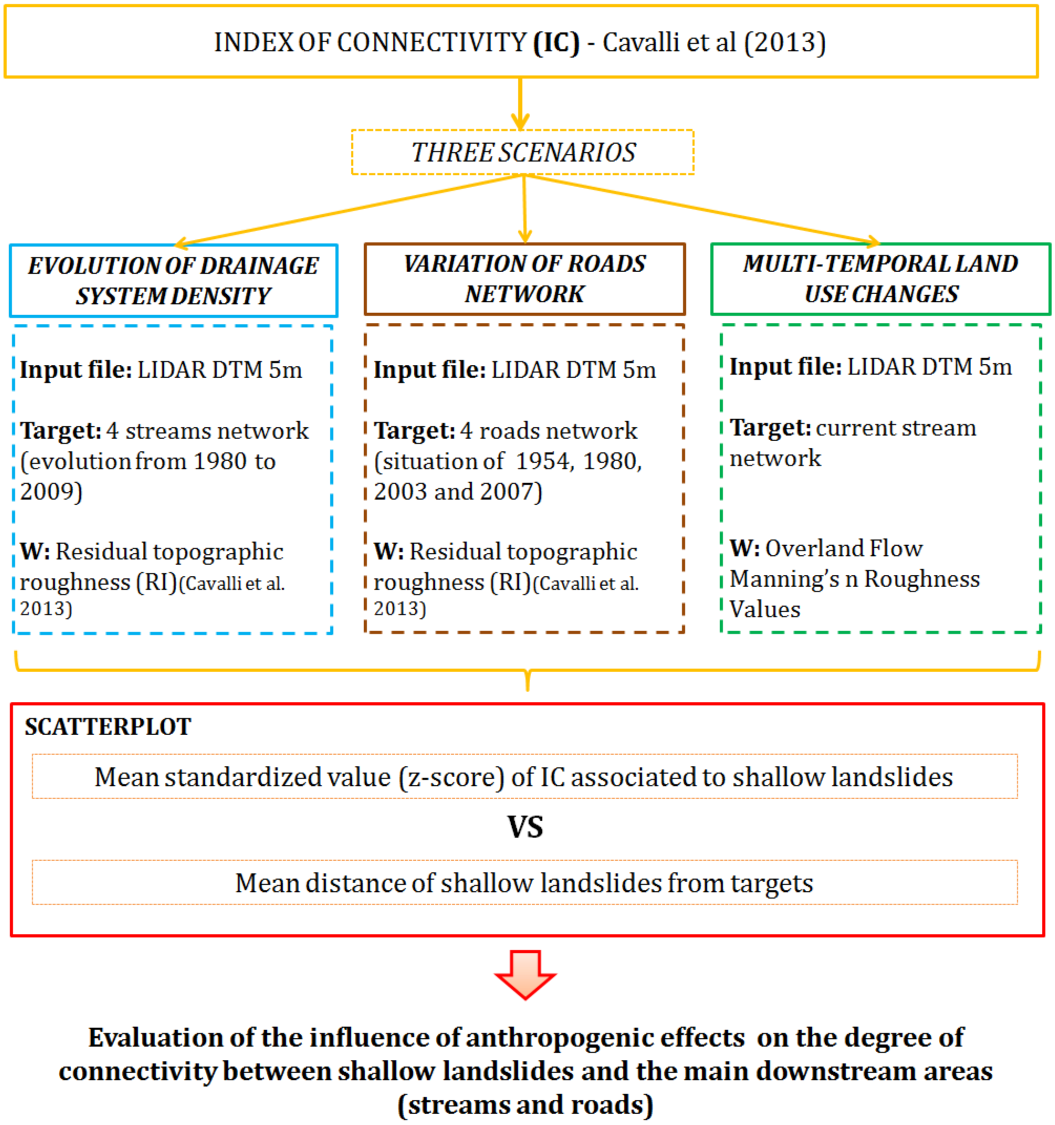

Figure 8. Scheme of developed methodology

IC was computed through the stand-alone application SedInConnect 2.1 (Crema et al., 2015).

IC was evaluated analysing several scenarios to understand the influence of anthropogenic factors on the sediments delivery dynamic in response to shallow landslides occurrence (Figure 2).

In particular, three scenarios were taken into consideration:

(i) The evolution of drainage system density

(ii) The variation of roads network

(iii) The multi-temporal land use change

In the first scenario, four different drainage network, characterised by a decreasing drainage density, were used as target in the IC calculation so as to evaluate the sediment connectivity change according to the drainage density variation.
The second IC scenario involved the use as target of 4 road network in order to evaluate the influence of gradual evolution of the road network on sediment connectivity.
Finally, in the third scenario, Overland Flow Manning's n Roughness Values (adapted from COE, HEC-1 Manual , 1990 and the COE , Technical Engineering Design Guide, No 19, 1997) were used as weight factor (W) to model the impedance to sediment fluxes process replacing the index of residual topographic roughness (RI) used by the Cavalli et al. (2013) approach.
After the extraction of the IC maps for each developed scenario, the mean standardized value (z-score) of IC was associated to each individual shallow landslides, and compared with their mean distance from the target of each scenario. This analysis was performed taking into consideration the different extension and typology of the shallow landslides.
Finally, the variation in the degree of connectivity between the sediment mobilized by the shallow landslides and the main downstream areas were evaluated, allowing to analyse the influence of anthropogenic effects on the sediment delivery dynamics.

3.2 Dataset used in the sediment connectivity analysis

For the IC calculation 5m resolution LiDAR derived DTMs of the Rio Frate and Versa catchments were used as input to derive the main parameters to representf the topographic and hydrological characteristics of the study areas and information on the surface roughness. DTMs were made available by the Ministry of the Environment and for Protection of the Land and Sea, following the realization of the Piano Straordinario di Telerilevamento Ambientale (Extraordinary Plan of Environmental Remote Sensing - PST-A).
Moreover, two inventories representing the shallow landslides occurred in 2009 in both catchments and in 2013 in the Versa catchment were built. For the event of 2009, post-event colour aerial photographs at resolution of 0.15 m (photo scale of 1:12000), obtained by aero-photogrammetric survey performed by a private company, were used to map the shallow landslides occurred (Zizioli et al. 2013). While, the shallow landslides occurred in the 2013, were identified using Pleiades satellite images. Pleiades triplet, available through evaluation program organized by AIRBUS Defence & Space, were used in stereo analyst environment in order to investigate the post- event status and to detect the shallow landslides location by visual interpretation (Zizioli et al. 2014).
The recorded shallow landslides were also grouped according to their typology. In particular, five typologies were identified according to the Cruden and Varnes (1996) classification: a) the Incipient translational slides: where fractures are present but the displaced mass has limited

movement with little internal deformation; b) Translational soil slides where the mass has moved, the failure surface is completely exposed and the collapsed materials break into different blocks; b2) Roto-translational slides: generally develop in the presence of a road cut; c) Complex landslides which start as shallow roto-translational failures and then evolve into earth-flows due to the large amount of water and the fabric loss of collapsed materials; d) Disintegrating soil slips: similar to type c) but in which the accumulation zone is not recognizable because the collapsed materials are completely dispersed along the slope and at its toe.

Orthophotos of 1954, 1980, 2000, 2003, 2007, 2009 and land use maps of 1954, 1980, 2000, 2007 and 2012 were also part of the dataset used to perform the sediment connectivity analysis.

The orthophotos were useful for the visual interpretation of the main change of the drainage system and of the roads network in the last 60 years. The orthophotos of 1954 were acquired by "Gruppo Aereo Italiano" (Italian Aerial Group), with a resolution of 0.5 m. Those of 1980, 2000, 2003 and 2007 were acquired by Lombardy Region, with a resolution ranging between 0.5 and 1.0 m. While, the orthophotos of 2009 were acquired with a resolution of 0.15 m after the shallow landslides event of 27-28 April 2009. The latter were also used for the comparison of the results with the field observations.

The land use maps were used to derive Manning's n to be used as weight factor (W) of IC to model the impedance to sediment fluxes. The maps are part of a tool for the land use analysis and monitoring developed by the Lombardy Region within the CORINE LAND COVER European Programme. In particular, the map of 1954 is a historical land use map realized by the use of aerial photographs acquired by "Gruppo Aereo Italiano" (Italian Aerial Group), with a resolution of 0.5 m. The land use map of 1980 was obtained by digitization of land use cartography derived from photo interpretation at the scale 1: 50000 of TEM flight. The land use maps of 2000, 2007 and 2012 are included in the geographic database called DUSAF (Destinazione d'Uso dei Suoli Agricoli e forestali - Intended Use of Soils Agricultural and Forestry) created in 2000-2001 as part of a project funded by the Directorates General of Territory, Urban Planning and Agriculture of Lombardy Region and realized by the Regional Agency for Development of Agriculture and Forestry (ERSAF), with the collaboration of the Regional Environmental Protection Agency of Lombardy (ARPA).

4 Results

4.1 First scenario: evolution of drainage system density

As first step, the Rio Frate and Versa DTMs were used for the automatically extraction of streams network by using a constant drainage area threshold approach (table 1).

Table 1. Drainage area thresholds used for the extraction of streams network with different drainage density

Catchment	Drainage area threshold (m^2)
Rio Frate	6250
	25000
	125000
	250000
Versa	62500
	250000
	1250000
	2500000

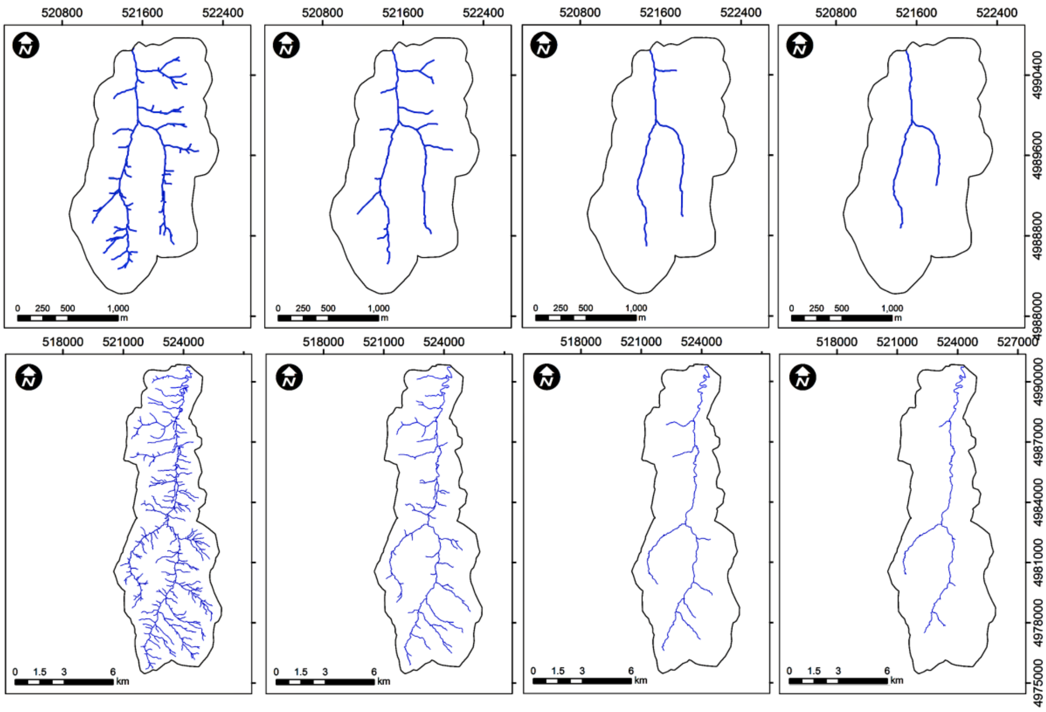

Figure 9. The drainage systems automatically extracted and used as target in the IC calculation. Above: the four streams network realized in the Rio Frate catchment. Bottom: the four streams network realized in the Versa catchment. Starting from the left, the four scenarios are representative of the situation observed from 1980 to 2009.

Four different channel network, characterised by the decrease of drainage density, were realized in order to represent the gradual reduction of the minor water network that characterised the two study areas in the last 60 years (Figure 3).

A visual interpretation of aerial photographs from 1980 to 2009 was performed in order to compare the automatic extraction of the stream network with the real evolution of the drainage system observed.

The four streams network were then used as target in the IC calculation. This allowed to evaluate, for both the study areas, the influence of the drainage system density modification on the sediment transfer processes over the years, and in particular on the hillslope-to-channel coupling\decoupling.

The IC maps in regards to the different channel network are showed in the Figure 4.

The IC values were classified in 4 classes:

- Low
- Medium-low
- Medium-high
- High

The range of each class was chosen through the use of the Jenks's natural break classification (Jenks 1967) and these values were then slightly modified for making uniform and comparable the classification in the different scenarios.

The Rio Frate catchment, for all the analyzed scenarios, was characterised by a high percentage of areas with medium-high values of IC. With the decrease of the drainage density, these areas gradually diminished, remaining localized only in correspondence of the highest slope gradients included between 25°-35°.

In the Versa catchment a high percentage of territory was characterised by areas decoupled from the stream network, showing low and medium-low values of IC. Moreover, with the decrease of drainage density the disconnected areas gradually increased.

After the IC maps extraction, the degree of connection between the shallow landslides and the river network with different drainage density was evaluated. The results are illustrated by means of scatterplots where the mean standardized value (z-score) of IC associated to each individual shallow landslides, taken by the inventories available for each study areas, is plotted against their mean distance from the stream network, according to the four drainage scenarios considered.

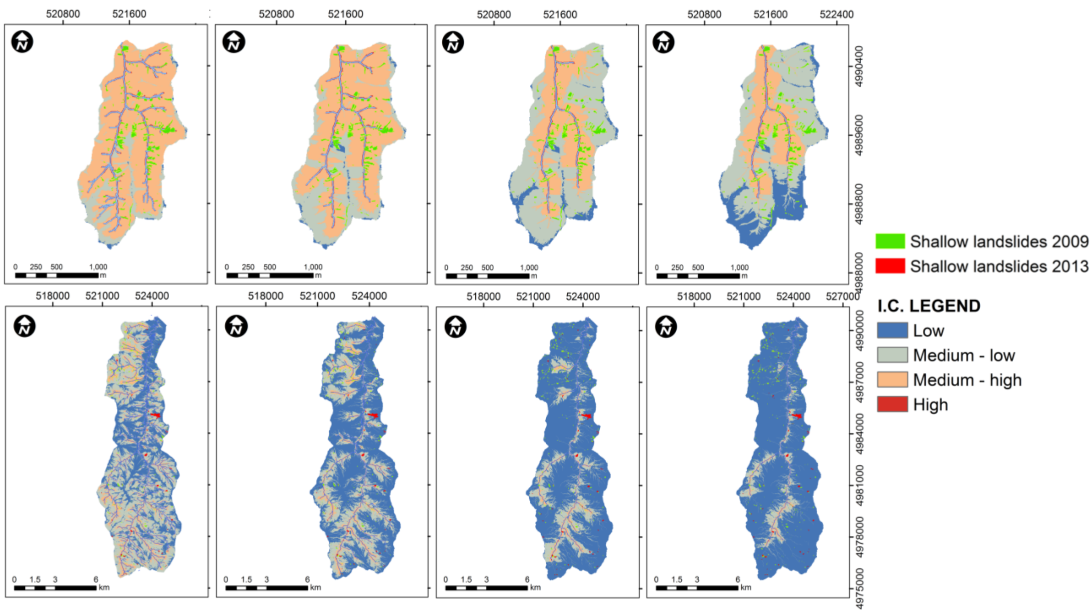

Figure 10. IC maps obtained by the use of the four streams network scenarios as target in the IC calculation. Above: IC maps of the Rio Frate catchment. Bottom: IC maps of Versa catchment

Each shallow landslide was represented with different colours depending on their typology, and with different sized points, according to different areal extent.

In the Rio Frate catchment, the analysis highlighted a gradual decrease in the number of shallow landslides characterised by high connectivity values with the gradual reduction of the minor water network. The shallow landslides characterised by the highest index of connectivity values were localized within 50 m distance from the river network .

In addition, through the scatterplot visual interpretation, a main linear trend (in a semi-log scale) was recognised, showing a gradual decrease of the connectivity with the increase of the distance of the shallow landslides from the river network (Figure 5). A particular vertical trend was also noticed at the distance of about 100 m from the drainage system (Figure 5a). This means that at the same distance from the stream network the shallow landslides showed different degree of connectivity. In fact, higher values of IC were reached by shallow landslides directly linked to the stream network (Figure 5b), while, the shallow landslides with lower connectivity were those intercepted at first by other buffers, such as streets and buildings, before reaching the main river (Figure 5c).

The highest values of IC were achieved by shallow landslides of type c, namely complex landslide (Figure 6a).

Two different behaviours, instead, are showed by the shallow landslides type d, so the disintegrating soil slip.

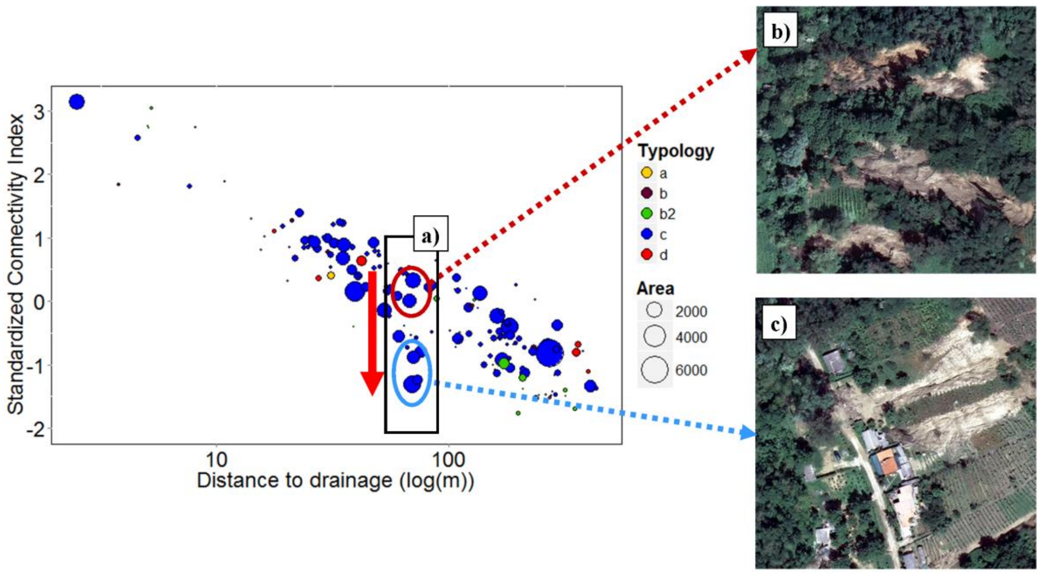

Figure 11. Rio Frate catchment: mean standardized value (z-score) of IC associated to each individual shallow landslides plotted against the mean distance of the shallow landslides from the stream network. a) Detail of the vertical trend observed; b) shallow landslides with higher connectivity directly linked with the stream network; c) shallow landslides with lower connectivity intercepted at first by other buffers as streets and buildings. The aerial photograph of the area was taken by Ditta Rossi s.r.l. (Brescia, Italy) on May 18th 2009.

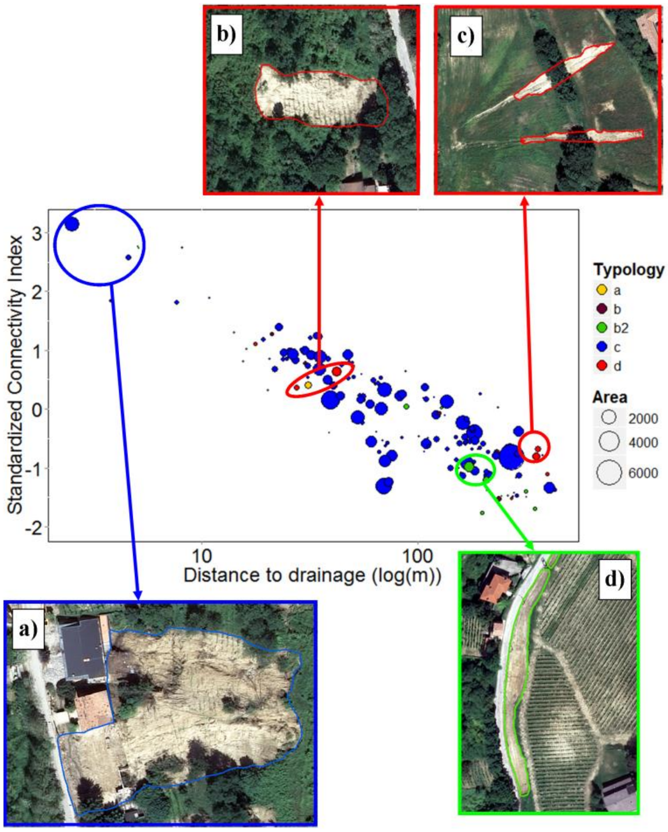

Figure 12. Degree of connectivity influenced by the shallow landslide location and typology. a) the complex landslides (type c) are showed the highest connectivity values; b) the disintegrating soil slip (type d) with medium-high connectivity directly linked to the streams; c) the disintegrating soil slip (type d) with lower connectivity because intercepted at first by other buffers; d) roto-translational slide developed in correspondence of roads cut (type b2) that reached the lowest connectivity values in this fist scenario. The aerial photograph of the area was taken by Ditta Rossi s.r.l. (Brescia, Italy) on May 18th 2009.

They were characterised by medium-high connectivity if directly linked to the stream (Figure 6b), while, they reached lower connectivity when intercepted by other buffers (Figure 6c).

The lowest connectivity was showed by the shallow landslides of type b2 since they are developed in correspondence of road cut and, thus, intercepted by the streets and not by the channel network (Figure 6d).

The Versa catchment was similarly characterised by a progressive decreasing in the number of shallow landslides strongly connected with the stream network with the decreasing of the drainage pattern density.

The trend showed by the scatterplot was completely linear (in a semi-log scale), with a clear decreasing of connectivity with the increase of the distance of shallow landslides from the drainage system (Figure 7). The shallow landslides characterised by a higher connectivity were located within the 500 m from the river network and they were mainly shallow landslides of type c, namely complex landslides. Furthermore, also shallow landslides of type a (incipient translational slides), despite the fact of being characterised by limited movements of the displaced mass, reached high values of IC when localized near the channel network. (Figure 7a,b).

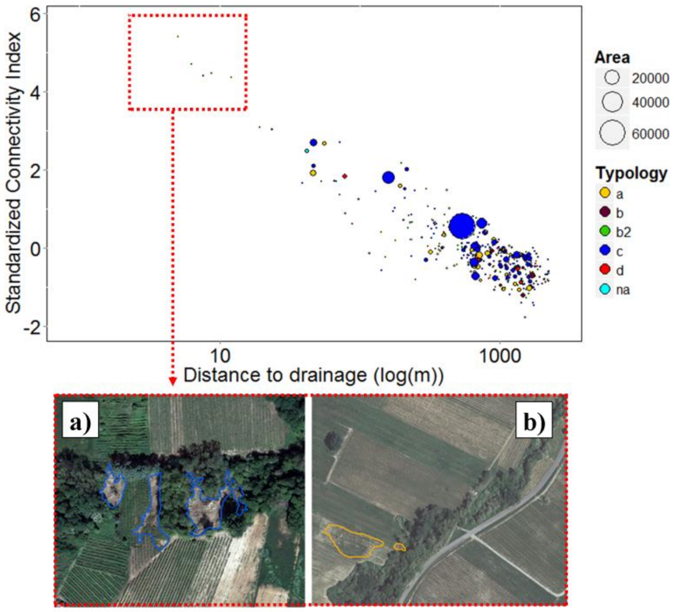

Figure 13. Linear trend showed by the scatterplot analysis of Versa catchment. The red dashed rectangle include the shallow landslides with the highest IC values: a) complex landslides, b) incipient translational slides. The aerial photograph of the area was taken by Ditta Rossi s.r.l. (Brescia, Italy) on May 18th 2009.

4.2 Second scenario: variation of roads network

In the second scenario, the target for the IC calculation was the road network. The analysis was carried out only in the Rio Frate catchment, since only in this area, it was possible to observe a gradual evolution of the road network over the past 60 years. In particular, four road network were extracted by the visual interpretation of orthophotos of 1954, 1980, 2003 and 2007, the latter similar to the present.

As showed by the IC maps of Figure 8, some areas of the Rio Frate catchment were characterised by medium-high values of IC constant over time and correspondent to the sectors of the catchment where most of the shallow landslides related to the 2009 event occurred. Moreover, from 1954 to the 2007 a gradual increasing of connectivity in the southern part of the catchment was observed, in this portion of the basin in fact new agricultural roads were constructed between the 2003 and 2007.

The increasing of the roads network density, observed from the 1954 and 2007, led to an increasing of shallow landslides characterised by high and medium-high connectivity with the main roads. The highest value of IC were registered by the shallow landslides of type b2, those developed in correspondence of roads cut (Figure 9a). Moreover, medium-high values of IC were registered also by the shallow landslides of type c that have reached the streets and the buildings (Figure 9b).

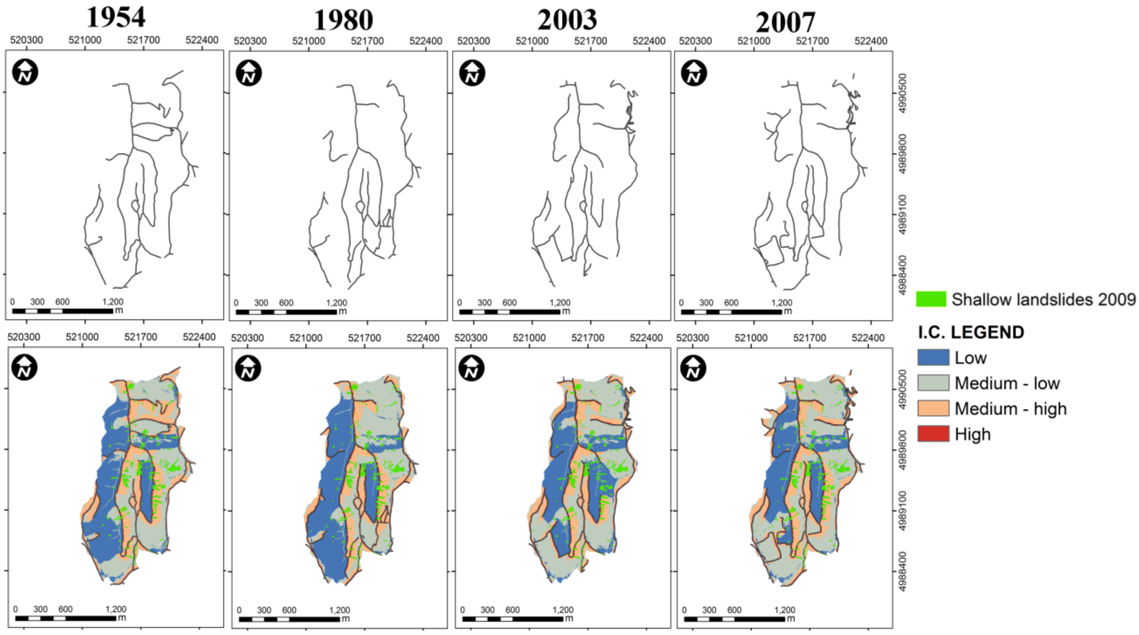

Figure 14 Above: from left to right the four roads network manually extracted by the visual interpretation of othophotos of 1954, 1980, 2003 and 2007. Bottom: the four IC maps obtained.

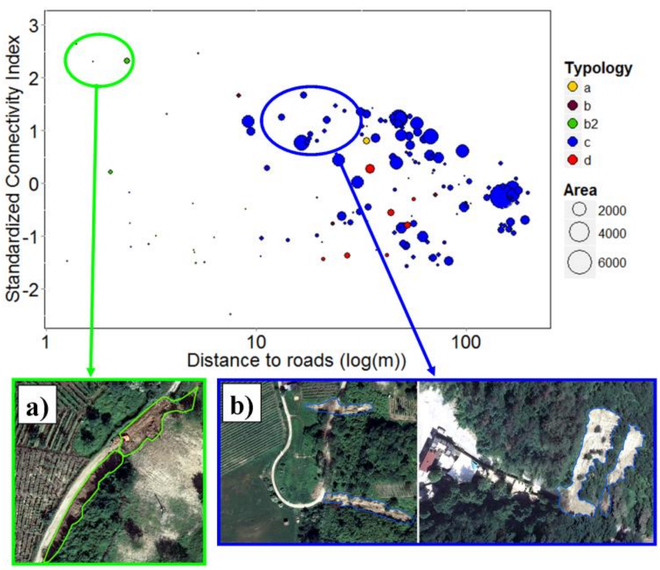

Figure 15. Scatterplot obtained analysing the mean standardized IC of shallow landslides against their mean distance from the road network: a) shallow landslides type b2, occurred on the road cut, that reached the highest values of IC because; b) shallow landslides of type c that reached the streets, characterised by medium-high connectivity. The aerial photograph of the area was taken by Ditta Rossi s.r.l. (Brescia, Italy) on May 18th 2009.

4.3 Third scenario: multi-temporal land use change

In the third scenario, the land use changes that characterised the two study areas in the last 60 years, were take into consideration for IC extraction. Land use map of 1954, 1980,2000,2007 and 2012 were use for both the catchments. Then, Overland Flow Manning's n Roughness Values (adapted from COE, HEC-1 Manual, 1990 and the COE , Technical Engineering Design Guide, No 19, 1997) were assigned to each land use class and the final maps were used as weight factor (W) to model the impedance to sediment fluxes process, replacing the index of residual topographic roughness (RI) developed by Cavalli et al. (2013).

Overland Flow Manning's n Roughness Values were assigned to each class of land use maps available, and then, it were used to derived W to model the impedance to sediment fluxes process (table 2)

The W was extracted using the following equation:

$$W = 1 - \mathit{Manning's\ n\ Roughness\ Values} \qquad (2)$$

For all the considered IC scenario the same stream network was used as target . The channel network was the one observed in 2009, in order to take into consideration only the most representative drainage system patterns related to the present situation.

The obtained IC maps are showed in the Figure 10. Analysing the results, both in Rio Frate and Versa catchment, the spatial distribution of the connectivity resulted very similar in all the cases.

Table 2 Overland Flow Manning's n Roughness Values assigned to each class of land use maps available and the derived W factor

Land use classes	**Overland Flow Manning's n Roughness Values**	**Weight factor (W)**
Woods	0.40	0.60
Uncultivated areas	0.35	0.65
Vegetated areas	0.30	0.70
Grasslands	0.25	0.75
Orchard /Arable areas /Vineyards	0.20	0.80
Sparse vegetation	0.05	0.95
Urban areas	0.02	0.98

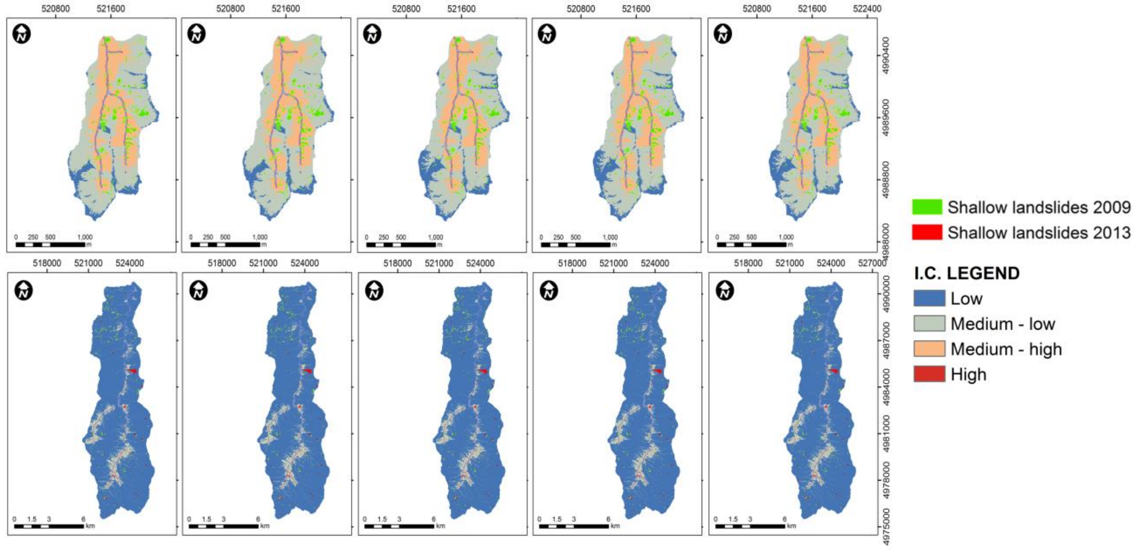

Figure 16. Above: IC maps of land use scenario in the Rio Frate catchment. Bottom: IC maps of land use scenario in the Versa catchment.

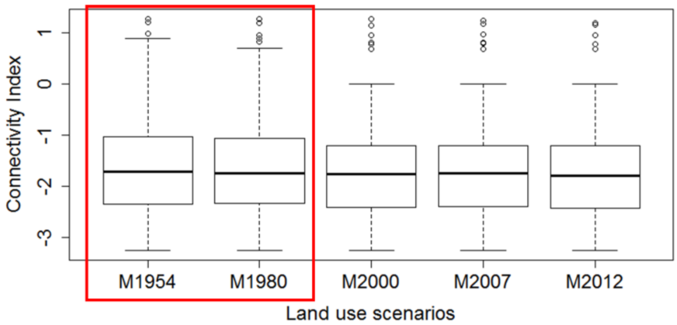

Figure 17. Boxplot used to compare the mean IC of each land use scenario associated to shallow landslides. The red rectangle highlight the decreasing of connectivity observed after the use of land use maps subsequent to the1980.

However, comparing the mean IC value of each land use scenario associated to each shallow landslides, some differences have been observed in the Rio Frate catchments (Figure 11). Specifically, it was noticed a decrease of connectivity after the 1980.

5 Discussion

The work is aimed at understanding as the landscape modification, due to anthropogenic effects, can affect the sediment transfer processes, especially, in response to slope instability. IC, based on the Cavalli et al 2013 approach, was used and applied to three different scenarios that allowed to evaluate three aspect linked to the effects of human activities on the territory: drainage system variation with the gradual disappearance of the minor water network, the increasing of roads network due to urbanization phenomenon, land use changes. These three scenarios permitted to analyse the degree of connectivity between shallow landslides and major targets, such as roads and streams, specifically relevant for the risk management during the occurrence of shallow landslides phenomena. In the first scenario, the main changes of drainage system, that occurred in the two study areas, were represented. In these areas, in fact, the land use changes and, in particular, the modification of cultural practices, over the years, have influenced the evolution of the drainage system, leading to a gradual reduction of its density and, thus, to a subsequent disappearance of the minor water network. Therefore, IC calculation allowed to highlight as the gradual reduction of the drainage has strongly influenced the connectivity of sediment inside the two basins analyzed.

However, the differences obtained in the two basins are also strongly related to the different morphological characteristics and extension of the two areas. In fact, the Versa catchment, being characterised by higher extension and lower average slope gradients with respect to the Rio Frate, tends to be characterised by the presence of a greater number of sediment storage areas.

In addition, the comparison between the mean standardized value (z-score) of IC associated to each individual shallow landslides and the mean distance of the shallow landslides from the stream network, allowed to identify the instability phenomena characterised by the highest connectivity and their location within the catchments. Moreover, the shallow landslide typologies characterised by the highest IC values were highlighted. In the Rio Frate catchment, they were localized within 50 m from the river network, and the most of them were shallow landslides of type c (complex landslides), so roto-traslational slides evolving into earth flow. Instead, in the Versa catchment, the highest values of IC were obtained by shallow landslides occurred within the 500 m from the drainage system and of type c and a, namely complex landslides and incipient translational slide, respectively. The observation of orthophotos and images, acquired in correspondence of the event of 2009, permitted to compare the IC outcomes with the real situation, confirming the accuracy of the performed analyses (Figure 12).

The second scenario considered for the Rio Frate catchment, showed the strong connection between slopes that were affected by the totality of shallow landslides, during the event of 2009, and the main road network.

In particular, the analysis shows clearly as the increase of shallow landslides characterized by high connectivity values was mainly due to the increasing of roads density. In fact, analysing the connectivity of the shallow landslides with the road network of each scenario, it was possible to observe an increasing of shallow landslides characterised by high value of IC (Standardized IC ≥ 1) with the increase of road network density, from 1954 to 2007 (from 15 shallow landslides in 1954 to 26 in the 2007). The highest values of IC were reached specifically by those shallow landslides that during the event of 2009 were triggered in correspondence of road cut (shallow landslides of type b2) and that have caused the main damages to the roads and buildings, as demonstrated by the observation of orthophotos and field data (Figure 13).

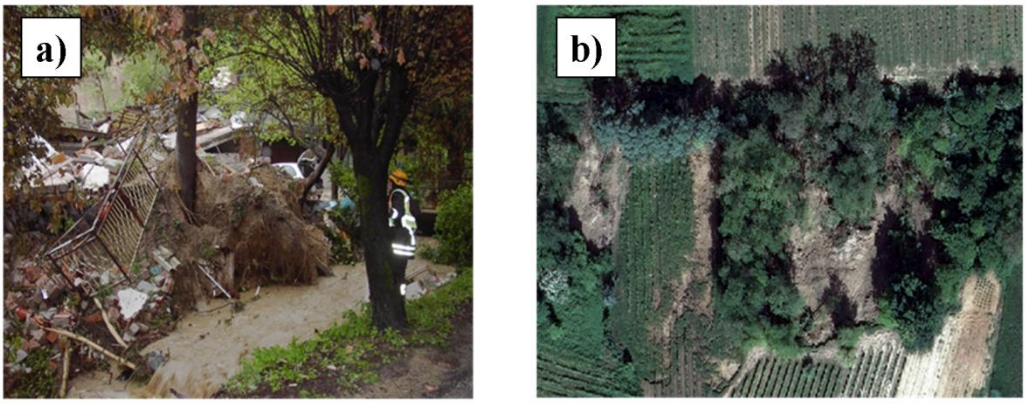

Figure 18. Shallow landslide characterised by high value of IC that effectively reached the main channel network during the event occurred in the 2009: a) the Rio Frate catchment; b) the Versa catchment. The aerial photograph of the area was taken by Ditta Rossi s.r.l. (Brescia, Italy) on May 18th 2009.

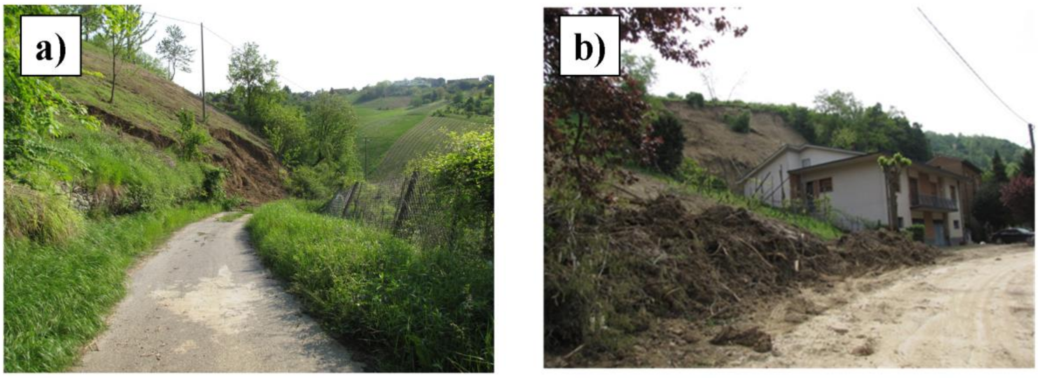

Figure 19. Shallow landslides that reached high value of IC that effectively hit the main road network during the event of 2009 in the Rio Frate catchment.

Concerning the last scenario, the influence of the land use change to the sediment flux impedance was investigated. Analysing the results, it was observed as the land use change had no influence on the connectivity over time. Only in the Rio Frate catchment, the land use modification occurred after the 1980 led to a decrease of the connectivity of shallow landslide with the main stream network. After the 1980, in fact, the Rio Frate catchment was affected by a large phenomenon of land abandonment, during which the areas cultivated with vineyards were gradually substituted by abandoned vineyards and woods. These changes have increased the presence of vegetation along the hillslope that most likely has contributed to disconnect the upstream sediment sources from the downstream areas. While in the Versa catchment, no changes occurred, since in this area the land use change concerned only modification of agricultural practices, regarding the transformation from arable areas to vineyards. Thus, the catchment remained always characterised by agricultural areas, without any important modification to the sediments flux impedance.

6. Conclusions

The role of anthropogenic effects on the sediments delivery dynamics in response to slope instability was investigated by means of a sediment connectivity analysis, based on the application of the geomorphometric index IC (Cavalli et al 2013). Three scenarios, intended to represent the main landscape changes occurred in the two study areas due to anthropogenic activities, were analyzed. In particular, the drainage system variation with the gradual reduction of the minor network and the increase of road network due to urbanization and land use changes were represented. These scenarios were used to model the sediment transfer processes in order to understand how the changes that occurred on the landscape may have influenced the behavior of sediment connectivity within the investigated catchments. Moreover, shallow landslides were used as major sediment source areas to evaluate sediments supply to the channel network and roads in response to slope instability phenomena.

The Rio Frate catchment was the study area characterised by the highest values of connectivity evenly distributed across all the catchment. The reduction of the minor drainage network and the increase of road network over the years led to a general increase of the connectivity values in correspondence of hillslopes located within the mean distance of 50 m from river and roads network. By the use of shallow landslide inventories, as sediment source areas, it was possible to highlight these areas as the most affected by surface instability phenomena during the event that hit the Rio Frate catchment in 2009. Furthermore, the analysis allowed also to identify the shallow landslide typologies characterised by the highest connectivity (complex landslides) and that have effectively reached streams roads during the instability phenomena occurred in the 2009.

In the Rio Frate catchment, it was also observed a relationship between the main land use modification occurred in the last 60 years and the changes in the sediment connectivity distribution. In particular, the pronounced phenomenon of land abandonment, occurred after the 1980, contributed to a slightly decreasing of the connectivity of shallow landslide with the main stream network due to the increase of vegetation along the hillslope after the gradual transformation of areas cultivated with vineyards into abandoned vineyards and woods.

The Versa catchment was instead characterised by a high percentage of disconnected areas with medium-low and low value of connectivity, despite the effects produced on the territory by the main anthropogenic changes. Very few sectors of the Versa catchment showed medium-high values of connectivity and were concentrated on the areas affected by shallow landslides in 2009 and 2013, located within a mean distance of 500 m from the river network. Also in this case, it was possible to identify the shallow landslide types most coupled with the downstream areas (complex landslides and incipient translation slides), comparing the results with those observed during the event of 2009 and 2013. In this case, analysing the effects of land use change on the sediment connectivity, not changes were observed, since in this area the land use modification did not lead to important changes of sediment flux impedance.

The exploitation of sediment connectivity analysis allowed to evaluate the influence of anthropogenic effects on the sediment delivery dynamics. In particular, the role of the landscape complexity in coupling/decoupling upstream sediment sources, such as shallow landslides, from the main channel network and roads was highlighted. Moreover, the assessment of the sediment connectivity in response to slope instability phenomena allowed to provide useful information for the improvement of land planning and management strategies. In particular, the understanding of the degree of connection between sediment sources and roads or rivers will permit to implement a detailed monitoring of those areas in which the mobilized sediment could damage the road network or cause flooding induced by aggradation or obstruction of the riverbed.

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8 The role of land use changes in the distribution of shallow landslides

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The role of land use changes in the distribution of shallow landslides

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ABSTRACT

The role of land use dynamics on shallow landslide susceptibility remains an unresolved problem. Thus, this work aims to assess the influence of land use changes on shallow landslide susceptibility.

Three shallow landslide-prone areas that are representative of peculiar land use settings in the Oltrepò Pavese (North Apennines) are analysed: the Rio Frate, Versa and Alta Val Tidone catchments. These areas were affected by widespread land abandonment and modifications in agricultural practices from 1954 to 2012 and relevant shallow landslide phenomena in 2009, 2013 and 2014.

A multi-temporal land use change analysis allows us to evaluate the degree of transformation in the three investigated areas and the influence of these changes on the susceptibility to shallow landslides.

The results show that the three catchments were characterised by pronounced land abandonment and important changes in agricultural practices. In particular, abandoned cultivated lands that gradually recovered through natural grasses, shrubs and woods were identified as the land use change classes that were most prone to shallow landslides.

Additionally, the negative qualities of the agricultural maintenance practices increased the surface water runoff and consequently intensified erosion processes and instability phenomena.

Although the land use was identified as the most important predisposing factor in all the study areas, some cases existed in which the predisposition of certain areas to shallow landslides was influenced by the combined effect of land use changes and the geological conditions, as highlighted by the high susceptibility of slopes that are characterised by adverse local geological (thick soils derived from clayey-marly bedrocks) and geomorphological (slope angle higher than 25°) conditions.

Thus, the achieved results are particularly useful to understand the best land conservation strategies to be adopted to reduce instability phenomena and the consequent economic losses in areas that are strongly linked to agricultural land use in these territories.

Keywords: land use changes, multi-temporal analysis, land abandonment, frequency ratio method, shallow landslides susceptibility, North Apennines

1. INTRODUCTION

Shallow landslides are particularly destructive phenomena because of the absence of incipient movement evidence and the high velocity of propagation. Effectively, the absence of warning signs from unstable landslide-prone areas makes shallow landslides very difficult to monitor. Despite the small soil volume that is involved (generally less than 2.0 m), shallow landslides can be densely distributed across territories. Thus, their rapid formation and high velocity of propagation makes correct and early predictions of their occurrence difficult to achieve, causing significant property damage to cultivation, structures and infrastructures and sometimes human losses.
As stated by Glade (2003), the type of movement, occurrence and behaviour of shallow landslides is often strongly influenced by land use and land use change dynamics, which are recognized throughout the world as one of the most important factors that influence the occurrence of shallow landslides.
In particular, the vegetation cover has important effects on shallow landslide susceptibility because of its effects on the hydrological processes and mechanical structure of the soil. To date, the literature has mainly focused on the mechanical effects of vegetation in terms of providing additional mechanical root reinforcement to be used in slope stability models (Bischetti et al. 2009; Greenway 1987; Schmidt et al. 2001). The mechanical contributions, which affect the soil strength, are derived from the physical interactions of plant root systems with the slope. Two main actions are recognised. The first involves small flexible roots that mobilise their tensile strength by soil-root friction, increasing the compound matrix (soil-fibre) strength. The second involves large roots intersecting the shear surface, which mobilise a soil-root friction force instead of the entire tensile strength (Waldron 1977; Bischetti et al. 2009).
The magnitude of such effects depends on the environmental characteristics (structure and texture of the soil, and the humidity, temperature and competition between the different species) and on the genetic properties of the different species (development of root systems). The environmental characteristics, in particular, induce great spatial variability in root patterns, introducing dramatic heterogeneity in soil reinforcement across different depths, planes and locations.

Thus, understanding the main land use changes through time could be very useful to evaluate the role of vegetation cover on slopes that are prone to shallow landslides and, in particular, the effect of its modification over the time on shallow landslide susceptibility (Carone et al. 2015; Glade 2003; Reichenbach et al. 2014; Van Beek and Van Asch 2004).

Generally, changes in vegetation cover are related to a combination of natural and socio-economic processes that operate at different spatial and temporal scales and often modify shallow landslide behaviour. Of particular interest is the role of human activity on vegetation changes. In fact, large areas can be changed in a short time because of anthropogenic processes, influencing the environmental factors that control landscape stability (Glade 2003).

In some cases, land use changes may be also a consequence of landslide activity instead of its major cause. Some works underlined that the occurrence of environmental hazards such as landslides in farmland areas can represent an important threat to human security, leading to greater difficulty in continuing to manage the land and causing possible migration and land abandonment (Warner et al. 2010; Piguet 2013).

In Europe, particularly in the Mediterranean region, land abandonment has been one of the most specific environmental processes that caused the most important land use changes over the last century (Gerard et al. 2010). In particular, the agricultural abandonment in the Italian Alps and Apennines led to substantial increases in forest area, depending on the altitude and changes in the structural diversity of the landscape (Falcucci et al. 2007). These modifications have important effects on the hydrological processes and mechanical structure of the soil, leading to important positive and negative consequences for slope stability (Bischetti et al. 2009; Greenway 1987; Reichenbach et al. 2014; Schmidt et al. 2001; Schwarz et al. 2010; Wu 2012).

In many cases, changes in land use along steep terrains that are prone to shallow landslides, especially changes that are linked to the degradation and progressive abandonment of cultivations, had negative effects on the predisposition for landslide occurrence (Begueria 2006; Cevasco et al. 2014; Crosta et al. 2003; Galve et al. 2015; Glade 2003; Lorente et al. 2002).

For example, Lorente et al. (2002) and Begueria (2006) showed the negative effects of land degradation on landslide processes. In particular, these authors studied an extremely degraded area in the Central Pyrenees, where shifting agriculture on steep slopes and the frequent use of fire to control the expansion of thorny vegetation led to soil erosion and general land abandonment. This situation strongly contributed to shallow landslides even decades after human activities had ceased and after re-vegetation by shrubs or trees, confirming the strong influence of land degradation on the occurrence of shallow landslides. Other authors (Cevasco et al. 2014; Crosta et al. 2003; Galve et al. 2015) showed that the abandonment of cultivated plants and the lack of maintenance of human structures, such as drainage ditches and retaining walls, along the steep slopes of different Alpine and Apennines hilly areas increased erosional processes and the instability of slopes that were cultivated with vineyards and oliveyards.

Moreover, other studies (Bordoni et al. 2016; Bordoni et al. 2016a) highlighted the effect of vineyards and their abandonment on shallow landslide susceptibility, demonstrating that cultivated vineyards provide greater reinforcement to soil than abandoned grapevine plants.

However, directly relating the occurrence of shallow landslides to land use variations is difficult. Thus, the main aim of this research is to investigate geomorphic responses to land use changes, specifically by studying the temporal dynamics of land use variations, especially in abandoned agricultural lands.

In particular, this work focuses on the following:

i) The characterization of the land use changes and the modification of management practices in three shallow landslide-prone areas with peculiar land use and geological settings;

ii) The identification of the land use classes in each study site that are more prone to shallow landslides by analysing the distribution of past shallow landslides across several land use types;

iii) The effect of land use changes on the occurrence of shallow landslides.

A multi-temporal analysis is performed to obtain historical profiles of the study areas and to evaluate the main land use modifications that occurred over the last 58 years (from 1954 to 2012). Then, the main vegetation and agricultural land use classes (vineyards, arable areas, uncultivated areas, woods and grasslands) are analysed in detail to assess their degree and rate of transformation according to the characteristics of the land abandonment phenomena that affected the study areas. Finally, the Frequency Ratio Method (FRM - Lee and Talib 2005) is applied to analyse the influence of land use changes on the occurrence of shallow landslides.

The study areas include three hilly mountainous catchments from the northern Apennines in Italy: the Rio Frate, Versa and Alta Val Tidone. These sites represent three peculiar land use characteristics of the Italian Apennines. These catchments represent three rural contexts that are principally based on agriculture and wine-making traditions. Over the last 60 years, these areas were characterised by a high percentage of land abandonment, leading to important landscape modification. Moreover, all the study areas were affected by relevant shallow landslide phenomena, specifically in 2009, 2013 and 2014. Shallow landslides particularly affected agricultural lands, inflicting important damage to the local economy. In this context, understanding the possible relationship between the main land use changes and the occurrence of shallow landslides is very important for management and conservation purposes.

2. STUDY AREAS

The study areas are located in the north-eastern sector of Oltrepò Pavese, which belongs to the northern termination of the Italian Apennines (Figure 1). The Oltrepò Pavese is configured as an agricultural quality district. This area is a large Controlled Origin Denomination (C.O.D.) wine zone of the Lombardy Region, with approximately 130 km^2 of vineyard, and is among the top ten areas for the production of Italian wine. The central and southern sectors are characterised

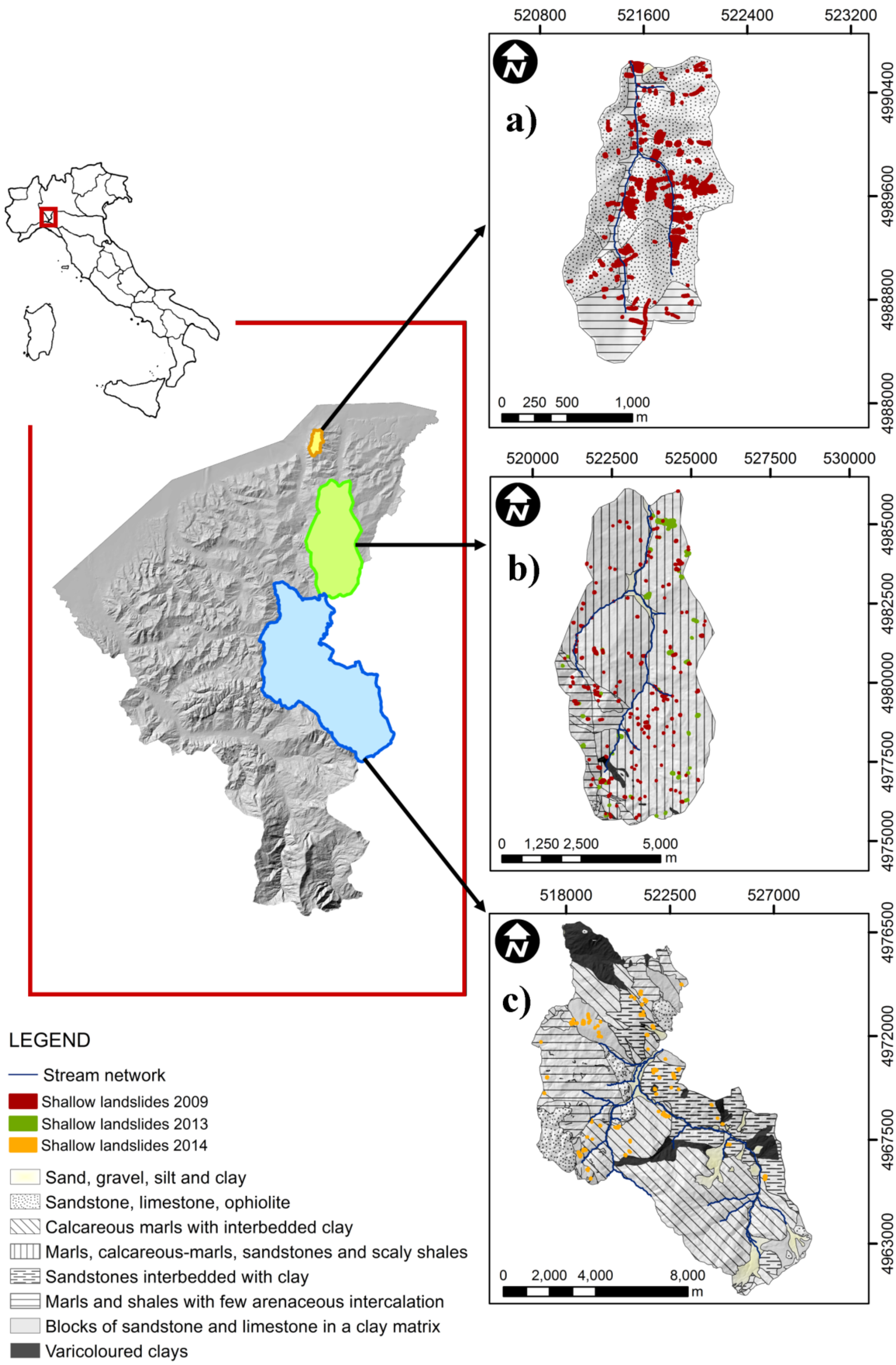

Figure 1. Study area's location, lithological settings and shallow landslide distribution: a) Rio Frate catchment; b) Versa catchment; c) Alta Val Tidone catchment.

by the production of arable crops. According to Koppen's classification of world climates, the climate is temperate/mesothermal. The mean annual temperature is approximately 12 °C, and the average annual rainfall is approximately 700 mm in low-lying areas and ca. 998 mm in the hills, with an increase in the rainfall amount from west to east. In particular, two distinct rainy seasons occur, with a primary peak of rainfall in autumn (October–November) and a secondary peak in spring (April-May). Over the last seven years, the Oltrepo Pavese experienced increasing mean annual precipitation, with a mean cumulative rate of ca. 900-1000 mm at altitudes below 600 m a.s.l. In addition, the mean annual amount of rainy days increased after 2008, changing from 65 mean rainy days to 89 and with peaks that reached 90 - 120 rainy days between 2008 and 2014.

The Oltrepo Pavese territory is particularly prone to shallow landslides, as testified by the occurrence of several events over the last seven years (Bordoni et al. 2015a; Zizoli et al. 2014, 2013). In particular, three catchments that were strongly affected by these instability phenomena were analysed: the Rio Frate, Versa and Alta Val Tidone catchments.

The study areas are characterised by a high density of landslides. In the Rio Frate catchment, the triggering event in 2009 was the most important during the last seven years and the first documented case of rainfall-induced shallow landslides since the 1950s. Historical documents that can testify to the presence of landslides are not available in these areas even before the 1950s.

The Versa and Alta Val Tidone catchments have been strongly affected by landslides during the last century, as testified by the IFFI (Italian Landslides Inventory) database and by Meisina et al. (2006). In particular, these areas were affected by the presence of several deep landslides with failure surfaces below 2–3 m from ground level. These phenomena include rotational slides, translational slides and complex landslides (roto-translational slides that evolve in earth flows) (Cruden and Varnes 1996) and do not show evidence of recent movement, so they can be classified as dormant landslides. Up to 40% of the Versa catchment is covered by these types of landslides. In the past, these two catchments were affected by shallow landslides, but with lower density compared to what has been observed from 2009 to the present. This observation has been linked to important modifications of the climatic conditions. In fact, the last seven years experienced strong increases in rainfall intensity, reaching a maximum intensity of 22 mm h^{-1} in 2009.

The three investigated areas represent different geological and land use settings (Table 1).

The Rio Frate catchment is characterised by uniform geology with geological formations that mainly consist of sandstones and conglomerates. A high percentage of land abandonment characterises the area, and the currently cultivated vineyards belong to a historical and valuable wine quality called “Buttafuoco dell'Oltrepò Pavese”. This area is one of the most important C.O.D. zones of the entire Oltrepo Pavese area.

The Versa catchment is also characterised by homogeneous geology that consists of geological formations with clay components. This area, although still cultivated, experienced an important modification in agricultural practices with a pronounced transition from arable lands to

Table 2. Schematization of the main geological, geomorphological and land use characteristics of the three study areas

Study Areas	Bedrock	Soil	Soil thickness (m)	Size (Km^2)	Altitude (m a.s.l.)	Slope (°)	Present Land use
Rio Frate	Sandstone, conglomerates	Clayey-sandy silts, Clayey–silty sands	< 2 m	1.9	100–300 m	22°-35°	Vineyards, Woodlands
Val Versa	Marls, calcareous-marls, sandstones and scaly shales	Clay	2- >4 m	38	200-600 m	15°-25°	Vineyards
Lower Alta Val Tidone	Marls and shale with few areanaceous intercalation emipelagic clays; Sandstones and limestones in a clay matrix	Silty and/or clayey soils	> 4 m	94	300-600 m	10°-20°	Arable areas, Woods
Upper Alta Val Tidone	Calcareous marls with interbedded emipelagic clay	Silty sand	< 0,2 m		600-1160 m	20°-35°	Woods

vineyards. This region corresponds to the most developed economic centre, especially thanks to the large valuable production of wine with Protected Designation of Origin.

Contrary to the other two sites, the Alta Val Tidone catchment is characterised by more heterogeneous geology and mostly consists of clayey and calcareous formations. The area is mainly characterised by semi-natural habitats with the predominant presence of woodlands, grasslands and fields of arable land.

2.1 Rio Frate catchment

The Rio Frate catchment (Figure 1a) has an extension of approximately 1.9 km^2, and its elevation is between 95 and 295 m a.s.l. The slopes have a medium-high gradient, which can reach values higher than 35°, and finish in small, narrow valleys that formed from creeks of limited extent, which range between 55 to 348 m^2.

In this area, the bedrock is characterised by a Mio-Pliocenic succession called the "Serie del Margine" (Vercesi and Scagni 1984). In particular, medium- to low-permeability arenaceous conglomeratic bedrock (Monte Arzolo Sandstones, Rocca Ticozzi Conglomerates) overlies impermeable silty-sandy marly bedrock and evaporitic chalky marls and gypsum (Sant'Agata Fossili Marls, Gessoso-Solfifera Formation). The superficial soils, which were derived by bedrock weathering, are mainly clayey-sandy silts and clayey-silty sands. The soil thickness ranges between a few centimetres to less than 2.0 m.

This area was affected by a high number of shallow landslides during the event on 27-28 April 2009 (Zizioli et al. 2013). In particular, 245 shallow landslides with an average area of extension of approximately 470 m^2 were recorded. The shallow landslides that were recorded during these events were classified according to Cruden and Varnes' (1996) classification.

Most of these landslides were classified as roto-translational slides that evolved into flows, with width/length ratios > 1. The source lengths vary between 4 and 36 m, with a mean value of approximately 15 m, and the source widths range from 3 to 46 m, with a mean value of approximately 17 m. The sliding surfaces are usually located between 0.5 and 2.0 m from the ground, corresponding to the contact between soil and bedrock.

The actual land use is characterised by a predominance of cultivated vineyards (26%) and woodlands (44%), the latter sometimes corresponding to abandoned vineyards.

2.2 Versa catchment

The Versa catchment (Figure 1b) covers an area of approximately 38 km^2, with altitude that ranges between 128 and 662 m a.s.l. The slopes have a low-medium gradient, with values that commonly range between 15 and 25°. This study area is characterised by older bedrock than the one in the Rio Frate catchment, whose age ranges from Cretaceous to Miocene. This area mainly consists of marls, calcareous-marls, sandstones and scaly shales, in some cases with few arenaceous intercalations. Above the bedrock, the soils have a clayey texture, and their thickness can reach values higher than 3-4 m.

According to these characteristics, this area was previously affected by deep-seated complex landslides (rotational and translational slides that were associated with earth flows) whose sliding surfaces could reach depths greater than 10 m. These types of landslides were located on sandstones that were interbedded with clays, marls, calcareous marls, and scaly shales. In some cases, deep-seated and large translational slides that included bedrock, which consisted of marls and shales with few arenaceous intercalations, were registered (Meisina et al. 2006).

The catchment was also affected by shallow landslides between 2009 and 2013. These shallow landslides were triggered on 27-28 April 2009 by the same rainfall event that affected the Rio Frate catchment and during different rainfalls events between March and April 2013 (Bordoni et al. 2015a). In particular, 196 and 193 shallow landslides were recorded during the events in 2009 and 2013, respectively. The shallow landslides reached an average extension of 490 m^2 during the 2009 event, while the landslides were characterised by a higher mean dimension of approximately 1155 m^2 during the 2013 event. Most of these phenomena occurred over marls, calcareous-marls, sandstones and scaly shales. The shallow landslides were characterised by a width/length ratio > 1. The scar lengths of the 2009 landslides range between 4 and 93 m, with a

mean value of approximately 28 m, while the scar widths range from 5 to 60 m, with a mean value of approximately 28 m. The source length of the 2013 landslides range between 4 and 53 m, with a mean of 20 m, and the source widths vary between 8 and 65 m, with a mean of 35 m.
Regarding the actual land use, vineyards are the most widespread cultural practice because they cover 65% of the entire territory.

2.3 Alta Val Tidone catchment

The Alta Val Tidone catchment (Figure 1c) covers an area of 94 km^2. Its elevation ranges between 300 and 1160 m a.s.l. According to its altimetry and the slope gradient distribution, this area can be subdivided into the Lower Alta Val Tidone, which is located in the northern part of the catchment, and the Upper Alta Val Tidone, which is located in the southern sector. The Lower Alta Val Tidone ranges between 300 and 600 m a.s.l. and is characterised by slope of 10°-20°. The Upper Alta Val Tidone has a higher altitude between 600 and 1160 m a.s.l. and steeper slopes with a gradient of 20°-35°.
The two zones in the Alta Val Tidone catchment exhibit different lithological conditions. The Lower Alta Val Tidone contains a predominance of marls and shale with few arenaceous intercalations, hemipelagic clays (varicoloured clay) and sandstones and limestones in a clay matrix. Silty and/or clayey soils that formed from weathering and down-slope transportation cover the argillaceous bedrock, and the soil thickness can reach values higher than 4 m. The Upper Alta Val Tidone mainly consists of calcareous marls with interbedded hemipelagic clay (Ghiselli et al. 1994) and is covered by silty sand soil with thickness less than 0.20 m.
As in the Versa catchment, rotational and translational slides that were associated with earth flows (complex landslides) and involved calcareous marls with interbedded clays have been registered. Moreover, very large rotational and translational slides were distinguished in the southern part of the study area in relation with calcareous marls with interbedded hemipelagic clay (Meisina et al. 2006).
The study area was also affected by shallow landslide phenomena over the last 7 years (2009-2016). In particular, the most significant event occurred during 18-20 January 2014, when 90 shallow landslides with an average area of 1300 m^2 occurred. These landslides are characterised by a width/length ratio > 1. The source lengths vary between 5 and 48 m, with a mean of 16 m, and the source widths range between 5 and 55 m, with a mean of 25 m.
These shallow landslides are especially concentrated in the Lower Alta Val Tidone, corresponding to slopes with bedrock that consists of sandstones that are interbedded with clay and sandstones and limestones in a clay matrix. A few landslides were also located along slopes with bedrock that consists of calcareous marls with interbedded clay but is characterised by very high soil thickness (3-4 m from ground level). The actual land use in this area is different from that in the other two sites. This territory is mostly covered by woods (44%) and by arable lands

(29%) in the Lower Alta Val Tidone. The other two land use classes within the catchment are uncultivated areas (11%) and grasslands (8%).

3. MATERIALS AND METHODS

3.1 Datasets

Land use maps from 1954, 1980, 2000, 2007 and 2012 were used to analyse the land use change in the study areas across the last 58 years (www.geoportale.regione.lombardia.it). These data are part of a tool for land use analysis and monitoring, which was developed for the Lombardy Region within the CORINE LAND COVER European Programme. In particular, the land use maps were provided by the Lombardy Region and shared as part of the Infrastructure for Spatial Information in Lombardy (IIT) via the Geoportal (http:// www.cartografia.regione.lombardia.it/geoportale).

Detailed information regarding the method to realize these land use maps were obtained through the consultation of the site (http://www.territorio.regione.lombardia.it) and through a more in-depth documentation by Fasolini (2014) regarding some specifications on their implementation and the observed accuracy levels.

The map from 1954 is a historical land use map that was realized by the use of aerial photographs from "Gruppo Aereo Italiano" (Italian Aerial Group), with a resolution of 0.5 m. This map is the first stereoscopic shooting of the entire Italian territory with panchromatic film. The absence of calibration certificates by the GAI, which are fundamental for the internal orientation of the frames, has represented an obstacle to the management of this data. Ortho-rectification was realized by the use of printed frames in the regional cartographic archive and complemented by approximately 80 missing frames. The ortho-rectification did not always produce homogeneous results, particularly in alpine areas. The problems were linked to the lack of homogeneity, and the positioning inaccuracy of the orthophotos was solved by performing photo interpretation of more recent orthophotos, specifically, the IT2007 by Blom CGR - pixels 50 cm. Generic auxiliary data were used from the IGMI tablets (Italian Military Geographical Institute) of the 25 / V series from the 1950s, which has a scale of 1:25.000.

The land use map from 1980 was obtained by the digitization of land use cartography from photo interpretation at a scale of 1:50000 from the TEM1 flight (Lombardia 1980-82, scale 1:20.000). The land use maps from 2000, 2007 and 2012 are included in the geographic database DUSAF (Destinazione d’Uso dei Suoli Agricoli e forestali - Intended Use of Soils Agricultural and Forestry), which was created in 2000-2001 as part of a project by the Directorates General of Territory, Urban Planning and Agriculture of Lombardy Region and realized by the Regional Agency for Development of Agriculture and Forestry (ERSAF) with the collaboration of the Regional Environmental Protection Agency of Lombardy (ARPA). The maps from 2000 were obtained from the photo interpretation of aerial images from 1998-1999

(Flight IT2000, built by Blom CGR - 1 m pixels). The land use maps from 2007 were realized by using colour and infrared orthophotos from IT2007 (made by Blom CGR - pixels 50 cm).
The map from 2012 was obtained by photo-interpretation of aerial photos realized by Agency for Disbursement in Agriculture (AGEA).
Starting with the land use map from 2007, auxiliary data were processed and managed by the regional system to support the photo-interpretation. The availability of such data improved the thematic accuracy. In fact, the use of databases from the regional database, particularly ERSAF and ARPA Lombardia (e.g., Regional Agricultural Information System, the Forest Types maps, Land cover from satellite, map of the resident population, Archive of Integrated Activities production, etc.), allowed us to improve the simple photo interpretation.
The overall accuracies of the DUSAF products were reported in Zaffaroni (2010) as approximately 95%.
Detailed land use maps were built for the Rio Frate catchment, which registered the highest shallow landslide density during the 2009 event, to evaluate the modifications in the principal agricultural practices. These maps were realized by visually interpreting aerial photographs from 1954, 1980 and 2009. Orthophotos from 1954 were acquired by "Gruppo Aereo Italiano" (Italian Aerial Group), with a resolution of 0.5 m; photos from 1980 were acquired by the Lombardy Region, with a resolution ranging between 0.1 and 1.0 m; and photos from 2009 were acquired by Ditta Rossi s.r.l. (Brescia, Italy), with a resolution of 0.15 m. The accuracy in the classification was approximately 100%. In addition, the land use maps from 2009 were verified through field observations.
Detailed landslide inventory maps were used to understand the relationship between land use changes and the occurrence of shallow landslides. These shallow landslide inventories reference the events in 2009 (Rio Frate and Versa catchments), 2013 (Versa catchment) and 2014 (Alta Val Tidone catchment).
The maintenance time of shallow landslide evidence is strongly influenced by the time that is spent to repair the affected areas and by the natural recovery of vegetation on the exposed failure surface. Evidence of the shallow landslides from 2009 was present until four months after the events occurred.
Post-event colour aerial photographs at a resolution of 0.15 m (photo scale of 1:12000), which were obtained from an aero-photogrammetric survey that was performed by the company Rossi s.r.l., were used to map existing landslides from the 2009 event (Zizioli et al. 2013). The shallow landslides that occurred in 2013 were recorded by means of Pleiades satellite images. PLEIADES triplets from an evaluation program that was organized by AIRBUS Defence & Space (PUG 47 / P.I. Claudia Meisina UNIPavia) were used in a stereo analyst environment to investigate the post-event status and detect the shallow landslides' location by visual

interpretation (Zizioli et al. 2014). Google Earth images were also used alongside field surveys for the shallow landslides from 2014 to analyse areas that were not covered by aerial reliefs.
The data were analysed by means of GIS technologies, which provide a suitable platform for data analysis to determine the qualitative and quantitative aspects of land use changes.

3.2 Land use change detection

Change detection analysis was conducted to investigate the main modifications from 1954 to 2012 and to quantify the percentage of changed area in the three different study areas.
Change detection analysis comprises a wide range of methods to describe and quantify differences in the state of an object, matter, or phenomenon by observing it at different times (Singh 1989). In this case, the total area and proportion of land use occupation throughout the years were analysed by using all the available land use maps. Hereafter, different periods were chosen to provide information regarding the transition rates between the main land use classes. Specifically, the land use variation rates were calculated between the years where significant modifications in land use occurred to highlight the principal variation trends that characterised the three study areas during the investigated time span (1954-2012).

3.3 Frequency ratio analysis

The distribution of shallow landslides on each land use type was obtained by superimposing the position of the landslides' source areas to the land use maps. The available land use map of a period immediately before the considered shallow landslide event was considered for each landslide database. According to these maps, the shallow landslides from the 2009 event, which occurred in the Rio Frate and Versa catchments, were compared to the land use maps from 2007. Meanwhile, the land use map from 2012 was used for the shallow landslides events from 2013 and 2014, which occurred in the Versa catchment and Alta Val Tidone catchment, respectively.
The FRM (Lee and Talib 2005; Regmi et al. 2010) was applied to quantify the influence of land use changes on the occurrence of landslides in each study area. The FRM is based on the observed relationships between the distribution of landslides and a landslide-related factor, in this case, land use changes, to reveal the correlation between landslide locations and this factor in the study area (Lee and Talib 2005; Karim et al. 2011). The frequency ratio (Fr) is calculated by the ratio of the percentage of the landslides in each land use change category to the percentage of each land use change class. This ratio is represented by the following equation equation (equation 1):

$$Fr = \frac{AF_{lu(i)}/A_{lu(i)}}{\sum AF_{tot}\,/\sum A_{tot}} \tag{1}$$

where

$AF_{lu(i)}$ = area that is occupied by shallow landslides within each land use change class *(i)*

$A_{lu(i)}$ = total area that is occupied by each land use change class *(i)*

$\sum AF_{tot}$ = total area that is occupied by shallow landslides in the entire catchment

$\sum A_{tot}$ = total area of the entire catchment

If the value of Fr is higher than 1, the density of landslides in a particular land use change category is higher than the density for the entire map; if the value is lower than 1, the density of landslides in that category is lower than the density for the entire map (Regmi et al. 2010). Then, the land use change class with the highest Fr value can be considered more susceptible to landslides, while those with the lowest values have minor roles in landslide occurrence. The Fr also allows us to consider the area in a region that is occupied by a single land use change type, so this factor can better convey the effective influence of a land use change on the occurrence of shallow landslides. Thus, the distribution of shallow landslides in each area was compared to the most significant identified land use change that occurred in the study area immediately before the landslide event.

4. RESULTS AND DISCUSSION

4.1 Land use analysis

According to the available land use maps for the study areas (1954, 1980, 2000 2007 and 2012), the main land use classes that characterise the territory of all the areas are as follows: vineyards, uncultivated areas, arable areas, urban areas, woods and grasslands (Figure 2).

The land use maps that represent the most important land use changes are shown in Figure 2. The land use maps from 1980, 2007 and 2012 represent the Rio Frate catchment, while the maps from 1954, 2007 and 2012 represent the other two catchments.

Uncultivated areas are mainly composed by shrubbery species, which sometimes grow because of abandonment and reduced management of agricultural areas, particularly slopes that were previously cultivated with vineyards or sowed species (arable lands). Arable areas represent field crops of annual herbaceous plant communities, especially forages, which mostly consist of Medicago sativa. Woods mainly consist of broad-leaved trees, with rare conifer trees that were planted after 1960 in the Alta Val Tidone area. Grasslands are zones that are dedicated to pasture and are characterised by a dominant percentage of permanent grass species with scattered trees and shrubs (Brambilla et al. 2010). Urban areas are anthropic settlements of small dimension within a rural context. These areas are characterised by negligible modifications over the last 60 years, so they were excluded from further analyses.

The land use map from 2012, which represents a similar land use distribution to the present, was used to describe the main land use classes that currently characterise each study area.

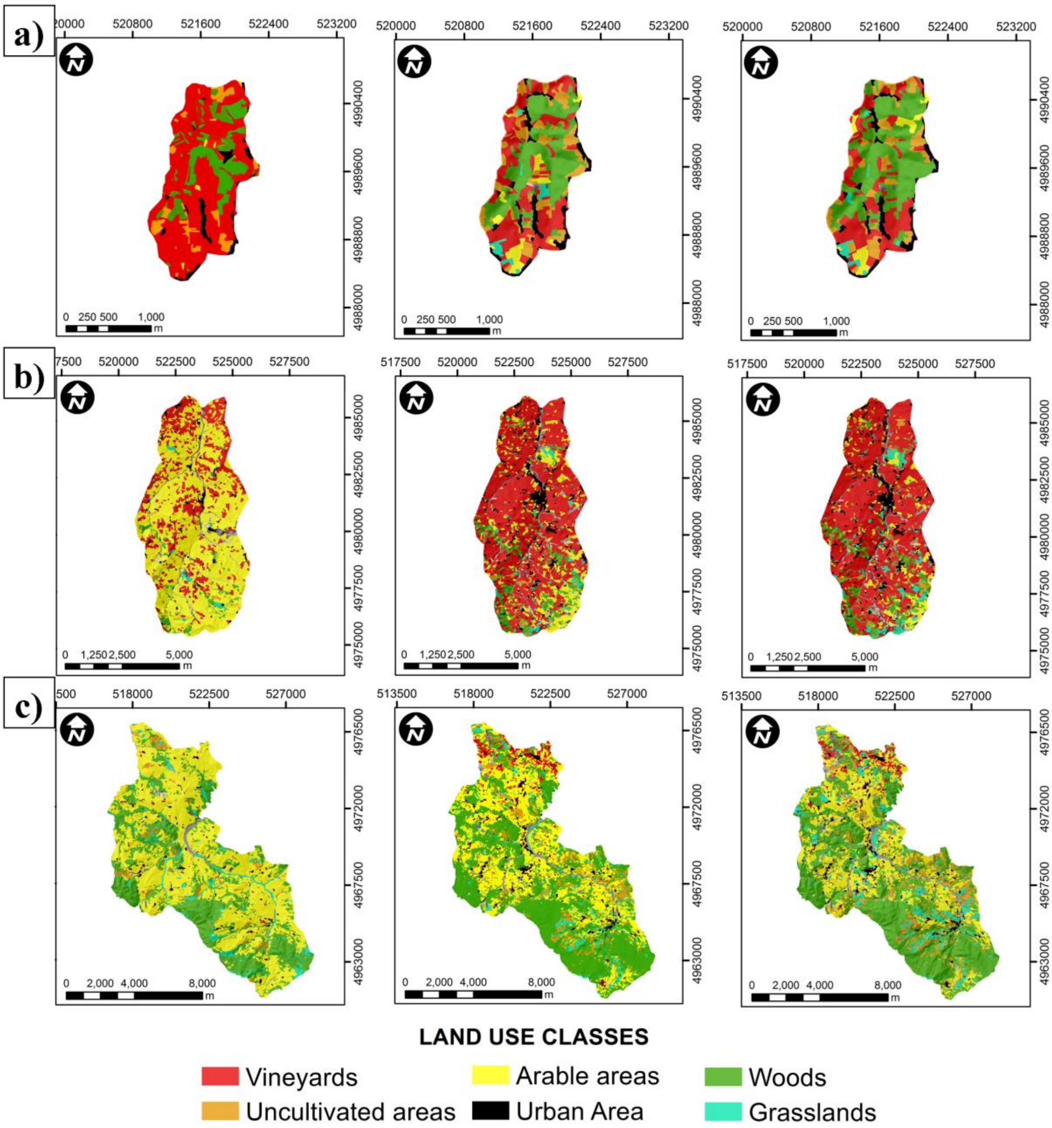

Figure 2. Maps that show the main land use changes that occurred in each study area: a) Rio Frate catchment: from left to right, land use maps from 1980, 2007, and 2012; b) Versa catchment: from left to right, land use maps from 1954, 2007, and 2012; c) Alta Val Tidone catchment: from left to right, land use maps from 1954, 2007, and 2012

Specifically, the Rio Frate catchment is mostly characterised by cultivated vineyards (26%) and woods (44%) (Figure 2a). Most of the woods along the slopes of the Rio Frate developed in correspondence with vineyards that were abandoned after the 1980s and mostly consist of black locust (Robinia pseudoacacia) trees. The remaining woods (15%) are represented by historical woods, which have been present since 1954. These woods are located principally in the northern and central parts of the catchment and include mixed woods that consist of broad-leaf species (Sartori and Bracco 2011), particularly black locusts and maples. Uncultivated areas (13%) are also well distributed across the territory and correspond to shrub lands that developed along slopes that were previously cultivated with vineyards.

The Versa catchment is mostly characterised by cultivated land, namely, arable land (9%) and vineyards (65%) (Figure 2b). In this case, woods are extensive compared to those in the Rio Frate (9.50%) and can be divided into recent woods, which mainly consist of black locusts, and historical woods (ca. 4%) with mixed species of broad-leaf plants.

Compared to the other two sites, the Alta Val Tidone catchment is represented by different land use characteristics. A total of 44% of territory is covered by woods, including 24% of the Upper Alta Val Tidone, which contains calcareous marls with interbedded clay and is characterised by low-lying soil thickness. These woods mainly consist of mesophilous Ostrya carpinifolia woods, thermophilous Quercus pubescens woods and mixed Fagus sylvaticae woods (Assini et al. 2014). In particular, Ostrya carpinifolia woods and mixed Fagus sylvaticae woods are mainly distributed in the southern part of the catchment above 800 and 1000 a.s.l., respectively, mostly in areas with very steep slopes. Quercus pubescens woods are mainly found in the centre of the catchment below 800 m a.s.l., where the slopes are less steep. Arable lands (29%) are predominant in the Lower Alta Val Tidone, reaching a value of 21% compared to 8% in the southern part. These lands are distributed at lower altitudes below 600 m a.s.l. and along slopes between 8° and 15°, in correspondence with sandstones that are interbedded with clay and sandstones and limestones in a clay matrix. The Alta Val Tidone catchment is also characterised by a higher percentage of grasslands (8%), which represent a valuable semi-natural habitat for biodiversity conservation. In particular, 5% of the total grassland area is distributed principally in the central and southern parts of the catchment. These lands mostly consist of Onobrychis viciifolia, Brachypodium rupestre and Bromus erectus communities (Assini et al. 2014) and are located at altitudes between 500 m and 900 m a.s.l., with slopes ranging between 15° and 20°, especially in areas with calcareous marls and sandstones with interbedded clay. The lands that are cultivated with vineyards in this study area are negligible, as demonstrated by their limited presence (2.60%) in the northern part (Figure 2c).

4.2 Land use change characterization

Analysing the different available land use maps for the study areas allows us to identify the main land use changes that occurred during the monitored time span. Some limitations were encountered during this phase because of the difficulty in managing land use maps, which often include different classification criteria.

The main land use changes in the Rio Frate catchment were observed after 1980, as shown in Figure 2a and specified in the histograms in Figure 3. Specifically, more than 75% of the Rio Frate catchment was covered by vineyards, 15% by woods and only 0.95% by uncultivated areas until the 1980s. From 1980 to 2000, the area was characterised by an important land use modification: a significant increase in uncultivated areas and recent woodlands, which developed along most of the slopes that were cultivated with vineyards from 1954 to 1980.

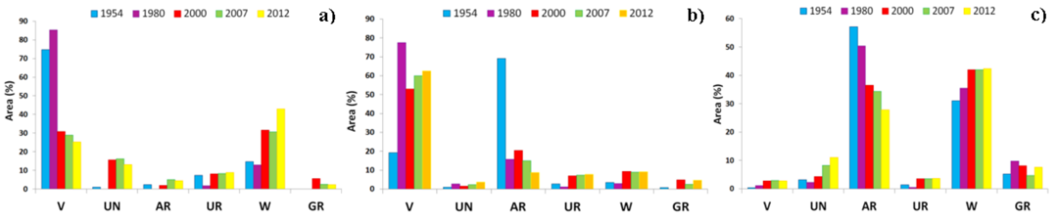

Figure 3. Histogram of the land use distribution and land use changes from 1954 to 2012 in the three study areas: a) Rio Frate catchment; b) Versa catchment; c) Alta Val Tidone catchment. V: Vineyards; UN: uncultivated areas; AR: arable areas; UR: urban areas; W: woods, GR: grasslands.

In fact, 57% of the area was covered by uncultivated areas and recent woods from 2000 to 2012, while only 26% of the territory remained cultivated with vineyards (Figure 3a).

Pronounced transformation occurred in the Versa catchment after 1954. In particular, the arable areas decreased from 72% in 1954 to 9% in 2012 and were substituted completely by vineyards, which now represent 65% of the total area (Figure 3b).

Despite the geographic proximity of the Rio Frate and Versa catchments, a huge contrast exists between the land use changes that characterised these two study areas. These changes were mainly linked to the geomorphological characteristics of these two study areas, which in turn were strongly influenced by the peculiar geological settings of these two catchments. In particular, the very steep slopes (25°-35°) that characterised almost the totality of the Rio Frate catchment strongly contributed to the principal modifications of agricultural land management that occurred in this area. In fact, the difficulty in performing maintenance practices by means of agricultural equipment led to the abandonment of vineyards that could not be cultivated with mechanical tools, beginning with the most impervious slopes, which are characterised by a high slope gradient (> 25°).

Most of the territory in the Versa catchment was characterised by gentle slopes (15°- 25°), which allowed the high exploitation of the mechanical practices that were introduced after 1954. This process allowed the optimization of these agricultural practices, leading to a complete conversion of the territory from arable areas to vineyards and permitted the transformation of the area in the most-developed economic centre, especially thanks to the large valuable production of wine.

The Alta Val Tidone catchment was characterised by a progressive phenomenon of land abandonment, especially in the Upper Alta Val Tidone. The changes mainly involved a gradual decrease in arable areas and a consequent increase the area of uncultivated areas and woods (Figure 3c).

Two time intervals were considered to highlight the principal land use variation trends that characterised the three study sites in correspondence with the main shallow landslide events (Table 2): 1) the time span between 1954 and 2007 was selected to represent the situation before the occurrence of the shallow landslide events; and 2) the interval from 2007 to 2012 was chosen to represent the catchments' peculiarity during the main shallow landslide phenomena (2009, 2013 and 2014).

Table 2. Area ad amount of change in different land use classes from 1954 to 2007 and from 2007 to 2012. V: vineyards; UN: Uncultivated areas; AR: arable areas; UR: Urban areas; W: Woods; GR: Grassland.

STUDY AREAS	LAND USE	1954		2007		2012		Change 1954-2007		Change 2007-2012	
		km^2	%	km^2	%	Km^2	%	Km^2	%	Km^2	%
Rio Frate	V	1.44	74.80	0.61	29.76	0.50	26.06	-0.11	**-45.03**	-0.11	**-3.71**
	UN	0.02	0.95	0.34	16.68	0.26	13.43	-0.08	**15.73**	-0.08	**-3.25**
	AR	0.05	2.35	0.10	5.12	0.09	4.63	-0.02	2.76	-0.02	-0.48
	UR	0.14	7.27	0.17	8.55	0.18	9.16	0.00	1.28	0.00	0.61
	W	0.28	14.64	0.64	31.56	0.85	44.24	0.21	**16.93**	0.21	**12.68**
	GR	0.00	0.00	0.17	8.33	0.05	2.48	-0.12	8.33	-0.12	**-5.85**
Versa	V	7.41	19.94	23.28	62.43	24.06	64.79	15.86	**42.49**	0.78	2.37
	UN	0.37	0.98	0.87	2.33	1.42	3.82	0.50	1.35	0.55	1.49
	AR	26.70	71.80	5.82	15.61	3.36	9.04	-20.88	**-56.19**	-2.47	**-6.57**
	UR	1.05	2.83	2.90	7.78	2.98	8.04	1.85	4.95	0.08	0.26
	W	1.36	3.65	3.46	9.28	3.53	9.50	2.10	5.63	0.07	0.21
	GR	0.30	0.81	0.96	2.57	1.79	4.82	0.66	1.77	0.83	2.25
Alta Val Tidone	V	0.28	0.30	2.78	3.08	2.66	2.96	2.50	2.78	-0.12	-0.12
	UN	2.96	3.20	7.78	8.63	10.40	11.57	4.82	5.43	2.62	2.94
	AR	53.80	58.17	32.29	35.81	26.25	29.21	-21.51	**-22.35**	-6.04	**-6.61**
	UR	1.30	1.41	3.37	3.74	3.44	3.83	2.07	2.33	0.07	0.09
	W	29.24	31.61	39.54	43.86	39.93	44.43	10.30	**12.24**	0.39	0.57
	GR	4.91	5.31	4.40	4.88	7.20	8.01	-0.51	-0.43	2.80	3.13

Although the time spans of the two intervals are too diverse, the period 2007-2012 was chosen because modifications in the land use change trends were only observed after 2007. Unfortunately, land use maps from after 2012 are not available.

The Rio Frate catchment experienced significant land abandonment, with a progressive increase in woods (+17%) and uncultivated areas (+15%) and a drastic decrease in vineyards (-45%). Starting from 1954, the area was almost completely occupied (75%) by vineyards, which began to decrease since 1980 in response to important modifications to agricultural land management. In particular, the conversion from manual to mechanical cultural practices had made the maintenance of vineyards difficult, especially those along very steep slopes, encouraging the abandonment of these areas because of the lack of safety measures during the performance of maintenance practices by means of agricultural equipment.

The major changes in the Versa catchment involved the modification of agricultural practices, with a decrease in arable areas (- 56%) and increase in vineyards (+42 %).

The amount of arable areas in the Alta Val Tidone catchment have decreased by approximately 22%, with a correspondent increase in woods (+12%) and uncultivated areas (+5%). This progressive abandonment of cultivated areas was manly associated with the human-depopulation of mountainous rural territories and landslide activity, which had characterised the areas since 1954.

After the period 1954 -2007, the land use changes gradually decreased in all the catchments, as demonstrated by the changes that were calculated from 2007 to 2012 and as shown in Table 2. These results can be attributed to new land use management policies that were developed at the municipal level. In fact, approximately 15 municipalities in the Oltrepo Pavese hills approved municipal regulations between 2009 and 2013 to regulate the processing techniques of agricultural lands and the management of uncultivated areas (Rural Police Regulation 2008).

Nevertheless, the woods in the Rio Frate catchment recorded almost the same increases between 1954-2007 and 2007-2012 because of the progressive transformation of uncultivated areas into woods.

Finally, a cross tabulation matrix was obtained to determine the quantities of conversion from a particular land use class to another (Table 3). This process allowed us to better understand the land encroachment that characterised the time span between 1954 and 2007 and to define the principal transition rates between the main modified classes.

Table 3. Land use change matrix of land encroachment (%) from 1954 to 2007. V: vineyards; UN: Uncultivated areas; AR: arable areas; UR: Urban areas; W: Woods; GR: Grassland.

STUDY AREAS	LAND USE		1954					
			V	UN	AR	UR	W	GR
Rio Frate	2007	V	40.28	61.83	12.43	1.01	2.20	0.00
		UN	**21.04**	27.46	**28.13**	1.23	5.67	0.00
		AR	7.06	0.00	0.00	0.77	0.00	0.00
		UR	4.14	10.71	2.52	76.44	1.67	0.00
		W	**23.54**	0.00	**56.91**	19.50	89.76	0.00
		GR	3.37	0.00	0.00	1.04	0.68	0.00
Versa	2007	V	73.11	**31.12**	**63.31**	5.56	8.08	**63.53**
		UN	1.81	9.61	2.41	0.03	0.71	13.09
		AR	12.29	6.34	16.59	2.13	3.15	10.97
		UR	6.56	4.34	4.95	89.35	3.36	0.74
		W	3.27	**30.05**	7.1	2.22	80.43	8.99
		GR	1.95	1.92	2.97	0.37	1.62	0.00
Alta Val Tidone	2007	V	16.50	1.89	4.85	0.99	0.09	0.46
		UN	9.79	20.45	10.66	1.53	1.67	14.36
		AR	**52.27**	5.06	57.53	8.72	1.82	5.34
		UR	7.57	0.43	0.01	80.96	0.26	0.89
		W	10.17	**65.28**	13.16	5.21	94.78	**49.81**
		GR	2.19	5.74	6.25	1.08	0.73	10.22

Pronounced abandonment occurred in the Rio Frate and Alta Val Tidone catchments. Around 23% of the vineyards in the Rio Frate site became woods and 21% into uncultivated areas, most of them corresponding to abandoned vineyards. Shrubs and wood plants gradually and naturally established in these abandoned vineyards, substituting grapevines with the complete abandonment of drainage works. Field evidence showed that shrubs completely colonized abandoned vineyards within 5 years. The plants in the shrub lands were progressively substituted by woody trees within another 5 years, transforming the shrub lands in woodlands. Another important modification occurred in the arable lands, with as much as 57% turning into woods and 28% into uncultivated areas.

Around 65% of the uncultivated areas and 50% of the grasslands in the Alta Val Tidone catchment became woods, underlining the progressive abandonment in this catchment. In particular, uncultivated areas and grasslands were progressively covered by shrubs, and shrub land was progressively invaded by trees. These fast and widespread environmental changes have been interpreted by some authors as an important cause of drastic decreases in habitat suitability (Assini et al. 2014; Brambilla et at. 2010; Farina 1997, 1995; Mazzoleni et al. 2004).

Compared to the previously described areas, the main transformation in the Versa catchment involved the use of different agricultural practices (Table 3). Around 63.3% of the arable areas, 63.5% of the grasslands and 31% of the uncultivated areas were converted into vineyards. Effectively, this area is part of the Oltrepò Pavese District of Quality Wines, including the production of DOP wines, which is marked with a Protected Designation of Origin.

In Table 3, the observed transition from urban areas (1954) to vineyards (2007) was caused by the different classification criteria that were used between the two land use maps. In fact, thematic auxiliary data, such as the Regional Agricultural Information System, Forest Types maps, Land cover from satellites, a map of the resident population and the Archive of Integrated Activities production, were used to increase the classification accuracy of the DUSAF map from 2007. However, the absence of thematic auxiliary data to support the photo interpretation did not allow us to obtain the same level of accuracy for the land use map from 1954. The urban areas in the land use maps from 1954 also included scattered and sparse residential areas that corresponded to farms and, in most cases, tool sheds. These areas were completely abandoned after 1954 because of the gradual migration of farmers into towns. Thus, these areas in the land use map from 2007 were classified as parts of the vineyards because they were located within the cultivated lands. In any case, the percentage of these changes was very small (between 1% and 5 %) and negligible for the purposes of this analysis, and the urban areas were excluded from further consideration regarding the relationship between land use changes and the distribution of shallow landslides.

4.3 Agricultural practice modifications

Aerial photographs from 1980 and 2009, which had spatial resolutions of 0.1 and 0.15 m, respectively, were taken from the Rio Frate catchment to evaluate the main modifications of agricultural practices in vineyards and their subsequent abandonment from 1980 to 2009 (Figure 4).

In addition to the previously mentioned land use classes, other specific classes were identified: abandoned vineyards (Ab VN), in which grapevine plants and the row tillage pattern are still present but cultivation works are no longer practiced, causing the gradual natural substitution of grapevines with shrubs and plants species; vineyards whose row directions are perpendicular to the maximum slope gradient (Perp VN); and vineyards whose row directions are parallel to the maximum slope (Par VN).

In cultivated vineyards, the tillage systems are usually characterised by a distance between the plants along the same row between 0.8 and 1.9 m and a distance between two adjacent rows between 2.1 and 2.4 m. The rows sometimes reach lengths greater than 100 m. The root stocks are 420A and SO4, both with the same combination of Vitis berlandieri and Vitis riparia.

Two main cultivation techniques have been adopted:

1) Permanently swarded interrows throughout the year. Grass cutting occurs during the spring-summer months according to its seasonal growth rhythm and the annual rainfall rate but without removing the grass completely;

2) Soil tillage within the first 0.2 m one or two times a year to ensure that the interrows are completely devoid of any type of herbaceous essence throughout the year.

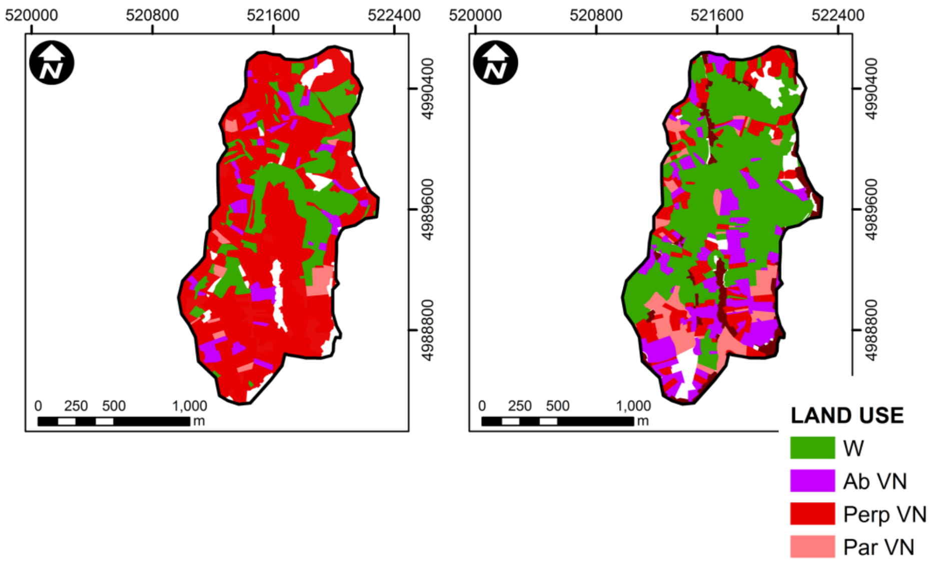

Figure 4. Detailed classification of the land use changes in the Rio Frate catchment. The left side shows the land use map from 1980, and the right side shows the land use map from 2009. The vineyards were subdivided into abandoned vineyards (Ab VN), vineyards with row directions that were perpendicular to the maximum slope gradient (Perp VN), and vineyards with row directions that were parallel to the maximum slope (Par VN). Woods were included to show their increasing area from 1980 to 2009.

As shown in Figure 4, woods and Ab VN increased drastically to the detriment of Perp VN from 1980 to 2009. After 1980, Par VN gradually replaced Perp VN (Figure 4). As shown in Table 4, the area was almost completely occupied (63.2%) by Perp VN in 1980. Ab VN experienced small growth, increasing from 5.4% in 1980 to 6.9% in 2009. At the same time, Par VN became more widespread than Perp VN, increasing from only 5.9% in 1980 to 21.7% in 2009. Until the 1980s, agricultural works were conducted in a traditional manner with weeding and digging, and the realization of Par VN allowed farmers to optimize the grapevine density and mechanical work. In addition, changes in the socio-economic context meant that vineyards that could not be cultivated with mechanical tools were completely abandoned, starting from the most impervious slopes with high slope gradients (> 25°). In Ab VN, grapevine plants can live for a number of years and are gradually substituted by natural vegetation species until the complete recovery of these slopes with shrubs (shrub lands) or broad-leaf plants (in this case, Robinia pseudoacacia). These transformations were realized principally to achieve greater efficiency in the mechanization of vineyard management. However, these practices decreased the maintenance activities of water regulation. Moreover, the Rio Frate catchment was characterised by a drastic reduction in drainage system density from 1980 to the present. This change worsened the effects of a lack of water regulation, such as increases in surface water runoff and the consequent intensification of erosion processes.

In addition, ground truth activities that were conducted in this study area indicated that these increases in soil erosion from the above agricultural techniques consequently increased soil instability.

4.4 Effect of land use changes on the occurrence of shallow landslides

Slope instability systems are typically multivariate, so an analysis was performed after a preliminary multivariate analysis (Bordoni et al. 2015; Persichillo et al. 2016).

Specifically, a nonlinear regression technique that was based on the Generalized Additive Model was applied. Twelve prediction variables were identified according to their influence on shallow landslide mechanisms: slope, aspect, profile curvature, planform curvature, catchment area, catchment slope, topographic wetness index, topographic position index, terrain ruggedness index, Euclidean distance from roads, geology, and land use. This analysis allowed us to identify the most important factors in the occurrence of shallow landslides. In particular, the frequency of predictive variables that were selected by the 100-fold bootstrap procedure was calculated, and the most significant variables were those that were selected 80% of the time. In the Rio Frate catchment, the land use reached a high percentage (63) but fell under the selection threshold because the shallow landslide susceptibility in this area was strongly influenced by the slope, which represented the most selected predisposing factor according to the GAM's performance (100%). In the Versa and Alta Val Tidone catchments, the land use was the variable that reached one of the highest selection frequencies: 92% and 95%, respectively.

After this first investigation, an in-depth analysis on the role of land use and its changes over time was perform to better understand its influence on the distribution of shallow landslides.

The analysis mainly involved identifying the land use classes that were more prone to shallow landslides through observations of the distribution of past shallow landslides across several land use types.

An initial observation of the distribution of shallow landslides within the study areas indicated that landslides tended to be concentrated within three main geomorphological contexts: (i) at the top of steep slopes (slope angles > 15–20◦) with continuous profiles; (ii) along slopes whose angles changed from a gentle slope to steep slope, which sometimes corresponded to changes in land use (from a gentle slope with vineyards to steep slopes with woodland); and (iii) in morphological jugs that break the continuity of the slopes. In these areas, the greater superficial runoff and the convergence of sub-superficial outflows in the cover materials increased the pore water pressure and the saturation of the covering soils.

In the Rio Frate, the land use classes that were affected by most of the landslides were woods and uncultivated areas, which were mostly represented by abandoned vineyards. This result was demonstrated by the Fr, as shown in Figure 5a.

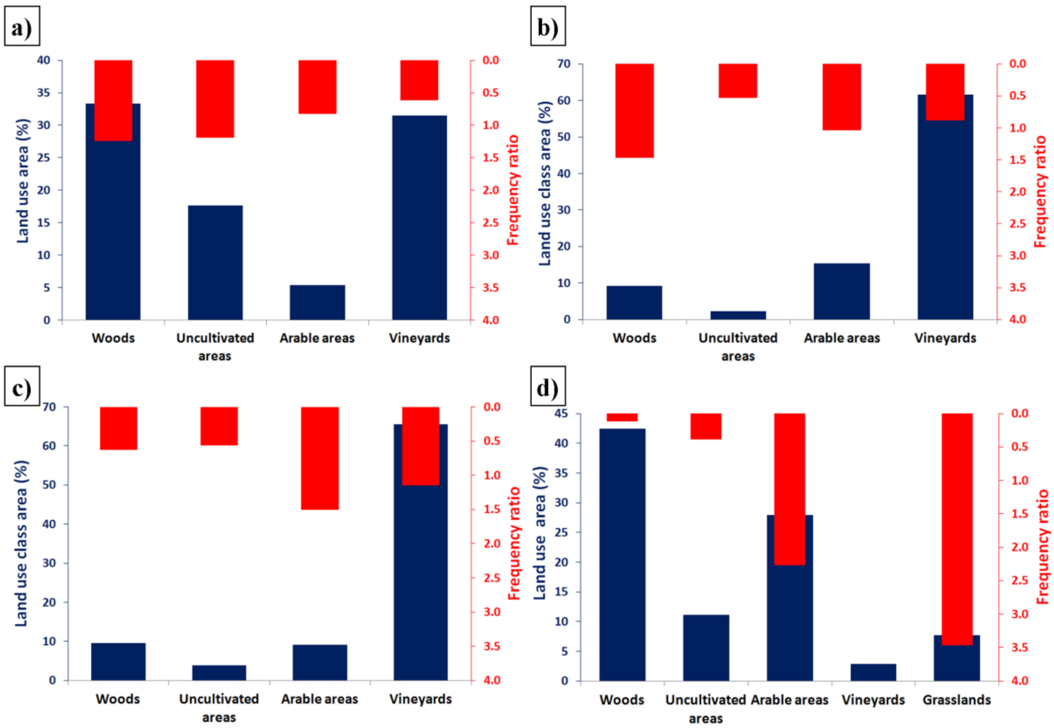

Figure 5. Frequency ratio of shallow landslides for each land use category. a) Event from 2009 in the Rio Frate catchment, b) event from 2009 in the Versa catchment, c) event from 2013 in the Versa catchment, d) event from 2014 in the Alta Val Tidone catchment.

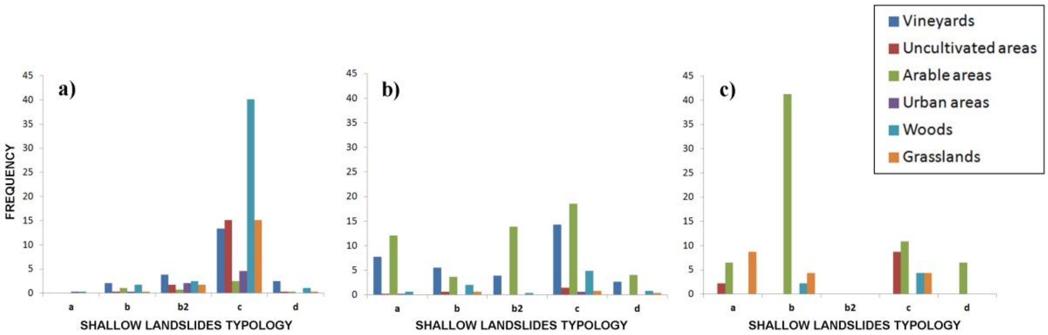

Figure 6. Typology distribution of shallow landslides in relation to the different land use classes. **a)** Rio Frate catchment; **b)** Versa catchment; **c)** Alta Val Tidone catchment

On the contrary, the land use classes in the Versa catchment that were the most susceptible to instability in both 2009 and 2013 were vineyards, arable areas and woods (Figure 5b, c).

Most of the shallow landslides in the Alta Val Tidone catchment occurred in arable areas and grasslands, as shown by the extracted Fr values (Figure 5d).

Analysing the shallow landslides' typology distribution in relation to the different land use classes indicated that the movement types of the shallow landslides were not influenced by specific land use categories, as shown in Figure 6.

The FRM (Lee and Talib 2005) was used to better understand the role of land use changes in the occurrence of shallow landslides. This method allowed us to highlight the land use changes that most influenced the occurrence of shallow landslides and therefore increased the susceptibility of the investigated territories to slope instability. Specifically, the shallow landslides from 2009 in the Rio Frate and Versa catchments were compared to the land use variations from 1954 to 2007, while the shallow landslides events in 2013 and 2014 that occurred in the Versa and Alta Val Tidone catchments, respectively, were compared to the land use change map that was obtained from an analysis of the land use variations from 1954 to 2012.

In all three study areas, the highest susceptibility to shallow landslides (Fr >1) was obtained for land use change categories that showed evident phenomena of land abandonment. In the Rio Frate catchment, the most susceptible land use change category, which reached Fr values greater than 1, were those that changed from vineyards to uncultivated areas and woods (Table 5a). This result reflects what occurred during the event in 2009, in which these two classes (woods and uncultivated areas) were affected by the highest number of landslides (Figure 5a). The old tillage patterns along the slopes where the cultivations were abandoned and vegetation recovery occurred were maintained, but the agricultural ditches to drive water along the slopes were no longer used. In this way, water infiltrates into the soil, causing the development of perched water tables during the most intense rainfall events (Bordoni et al. 2015a, 2015b) and increasing the probability of instability.

Additionally, the land use classes that transformed from arable land to vineyards showed high susceptibility (Table 5a) to shallow landslides. These classes included Par VN, which were located along steep slopes.

The high susceptibility to instability of this particular type of vineyard was confirmed by the detailed analyses that were performed to understand the role of vineyard management practices on the occurrence of shallow landslides in the Rio Frate catchment. In particular, the highest Fr values were registered in Perp VN that had transformed into Par VN (Table 6).

Table 5. Frequency ratio of shallow landslides for each land use changes. a) in the period 1954-2007 to analysed the shallow landslides event occurred in the 2009 in the Rio Frate and the Versa catchments; b) in the period 1954-2012 to analysed the shallow landslides events occurred in the 2013 and 2014 in the Versa and the Alta Val Tidone catchments, respectively. Each cell is split diagonally in two parts: in black (top) and in red (bottom) are shown the Area of land use change classes and the FRM scores, respectively; in bold and underlined are illustrated FRM scores higher than 1.0. V: vineyards; UN: Uncultivated areas; AR: arable areas; UR: Urban areas; W: Woods; GR: Grassland.

a) Shallow landslides 2009

STUDY AREA		AREA (%) / FRM score	LAND USE 1954				
			V	UN	AR	W	GR
Rio Frate	LAND USE 2007	V	34.74 0.50	0.00	0.34 **<u>3.25</u>**	0.00	0.00
		UN	18.14 **<u>1.01</u>**	0.00	0.76 **<u>1.79</u>**	0.00	0.00
		AR	6.08 0.69	0.00	0.00	0.00	0.00
		W	20.29 **<u>1.32</u>**	0.00	1.54 0.72	15.22 **<u>1.78</u>**	0.00
		GR	2.91 0.94	0.00	0.00	0.00	0.00
Versa	LAND USE 2007	V	20.67 **<u>1.19</u>**	0.00	58.98 0.87	0.00	0.00
		UN	0.51 0.32	0.00	2.24 0.55	0.00	0.00
		AR	3.47 **<u>1.03</u>**	0.00	0.00	0.00	0.00
		W	0.93 **<u>3.74</u>**	0.00	6.54 **<u>1.09</u>**	3.88 **<u>2.01</u>**	0.00
		GR	0.00	0.00	2.77 0.28	0.00	0.00

b) Shallow landslides 2013 - 2014							
STUDY AREA		AREA (%) / FRM score	LAND USE 1954				
			V	UN	AR	W	GR
Versa	LAND USE 2012	V	19.87 / **1.90**	0.00	57.41 / 0.78	0.00	0.00
		UN	1.01 / 0.73	0.00	3.37 / 0.04	0.00	0.00
		AR	1.66 / 0.40	0.00	0.00	0.00	0.00
		W	0.91 / **2.78**	0.00	6.31 / 0.74	3.64 / **1.11**	0.00
		GR	0.98 / 0.53	0.00	4.84 / 0.88	0.00	0.00
Alta Val Tidone	LAND USE 2012	V	0.00	0.00	0.00	0.00	0.00
		UN	0.00	0.00	10.84 / 0.37	0.00	0.00
		AR	0.00	0.00	33.66 / **2.00**	0.00	0.00
		W	0.00	2.55 / **1.60**	9.43 / 0.10	35.24 / 0.01	0.00
		GR	0.00	0.00	8.29 / **2.82**	0.00	0.00

Table 6. Detailed frequency ratio analysis about the modification on vineyards management practices occurred in the Rio Frate catchment from 1980 to 2009. Ab VN: abandoned vineyards; Perp VN: vineyards with row direction perpendicular to the maximum slope gradient; Par VN: vineyards with row direction parallel to the maximum slope.

Frequency ratio		Land use 1980		
		Ab VN	Perp VN	Par VN
Land use 2007	Ab VN	0.0	6.5	0.2
	Perp VN	0.2	7.6	0.3
	Par VN	0.3	**12.5**	1.2

The strong predisposition of this type of vineyard (Par VN) to shallow landslides can be principally linked to the agricultural techniques that had been practiced for their maintenance. Specifically, the row length characteristics; the presence of swarded interrows; the quality of maintenance activity, especially regarding water regulation; and the interrows' tillage practices can have strong influence on a slope's instability.

According to the results, even the woods that did not change reached a high Fr value (Fr = 1.78). These shallow landslides were located along very steep slopes (30° - 35°) with respect to this particular land use class, representing the main reason for the instability.
In the Versa catchment, the vineyards that became woods proved to be the land use change class that was most susceptible to shallow landslides in both 2009 and 2013 (Table 5a,b). Additionally, an important role may have been played by the vineyard management practices that were adopted, such as the row lengths, the water regulation systems and the presence of swarded interrows to control water infiltration.
As in the Rio Frate catchment, unmodified woods in the Versa catchment were very susceptible to shallow landslides (Fr of 2.01 for the event in 2009 and 1.11 in 2013). Additionally, these landslides are located on slopes with higher gradients with respect to the entire catchment (16° - 20°), making this area more susceptible to instability.
In the Alta Val Tidone catchment, Fr values greater than 1 were reached because of the progressive abandonment of cultivated fields, as indicated by the shift from uncultivated areas to woods (Fr = 1.60) and transformation from arable areas to grasslands, the latter reaching the highest Fr values (Fr = 2.82). Additionally, arable areas that had not undergone changes achieved Fr values equal to 2.00 (Table 5b). An analysis of the spatial distribution of these land use change classes revealed that the predisposition of certain areas to shallow landslides was sometimes influenced by the combined effect of land use changes and the local geological conditions. In particular, both the Lower and Upper Alta Val Tidone areas contained arable areas that changed to grassland and arable lands that did not change. However, only the mentioned classes in the northern sector were affected by shallow landslides during the 2014 event (Figure 1c). This difference is mainly explained by the different geological features that characterise the two zones. The Lower Alta Val Tidone is principally characterised by adverse local geological aspects, including marls and shale with few arenaceous intercalations and hemipelagic clays with very high soil thickness (c. 4 m). Meanwhile, the Upper Alta Val Tidone is characterised by more stable geological settings, such as calcareous-marls with interbedded clay and much lower soil thickness (less than 20 cm). More generally, very few shallow landslides were registered in the Upper Alta Val Tidone area during the event in 2014. The presence of a high percentage of woodlands, which principally consist of Quercus pubescens and Fagus sylvaticae, likely caused additional positive effects, such as an increase in the soil's mechanical strength (Bischetti et al. 2009), on the slope stability in this area. The positive influence of these woods was also confirmed by the Fr results, which showed that the woods never reached values greater than 1 (Table 5b).
Therefore, the slope instability in the Alta Val Tidone catchment was influenced not only by progressive land abandonment but also by the combined effect of the geological characteristics of this area and the geotechnical properties of the soil.

5. CONCLUSIONS

A multi-temporal land use change analysis and an evaluation of the influence of land use changes on the occurrence of shallow landslides allowed us to understand the geomorphic responses to land use changes. Specifically, the land use modifications that occurred over the last 58 years were investigated in three shallow landslide-prone areas that were representative of peculiar land use settings in the Oltrepò Pavese in the northern Apennines: the Rio Frate, Versa and Alta Val Tidone catchments.

The preliminary multivariate analysis, which was conducted through a nonlinear regression technique, highlighted that the land use throughout the study area was the most important landslide-predisposing factor.

Afterward, an in-depth analysis allowed us to evaluate the historical land use change profiles of the studied areas from 1954 to 2012. In particular, pronounced land abandonment and important modifications to agricultural practices were observed. These land use changes most influenced the shallow landslide susceptibility of the three study areas.

Specifically, abandoned cultivated lands such as vineyards and arable areas that gradually recovered through natural grasses, shrubs and woods were the land use classes that were most susceptible to instability. Moreover, the negative qualities of the practiced maintenance activities intensified erosion processes and subsequent instability phenomena.

In addition, the analyses allowed us to underline how the predisposition of certain areas to shallow landslides was influenced by the combined effect of land use changes and the geological and geomorphological conditions. The most susceptible areas were, in fact, located in correspondence with abandoned areas that were developed in thick soils (up to 2.0 m) from clayey-marly bedrock. Similar abandoned areas that were developed in thin soils (less than 0.5 m) from calcareous bedrock were significantly less susceptible because of the low soil thickness and their better shear strength properties. High susceptibility was also identified in correspondence with land uses that did not change over time but were located on slopes with gradients higher than 25°.

In conclusion, the present work showed the negative role of the abandonment of cultivated lands on the shallow landslide susceptibility of certain territories, highlighting the need to improve and increase maintenance activities in agricultural areas to guarantee greater land conservation. Furthermore, the achieved results underlined that sustainable management techniques within land management strategies should actually be implemented in the territory to reduce the occurrence of instability processes.

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9 The role of the vineyards on slope stability: a case study from an area susceptible to shallow landslides

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The role of the vineyards on slope stability: a case study from an area susceptible to shallow landslides

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ABSTRACT

Hilly slopes cultivated with vineyards of Oltrepò Pavese (northern Italy) are often affected by rainfall-induced shallow landslides, which cause destruction and loss of the cultivations. The assessment of soil reinforcement of grapevine roots is then fundamental for slope stability analyses. In sites affected by shallow landslides, root density is lower, probably due to the lowest soil permeability. Despite the differences of soil features, type of bedrock, grapevine age and vineyards row orientation, an unique relationship between root diameter and root tensile strength can be identified. The total root reinforcement follows the trend of the root density. Grapevine roots can give a good reinforcement on soil, usually in the first 0.9-1.0 m from ground level.

KEY WORDS: Shallow landslides, vineyards, root reinforcement.

INTRODUCTION

Rainfall-induced shallow landslides affect superficial soils located above bedrock materials and are the most frequent gravitational processes which develop in cultivated steep terrains (Glade, 2003). These phenomena are very common in areas with viticulture vocation, especially in Italy and in other countries of Central and Southern Europe (Van den Eeckhaut et al. 2010; Cevasco et al. 2014; Bordoni et al. 2015).

In spite of the diffusion and consequences of shallow landslides on vineyards, no significant studies have been carried out to investigate the role played by grapevine plants on preventing or promoting landslides triggering. At the same time it is well known from ages the beneficial effect of plants in preventing shallow slopes instabilities, in particular for forest trees (Schmidt et al., 2001; Bischetti et al., 2009; Schwarz et al., 2010; Wu, 2012). Generally the literature focused, up to now, mainly on the mechanical effects of vegetation accounting them in terms of additional mechanical root reinforcement to be used in slope stability models and in the assessment of shallow landslides susceptibility and in the development of both hazard and risk mitigation strategies.

As already provided for forest species, it should be fundamental assessing the mechanical reinforcement of agricultural plants cultivated in steep terrains, as the grapevine. To contribute to fill this gap, the soil strength contribution in terms of additional root reinforcement of grapevine plants was analyzed, linking the grapevine root distribution patterns within the soil profile to the measured grapevine root tensile strength, for the quantification of the grapevine additional root reinforcement to the soil.

STUDY AREA

The study area, 13.4 km^2 wide, is located in the north-eastern sector of Oltrepò Pavese, which belongs to the north-western Italian Apennines (Fig. 1). It corresponds to the so called “Buttafuoco dell'Oltrepò Pavese” Controlled Origin Denomination (C.O.D.) wine zone. It is a hilly area characterized with slopes of medium-high topographic gradient (ranging from 12 to 37°) and elevation between 59 and 323 m above sea level. The climatic regime is temperate/mesothermal according to Koppen's classification of world climates.

Bedrock materials are characterized by a Mio-Pliocenic succession, constituted of arenaceous conglomeratic deposits (Monte Arzolo Sandstones, RoccaTicozzi Conglomerates) overlying silty-sandy marly deposits and evaporitic chalky marls and gypsum (Sant’Agata Fossili Marls, Gessoso-Solfifera Formation; Fig. 1). In this area, cultivated vineyards represent the most widespread land use class (31.3%). The most common type of vineyard is the one with rows oriented parallel to the maximum slope gradient, with a slightly lower diffusion of vineyards with row orientation perpendicular to the slope gradient. In cultivated vineyards, the root stocks are the 420A and the SO4, both with the same combination of Vitis berlandieri and Vitis riparia. The study area is also characterized by vineyards abandoned in the last 20-30 years and by shrub lands and woodlands, constituted almost totally of Robinia pseudoacacia, developed where vineyards has been abandoned since more than 30 years. The area considered in this research is particularly prone to shallow landslides (Bordoni et al., 2015). The first and more significant event occurred in 27-28 April 2009, due to a rainfall of 160 mm of in 62 h (Zizioli et al., 2013), causing the triggering of 384 landslides. Further shallow landslide occurred in the period between March and April 2013 and between 28 February and 2 March 2014 (Bordoni et al., 2015). The most widespread landslides are complex landslides, which start as shallow rotational-translational failures and then evolve into earth-flows. Most of these movements (40.7%) started in vineyards.

Different test-site slopes (black star symbols in Fig. 1) were considered for assessment of cultivated vineyards root reinforcement. The tested slopes represent the different setting of study area vineyards, according to: hillslope morphological features (altitude, slope angle, slope exposition); type of bedrock; soil properties; land use; row tillage of the cultivated vineyards implants; age of the plants; presence of past shallow landslides and depth of their sliding surfaces. In the tested slopes, superficial soils are clayey silts or clayey-sandy silts, with high carbonate content (more than 20%). According to USCS classification, these soils are especially low-medium plastic soils (CL). CZ and CAC1 soils are Calcic Gleysol, for the persistence of saturated conditions along the year with the development of reducing conditions. In the other sites, soils are Haplic Calcisols (SOL1, CB, CB2, COL), for the high presence of secondary carbonate concretions, or Petric Calcisols (SOL2, CAC2), for the presence of a hardened calcic horizon at depth higher than 1.0 m from ground level. Unit weight of soils was determined by undisturbed soil samples taken in each soil horizon of a particular profile. It keep quite steady along depth in all the test-site profiles and it is averagely lower in SOL2 (Petric Calcisol) and CB (Haplic Calcisol) (15.2-17.2 kN/m^3) sites than in the other soil profiles (17.7-19.3 kN/m^3). Soil shear strength was estimated by direct shear tests.

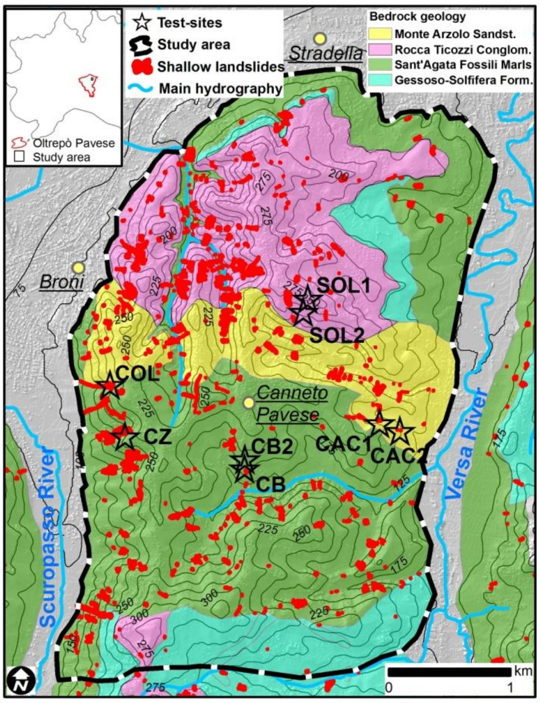

Fig. 1 – Location, geological setting and shallow landslides distribution of the study area. CZ and CAC1 soils are Calcic Gleysols, SOL1, CB, CB2 and COL soils are Haplic Calcisols. SOL2 and CAC2 soils are Petric Calcisols.

Friction angle range between 18 and 29°, while effective cohesion between 0.0 and 18.3 kPa. Soil saturated hydraulic conductivity (Ks), determined from undisturbed soil samples through a soil-evaporation method, is in the order of 10-6-10-7 m/s and it is higher in sites not affected by shallow landslides.

MATERIALS AND METHODS

Root reinforcement (c_{rtot}) was assessed in each tested slope by means of modeling the presence of roots into the soil matrix. The required variables are amount of roots in the considered soil profile and root tensile strength. Possible pull-out strength of large roots (diameters higher than 10 mm), was not considered, because large roots do not act in root reinforcement due to their stiffness (Bischetti et al., 2009). A trench pit was excavated in each site to collect grapevine root samples for mechanical properties measurement and to estimate root density, in terms of Root Area Ratio (RAR, the ratio between the area occupied by roots and the sample area). Root density was measured through the root-wall technique (Bischetti et al. 2009) by analyzing the images acquired along the depth in a frame of known size (0.3x0.3 m). Grapevine roots mechanical properties were measured through laboratory tensile tests on sampled roots, obtaining a power law relationship between the tensile force at failure (f) that represents the root mechanical behavior. Force-diameter (f/d) relationship and root density were used to estimate root reinforcement (c_{rtot}) by means of the Fiber Bundle Model (FBM; Pollen & Simon, 2005) at a particular depth in the soil profile.

c_{rtot} was assessed also through a back analysis procedure on each test slope where a shallow landslide happened by GeoSlope software (Version 8.13; Geoslope, 2012). The triggered phenomenon can be considered as a benchmark to put the factor of safety of the slope, Fs, equal to 1 and then to evaluate the contribution of plants in terms of crtot at depth of the sliding surface. c_{rtot} was considered having the same geotechnical behavior of the soil cohesion (Schwarz et al., 2010). For these analyses, a perched water table rising up from the soil-bedrock contact was considered. For each slope where back analysis was made, we assigned the required soil geotechnical properties (mean value of unit weight, friction angle and effective cohesion) of each particular slope. In this way, c_{rtot} was assessed in each slope according to its typical soil geotechnical and hydrological conditions.

RESULTS AND DISCUSSION

GRAPEVINE ROOT DENSITY

The root density (RAR) in cultivated vineyards shows great variations between the different sites (Fig. 2a). The highest amounts of roots were found between 0.2-0.6 m below the ground level, with a decreasing along the depth (Fig. 2a). The maximum rooting depth ranged between 0.7 m (CZ test-site) and 1.5 m (SOL2 test-site) from ground surface.

The mean RAR values obtained from the data collected in the different analyzed vineyards shows that an average value of 0% is present from the depth of 1.1 m (Fig. 2a), even if locally RAR values higher than 0.0% were detected till a depth of 1.5 m (SOL2 and COL test sites). Till 0.9 m from ground, mean RAR ranges between 0.06 and 0.18%. In unstable vineyards, at the same soil level, RAR is usually 0.10-0.15% lower than the value for stable sites. Between 0.85-0.9 m from ground, where sliding surfaces were detected in unstable sites, RAR is of 0.08-0.09%.

The mean RAR of the soil profile, which is a proxy of the vertical diffusion of the roots, seems relating with the slope angle (Fig. 3a). Although the number of tested sites is rather limited (8), the mean RAR decreases significantly (around 0.10%) for slopes steepest than 20° (Fig. 3a). The slopes with lowest RAR also corresponds to the sites affected in past by shallow failures, testifying a negative combined effect of low root density and high slope angle on slope stability. The mean RAR seems also correlating with the soil saturated hydraulic conductivity Ks (Fig. 3b). In fact, increasing the soil Ks, the mean RAR of the soil profile also increases, passing from 0.07-0.11% in soil with Ks in the order of 10^{-7} m/s to 0.22-0.27% in soil with Ks in the order of 10^{-6} m/s (Fig. 3b). This difference is evident between slopes with or without shallow landslides (Fig. 3). The lowest RAR values are reached in Calcic Gleysols (CZ and CAC1), where saturated conditions along the year do not allow for a great diffusion of the roots in the soil. Besides the high Ks, in COL and CAC2, RAR can be affected also by the young age of the grapevines (5-6 years).

The reasons of this behavior can be due to the development of completely saturated levels in the soil which cannot be crossed by the roots, causing water logging which does not seem promoting high root density (Smart et al., 2006).

ROOT TENSILE STRENGTH

In the study area, grapevine root tensile strength is not affected by location, type of soil and bedrock, grapevine plants age and type of vineyards (Fig. 4). The existence of a unique root mechanical behavior is demonstrated by a mean force-diameter power law for all the test-sites with a high value of coefficient of determination (R^2 = 0.80). This can be linked to the presence of the same combination of Vitis berlandieri and Vitis riparia rootstocks in the test-sites and it should be considered a peculiar feature of the vineyards in the study area.

GRAPEVINE ROOT REINFORCEMENT

Due to the detection of a unique f/d relationship, the differences in c_{rtot} of different test-sites are linked only to the peculiar root density of a site. As the RAR, c_{rtot} shows great variations on the

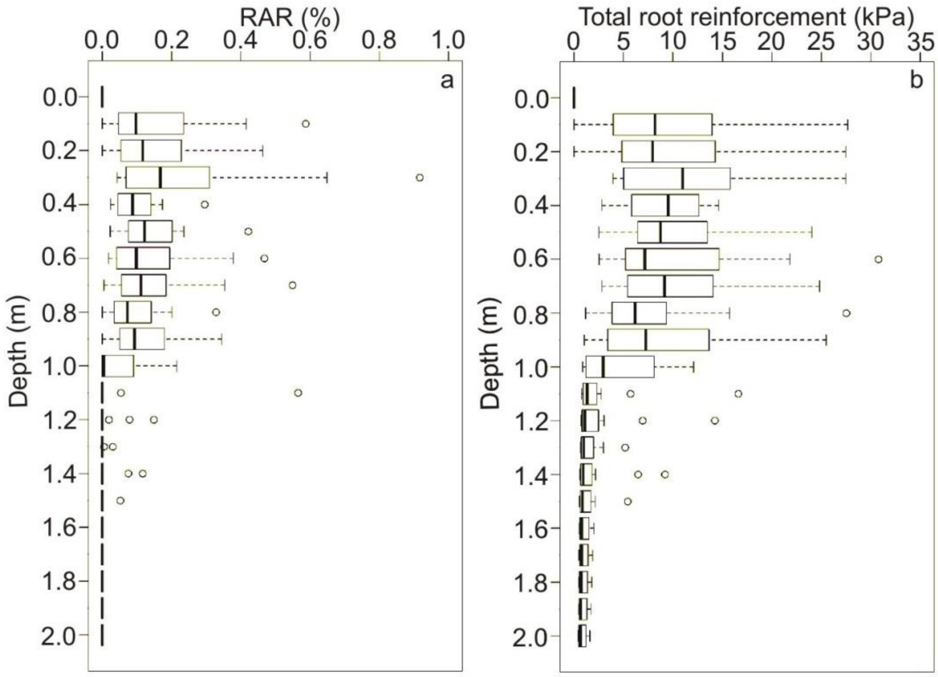

Fig. 2 – RAR (a) and total root reinforcement (b) trends with depth in the test-site slopes.

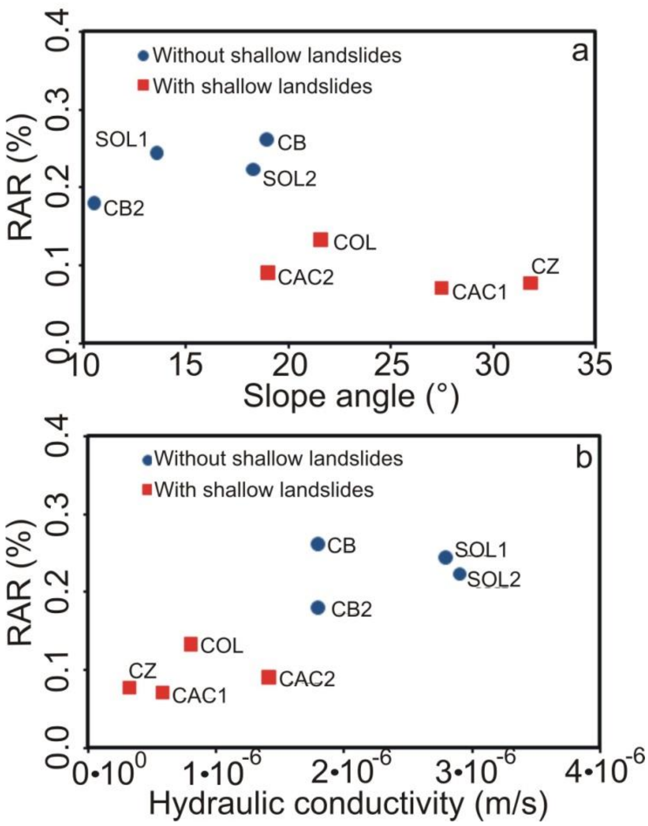

Fig.3 – Mean RAR value of the soil profile compared with slope angle (a) and saturated hydraulic conductivity (Ks) (b) for vineyards test-sites.

different analyzed pits and the highest values characterize the horizons between 0.1 and 0.6 m from ground level, attained an average values between 8.1 and 11.9 kPa (Fig. 2b). As for RAR trends, in tested vineyards affected by shallow landslides measured c_{rtot} is lower than in stable sites (Fig. 2b).

At about 0.9 m, where shallow landslides sliding surfaces were detected c_{rtot} values are of 7.3-8.0 kPa (Fig. 2b), whereas below 1.0 m, they decrease until values lower than 2.1 kPa (Fig. 2b). At depths higher than 1.0 m from ground level, the presence of the roots in the most shallow levels produces a lateral contribute which makes c_{rtot} always higher than nil values, even if the basal contribute is not present in the deeper levels for the absence of roots values between RAR trends in stable sites (Fig. 2b).

The estimated back analysis c_{rtot} at depth of the sliding surfaces is of 1.1 kPa for CZ, 4.5 kPa for COL, 5.0 kPa for CAC2 and 7.7 kPa for CAC1. The difference of these values respect to estimated through FBM c_{rtot} was of 0.1 kPa in CZ, 1.0 kPa in COL, 0.2 in CAC2 and 0.5 in CAC1. This testifies a good reliability of this procedure for the assessment of c_{rtot}.

According to the results of root reinforcement quantification, grapevine roots can give a good reinforcement on soil, usually in the first 0.9-1.0 m from ground where the roots are more abundant. In the slopes with a significant root density, the grapevines have a positive role, contributing on increasing the slope stability.

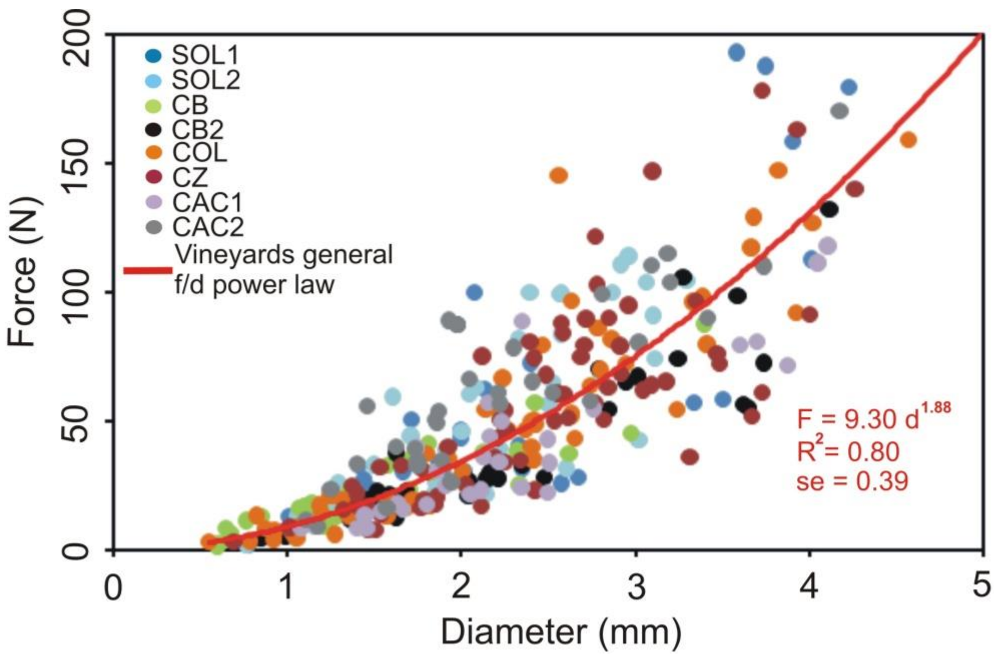

Fig.4 – General f/d relationship of study area cultivated vineyards.

CONCLUSIONS

The results of this research allows for the quantification of grapevine root reinforcement. Root reinforcement in cultivated vineyards is variable between different sites, due to the variability of the grapevine root density. The maximum values are reached between 0.2 and 0.6 m and a significant decrease is evident below 0.9 m from ground level. Root density is lower in the steepest slopes (slope angle > 20°) than in the gentler ones. Moreover, the low permeable soils, in particular Calcic Gleysols soils, are characterized by a lower root density and, then, by a lower root reinforcement.

In the first 0.9 m of the soil profile, the roots are widespread, thus the average values of total root reinforcement are high (7.3-11.9 kPa) and significantly decreases from 1.0 m from ground. For this reason, grapevine roots can give a good reinforcement on soil, usually in the first 0.9-1.0 m from ground where the roots are more abundant, and can guarantee a positive role in the slope stability. Thus, the obtained results represent fundamental tools for identifying the best agricultural practices which could lead to improve the root penetration in soil profile, promoting the increase in root reinforcement and preventing slope instability. Grapevine root reinforcement will be also implemented in physically-based models for assessing shallow landslides susceptibility at local and regional scales.

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10 Shallow landslides susceptibility analysis in relation to land use scenarios

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Shallow landslide susceptibility analysis in relation to land use scenarios

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ABSTRACT

Shallow landslides can represent a destructive phenomena due to the absence of incipient movement evidence and to their high velocity, especially when turning into debris flows. The occurrence and the behavior of rainfall-triggered shallow landslides are often influenced by land use. In particular, the analysis of the changes in land use through time may represent a relevant indicator to evaluate different shallow landslide susceptibility scenarios. In this work, a semi-parametric nonlinear regression technique, namely the Generalized Additive Model (GAM), was applied for landslide susceptibility mapping. The model was applied to four different study sites which recently were affected by widespread rainfall-induced shallow landsliding: the Rio Frate and the Versa catchments (Oltrepo Pavese - southern Lombardy), the Vernazza catchment (Cinque Terre - Eastern Liguria) and the Pogliaschina catchment (Vara Valley - Eastern Liguria). Moreover, the elaboration of different land use scenarios were used to assess the influence of the land use change on the landslides occurrence.

1 INTRODUCTION

The rainfall-induced shallow landslides are typically slope failures with shallow slip surface often triggered by heavy rainstorms with short duration and intense precipitation (Sidle and

Ochiai,2006; Lu and Godt, 2013). These phenomena affect colluvial deposit of small thickness (generally lower than 2.0 m), originating from the weathering of the bedrock and down slope transportation. Despite the small soil volume involved, the shallow landslides can be densely distributed across territories. They result particularly destructive when they initiate or coalesce to form debris flows, due to the absence of incipient movement evidence and their high velocity (Iverson et al., 1997, Hungr et al., 2001;D'Apporto et al., 2005; Meisina and Scarabelli 2007; Zizioli et al., 2013; Hungr et al., 2014).

The spatial distribution of shallow landslides is influenced by different climatic conditions and environmental settings including topography, morphology, hydrology, lithology, and land use. Among this factors, in slope stability analysis, lithology and geological structure can be considered constant over long periods whereas morphology, climate, and land use can be affected by major modifications (Reichenbach et al., 2014). In particular, land use can change in a relatively short time representing the most important factor influencing the landslide spatial distribution occurrence (Glade, 2003). Effectively, it is well known that different land use types may control the stability of slopes and, in particular, slope stability is enhanced by vegetation in terms of mechanical and hydrological characteristics (Greenway, 1987; Schmidt et al., 2001; Bischetti et al., 2009; Schwarz et al., 2010; Wu, 2012; Reichenbach et al., 2014).

The objectives of the work are: 1) to evaluate the influence of land use and land use changes on shallow landslide susceptibility in different geological and geomorphological contexts; 2) to analyse the shallow landslide susceptibility changes in relation to different land use scenarios.

The analyses were carried out by the application of a non linear regression technique. The model applied is the Generalized Additive Model (GAM), which has been used successfully in landslide susceptibility modelling and hazard zonation because of its predictive performance higher than linear regression model (Brenning, 2008, 2014; Jia et al. 2008; Goetz et al., 2011; Vorpahl et al., 2012; Petschko et al. 2014). GAM allows also to capture complex geomorphic processes that, usually, are difficult to be represented in linear form.

The GAM methodology was applied to four study sites in north-western Italy, which recently were affected by widespread rainfall-induced shallow landsliding (Fig.1): the Rio Frate and the Versa catchments (Oltrepo Pavese, southern Lombardy), the Vernazza catchment (Cinque Terre - Eastern Liguria) and the Pogliaschina catchment (Vara Val-ley - Eastern Liguria).

These four sites are characterized by different ex-tent, geological, geomorphological, climatic and land use contexts. In particular, the Rio Frate and the Vernazza catchments are characterized by an high percentage of abandoned land, previously cultivated with vineyards and vineyards/olive groves respec-tively. The Versa catchment is still intensively culti-vated with vineyards which have replaced the sowed areas after 1954. While, the Pogliaschina catchment, after 1960, was characterized by a slight reduction of agricultural areas that was abandoned, and after, replaced by woodland. These study areas were af-fected by relevant shallow landslides phenomena on 27-28 April 2009 (Oltrepo Pavese) and on 25 Octo-ber 2011 (Vernazza and Pogliaschina catchments).

2 STUDY AREAS

2.1 Rio Frate and Versa catchments

The Rio Frate catchment has an extention of about 1.9 km^2, it is characterized by sedimentary covers mainly formed by arenaceus silty/sand component, steep slopes and narrow valleys. The shallow soils, derived by the bedrock weathering, are prevalently clayey-sandy silts and clayey-silty sands, and soil thickness ranges between a few centimeters to 1.85 m. The land use is characterized by vineyards (26%) and woodlands (44%), the latter corresponding to vineyards which were abandoned after the 1980s.

The Versa catchment, extending about 38.2 km^2, is characterized by flysch rock formations with clay component, relevant soil thickness (> 2 m) and gen-tle slope. Regarding the land use, an important modification of agricultural practices occurred after 1954: sowed areas were substituted by vineyards, which are now the most widespread cultural practice (65%). Both areas were affected by a relevant num-ber of shallow landslides, triggered during the rain-fall event of 27-28 April 2009: 245 and 196 shallow landslides were triggered in the Rio Frate catchment and in the Versa catchment, respectively. Most of them were classified as roto-translational slides evolving into flows (Cruden & Varnes, 1996; Cam-pus et al., 1998).

2.2 Pogliaschina catchment

The Pogliaschina catchment is 25 km^2 wide, while its altitude ranges from 95 to 720 m a.s.l. The bed-rock is mainly composed of a sandstone-siltstone flysch and is covered by a soil thickness ranging from 0.5 to 1.5 m. The area is predominantly covered by woodland, characterized by hard-wood (mostly chestnut trees), coniferous (principally maritime pines) and mixed hard-wood and coniferous forests (93% of the whole basin). Vineyards, olive groves and other plantations occupy about 6% of area (D’Amato Avanzi et al., 2014). This agricultural areas, from 1960, have been affected by a small reduction (9%) and further substituted by scrublands and shrubbery.

On 25 October 2011, more than 500 mm of cumu-lated rainfall were recorded in the central and east-ern portion of the Pogliaschina catchment, while about 300 mm were re-corded in its western part. A total of 658 shallow landslide were mapped, 569 of which were classified as complex, translational debris slide-flow (Cruden & Varnes 1996). They were usually superficial (0.3-1.5 m thick), linear (width/length ratio 0.03-0.5) and involved mostly coarse-grained soil and sometimes portions of frac-tured bedrock. 89 landslides were classified as roto-traslational slides (Cruden & Varnes 1996), with a small size and a width/length ratio > 1 (Bartelletti et al., 2015).

2.3 Vernazza catchment

The Vernazza catchment (5.7 km^2) is located along the Tyrrhenian side of the northern Apennines. The bedrock is mainly composed of a sandstone-claystone flysch and a pelitic complex. Two types of land use prevail in this basin: terraced areas and woods, occupying 49% and 51% of the whole basin respectively. Despite the high percentage of total ter-raced areas, only a small part is still cultivated (Cevasco et al. 2014). Due to reworking of debris covers for terracing, the soil thickness is greater on agricultural terraces (up to 2.5 m) than on woodlands (up to 1.5 m). Several rainfall-induced shallow land-slides were triggered on 25 October 2011. In particu-lar, a total of 364 landslides were mapped (Cevasco et al., 2013), with predominance of debris flows and debris avalanches (Cruden & Varnes, 1996; Hungr et al., 2001).

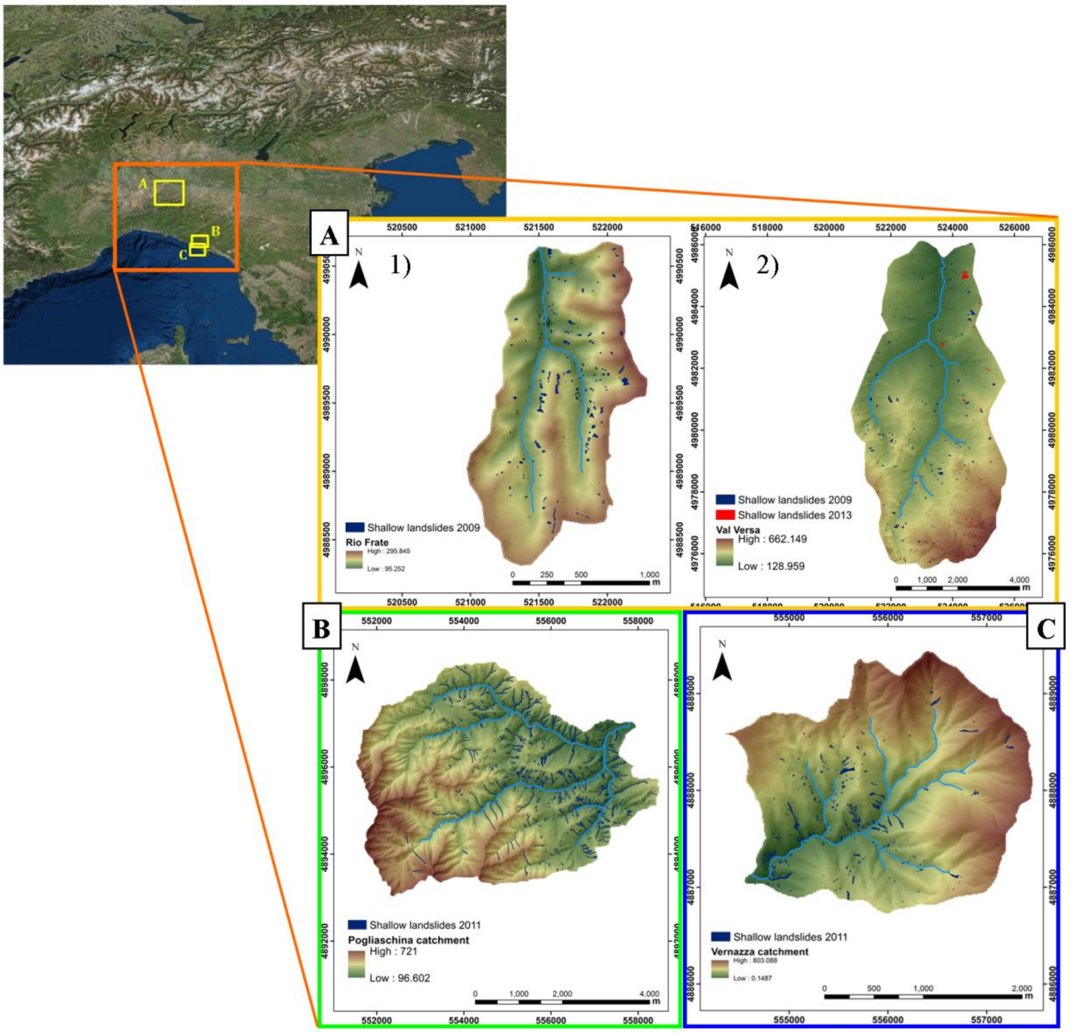

Figure 1. Study areas and rainfall-induced shallow landslides analyzed: A) Oltrepo Pavese catchments: 1) Rio Frate, 2) Versa; B) Pogliaschina catchment; C) Vernazza catchment

3 MATERIALS AND METHOD

3.1 Datasets

The shallow landslide susceptibility assessment was based on the use, as data source for each areas, of digital elevation model (DEMs) at 10 m resolution. Nine different terrain attributes were extracted from the DEMs, by means of geoprocessing func-tions. These parameters and the Euclidean distance from the streets networks are considered as responsible for controlling the landslide occurrence.

Slope, slope aspect, planform curvature and pro-file curvature were calculated basing on local polynomial approximations, according to Zevenbergen and Thorne (1987). The slope aspect was transformed into categorical variables, in order to avoid the misclassification of flat areas as "No Data" areas. The catchment area and the catchment slope were derived using the multiple-flow-direction algorithm (Quinn et al., 1991). The catchment area was transformed into the natural logarithm in order to reduce skewness (Brenning et al., 2014) and used as proxy for soil moisture and soil depth. The Topographic Wetness Index shows the tendency of water to accumulate at any point in the drainage basin and to move along a slope by the action of the gravitational forces, thus it can be correlated to the soil moisture content and the groundwater conditions (Beven and Kirkby, 1979; Seibert et al., 2007). The Topographic Position Index provides a simple proxy to study the effects of the location of a point on a landscape to the shallow landslides occurrence (Pourghasemi et al., 2014). The Terrain Ruggedness Index was used to quantify the landscape heterogeneities, which could have effects on the localizations of shallow landslides triggering area (Bendix et al., 2013; Zizoli et al., 2013). In addition to the terrain attributes, the Euclidean distance from roads was extracted by the direct use of streets network shapefile and an algorithm implementation. Moreover, among the predictor variables the geology, according to its influence on the weathering of bedrock and the resulting soils, and land use was also considered. In particular land use maps of different periods, from 1954 to 2012, were used.

All the parameters where used as predictors variables for the GAM application after a multicollinear analysis to avoid dependency between the predictors.

For all the study areas, detailed landslide inventories were considered as response variables in the GAM. In the Rio Frate and Versa catchments was used the inventory related to the shallow landslides event occurred on 27-28 April 2009. Whereas in the Vernazza and Pogliaschina catchments the inventories of the landsliding event occurred on the 25 October 2011 were utilized. The landslide source areas, which were extracted by an automatic procedure already adopted in Galve et al. (2015) as the upper part of the landslide area (corresponding to the 25% of the total landslide area), were used as response variables instead of simple initiation points.

3.2 Method implementation

The methodology applied for the shallow landslide susceptibility assessment was performed by the application of a non linear regression technique: the Generalized Additive Model (GAM, Hastie and Tibshirani, 1986, 1990).

The procedure adopted is composed of the following steps:

i. Application of the GAM to train and test datasets to evaluate the model accuracy and to select the most significant parameters for a better description of the shallow landslides occurrence;
ii. Use of the chosen parameters to assess the shallow landslide susceptibility of the entire study areas;
iii. Identification of the areas where the land use parameter is more significant;
iv. Assessment of shallow landslides susceptibility in relation to future land use change scenarios.

The GAM represents a semi-parametric extension of the generalized linear model (GLM). It can replace the linear function used in a GLM with an empirically fitted smooth function, in order to find the appropriate functional form for the data (Hastie and Tibshirani, 1990; Brenning, 2008; Goetz et al., 2011). Specifically, it uses a link function to establish the relationship between the mean of the response variables and a sum of a group of smooth functions of independent variables (Jia et al., 2008).

In this way the GAM allows the combination and application of different modelling policies according to the characteristics of the predictor factors and to the complex relationship between independents and response variables (Petschko et al 2014). In particular, the GAM is built using a stepwise variable selection. Starting from null model, each variable can be entered as linear (untransformed), nonlinear (non parametrically transformed predictor of two equivalent degrees of freedom), or not included in the model, using the Akaike Informaton Criterion (AIC) to choose the best model (Brenning, 2008; Guisan et al., 2010; Goetz et al., 2011). For instance, it may linearly integrate some forecast factors, while integrating the other ones by complicated smooth functions, well representing complicated relations between the variables, and providing high flexibility (Jia et al., 2008). The implementation of the GAM was provided by means of the R software and the *R package 'gam'* (Hastie, 2013).

To avoid non landslide area overestimation in the random sampling process, in the training and test sets a 1:1 ratio between landslide and non landslide areas was established, according to the general performance strategy (Dai and Lee, 2002; Ayalew and Yamagashi 2005; Duman et al. 2006; Mathew et al. 2009; Goetz et al., 2011; Regmi et al. 2014). In this way, the portion of the examined dataset consisted of all landslide cells and the same number of random selected non landslide cells. This dataset was subdivided into 2 subsets: the training and the test sets. The training samples, representing 2/3 of the dataset, was used to build the GAM fitting the samples, while the test dataset, including 1/3 of the dataset, was used to estimate the model accuracy.

The process of training and data sets random selection was repeated in a 100-fold bootstrap procedure, aimed to identify the most frequent predictors variables. The parameters that are present more than 80% of the time in the bootstrap extractions were identified as the most influent in the shallow landslide occurrence and were therefore chosen to built the model for the landslide occurrence prediction in the entire study area.

The predictive performance was evaluated plotting the Receiver Operating Characteristic (ROC) curve and computing the area under it (AUROC) (Hosmer and Lemeshow, 2000).

The GAM application allowed to investigate the land use parameters in the shallow landslides occurrence, leading to the exploitation of a susceptibility analysis based on the analysis of land use change scenarios. The resulting probability maps obtained by the GAM fit procedure were classified into 4 susceptibility levels (from high to low). Their range values were chosen on the basis of Jenks (1967) natural break classification, but were slightly modified in order to make uniform the classification in the different study areas.

4 RESULTS

The GAM performance was characterized by a good predictive capability, demonstrated by the mean of the AUROC extracted after the 100 model repetition and the evaluation of the RSME. For each areas the AUROC ranging between 0.7 and 0.8 and the RSME it is negligible.

The application of the GAM methodology allowed characterizing the predisposition of each territory to shallow landslide occurrence according to their different geological, geomorphological and land use contexts. The most influent parameters, that are selected more than 80% of the time by the model, were identified. In the Rio Frate only slope and aspect were considered, while in the Versa catchmnet, in addition, also the catchment slope and land use were chosen by the model.

In the Pogliaschina catchment the most important parameters were geology and land use, but geomorphological parameters (slope, aspect, plan curvature, topographic position index) were also significant.

Whereas, according to Cevasco et al., 2014 and Galve et al., 2015, in the Vernazza catchment the land use resulted the most influent predisposing factor for the shallow landslides susceptibility, in addition to the topographic position index.

The land use classes particularly susceptible to shallow landslides are terraced vineyards and the abandoned terraced areas with poor vegetation cover.

4.1 Land use change analysis

The land use change analysis was performed only in the study areas where the land use, during the bootstrap repetition, obtained a frequency of selection grater that 80. In the Pogliaschina, Versa and Vernazza catchments the land use was chosen with the higher percentage: 92%, 100% and 100% respectively. While, in the Rio Frate catchment the land use reached a lower selection frequency of 63%. Therefore only the Pogliaschina, Versa and Vernazza catchments were considered in the further analyses.

In the Pogliaschina catchment, land use data of 1960, 2000 and 2012 were analysed, showing that the percentage of the agricultural areas decreased from 14.7 % to 5.6% in the considered period (Fig. 2). This decrease was replaced by a higher extension of woodlands (coniferous and mixed hardwood and coniferous forests).

By comparing the land use maps of the Versa catchment , it was possible to observe, from 1954 to 2012, a pronounced transformation from sowed areas (from 70% in 1954 to 10% in 2012) to vineyards (now representing the 65% of the area).

In the Vernazza catchment, a strong reduction of agricultural practices occurred from 1960 to 2011, with abandonment of wide terraced areas previously cultivated with vineyards and olive groves (Fig. 3).

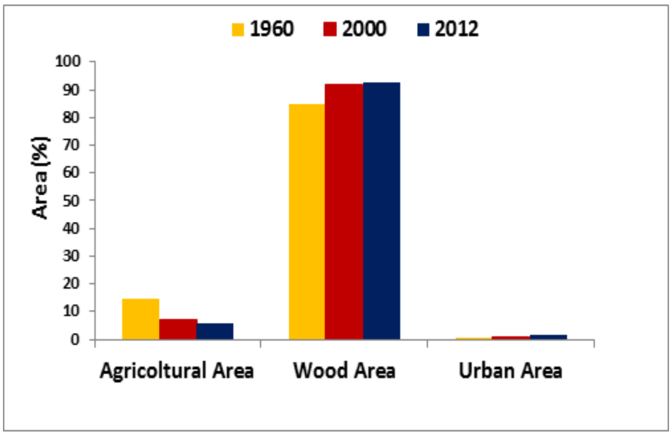

Figure 2. Land use change analysis from 1960 to 2012 in the Pogliaschina catchment

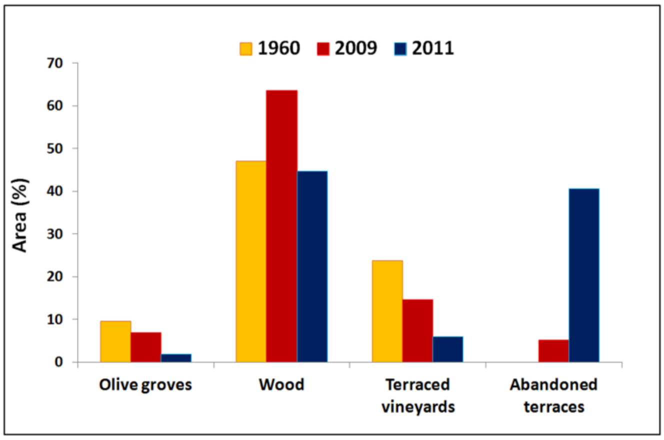

Figure 3. Land use change analysis from 1960 to 2011, in the Vernazza catchment

In the Pogliaschina and Versa catchments, despite the evident land use change in time, the strong influence of geomorphological parameters on the GAM predictive performance conditioned the results of the landslide susceptibility maps obtained by the realization of land use change scenarios. Effectively, was possible to appreciate very few modification in the Pogliaschina catchments and no significant changes in the Versa areas.

Whereas, a clearer modification of landslide susceptibility was detected in the Vernazza catchment with the application of land use scenarios. This is related to the high significance showed by land use parameter in the susceptibility modelling of this catchment.

Therefore, the frequency ratio method was performed in the last two catchments, in order to analyse the land use influence on the shallow landslide susceptibility distribution. This method allow to calculate the percentage ratio of area occupied by landslides for each factor considered and percentage of total area corresponding to each factor. If the ratio is higher than 1, the probability of developing landslides is high, and below 1 this decreases, relation between that factor and sliding being not very important or even negligible (Goţiu and Surdeanu, 2008).

As shown by the Figure 4, in the Pogliaschina catchment all land use classes have a frequency ratio higher than 1, except hydrophilic woodland. The agricultural areas have higher frequency ratio values than woodlands, probably due to the high density of landslides in agricultural areas and because woodlands are widely located in the western part of the basin, where on 25 October 2011 few landslides occurred.

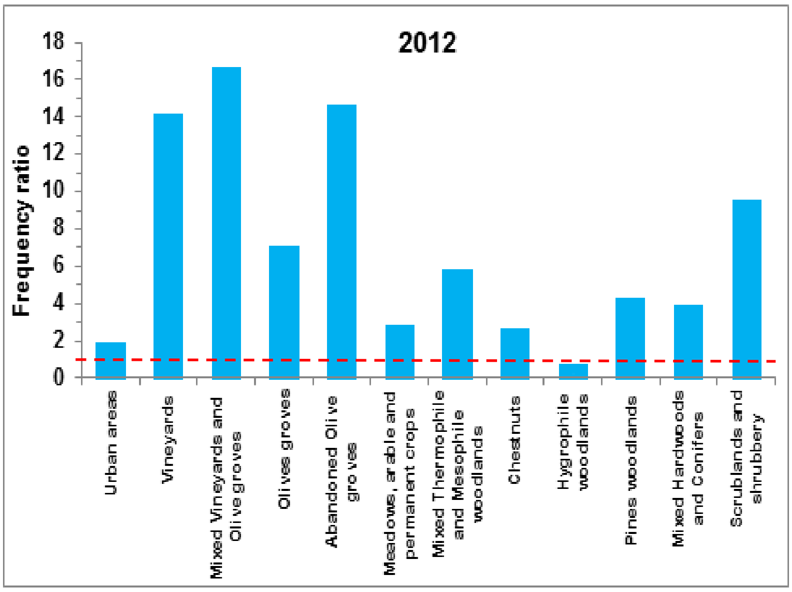

Figure 4. Frequency ratio analysis in relation to the shallow landslide event occurred on 25 October 2011 in the Pogliaschina catchment.

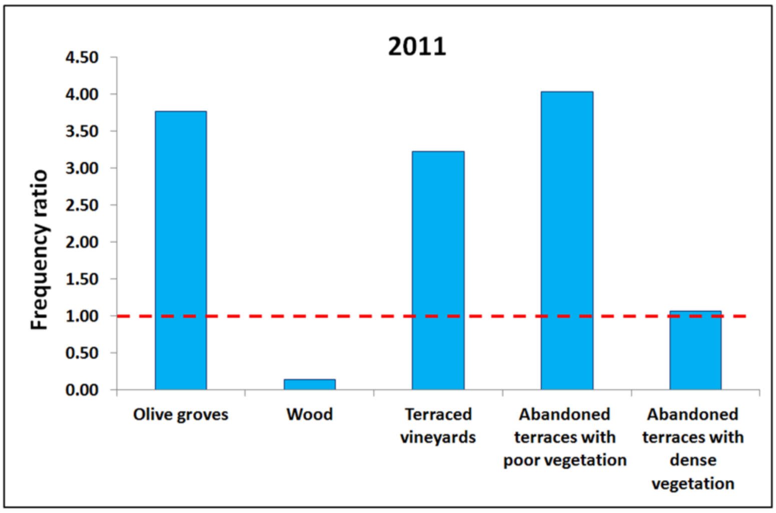

Figure 5. Frequency ratio analysis in relation to the shallow landslide events occurred on 25 October 2011 in the Vernazza catchment.

In the Vernazza catchment (Figure 5), according with previous studies (Cevasco et al. 2013; 2014; Galve et al., 2015), the most important land use class in relation to shallow landslides distribution are represented by abandoned terraced areas with poor vegetation cover, but also by terraced areas currently cultivated with vineyards and olive groves. On the other hand, the woods represent the class with the lowest probability of landslides occurrence.

According with this results, two land use change scenarios were elaborated and applied within the GAM.

In the Pogliaschina catchment, one scenario of landscape natural evolution (i.e. without anthropogenic modification in the middle term period within, for example, 30-40 years) was implemented. This scenario was built considering the results obtained by analyzing the land use change from 1960 to 2012 (Fig. 2).

These results have shown that anthropic activities, as the increase of agricultural areas or the woodland maintenance, are less probable, so that the landscape natural evolution could be favoured in the middle term period. The land use changes supposed by this scenario are the following: olive groves turn into abandoned olive groves; abandoned olive groves evolve into scrublands and shrubbery; chestnut woods transform into mixed hardwoods and conifers; mixed hardwoods and conifers turn into conifers; and mixed thermophile and mesophile woodlands take the place of scrubland and shrubbery.

Whereas, for the Vernazza catchment two scenarios were elaborated. The Scenario 1, representing the growth of abandoned terraced areas. In particular, the still cultivated terraced areas turn into abandoned terraced characterized by poor vegetation cover. While the Scenario 2 is characterized by the increasing of wood areas. Specifically, abandoned terraced areas that gradually increased the vegetation cover till to evolve into woodlands.

In the Pogliaschina catchment, as shown in the Fig. 6, a low increasing of medium-high and high landslide susceptibly classes was observed in case of natural evolution of landscape without anthropic activity. On the contrary, in the Vernazza catchment, with the increasing of abandoned terraced areas it is possible to see an evident increasing of the areas with high susceptibility compared with the results obtained in the event of 25 October 2011 (Fig. 7a, b). While, the increasing of wood areas led to the decreasing of susceptibility distribution (Fig. 7a, c), representing a land use class able to enhanced the slope stability, probably in relation to the root mechanical reinforcement.

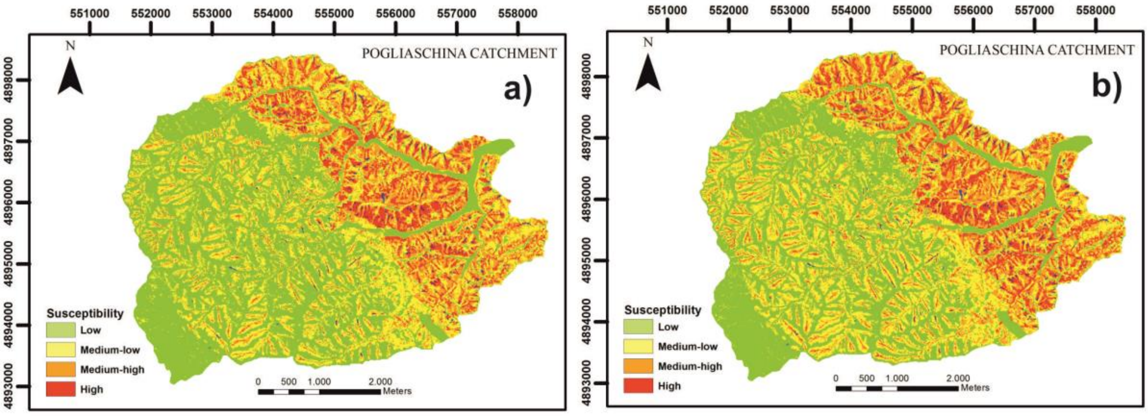

Figure 6. Shallow landslides susceptibility maps obtained by means of GAM in the Pogliaschina catchment. **a)** Real event of 25 October 2011; **b)** Scenario: natural evolution of landscape in the middle-term period.

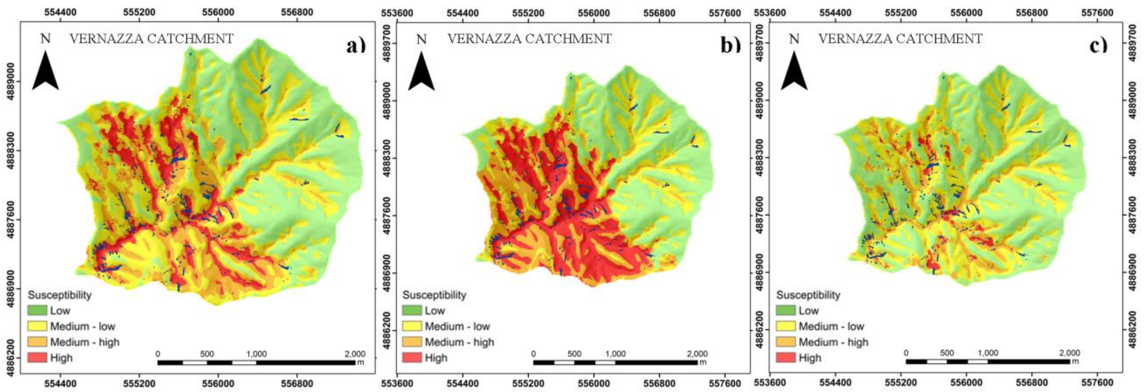

Figure 7. Shallow landslides susceptibility maps obtained by means of GAM in the Vernazza catchment. **a)** Real event of 25 October 2011; **b)** Scenario 1: land use scenario about the increase of abandoned terraced areas with low vegetation cover; **c)** Scenario 2: land use scenario about the increase of woodlands.

5 CONCLUSIONS

The methodology developed by means of a nonlinear regression technique (GAM) led to the evaluation of the shallow landslide susceptibility evolution in four environmental contexts. The exploitation of GAM allowed to characterize the predisposition of each territory to shallow landslide occurrence according to their different geological, geomorphological and land use aspects. In particular, the main significant predisposing factors for each study area were identified. This permitted to understand in which of the investigated areas the land use represents a primary variable, influencing the occurrence of shallow landslides phenomena.

The Rio Frate catchment resulted less influenced by the land use in the shallow landslides susceptibility analysis. In fact, during the model performance, the land use in this study site obtained a lower frequency of selection (63 %) than in the Versa, Pogliaschina and Vernazza catchment. Effectively, in these areas the land use obtained respectively the 92%, 100% and 100% of selection frequency.

In this three study sites, in addition to the statistical modelling, a multi-temporal analysis about the evolution of land use was performed. This showed the relationships between the land use change and the shallow landslides occurrence. Especially, in the areas characterized by a relevant land abandonment, the role of land use resulted fundamental in the slope stability.

For this reason, the elaboration of different land use scenarios represented a suitable approach to evaluate the related change in the shallow landslides susceptibility distribution.

In the Pogliaschina and Versa catchments, despite the evident land use change in time, the strong influence of geomorphological parameters on the GAM predictive performance, has conditioned the results of the landslide susceptibility maps obtained by the realization of land use change scenarios. Effectively, was possible to appreciate only few modification in the Pogliaschina catchments. Specifically, it was observed that the landscape natural evolution determined a slight increase of medium-high and high susceptibility areas (around 12%), with a consequent reduction of low susceptibility areas (Fig. 6).

Whereas, in the Vernazza catchment, where the land use was seen by the GAM as the most significant predisposing factor, the application of land use change scenarios allowed to appreciate important modification in the shallow landslides susceptibility within the territory (Fig. 7a, b, c).

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11 CONCLUSIONS

Two main topics were addressed in this PhD research project: 1) the development and the implementation of a new methodology for the shallow landslide susceptibility assessment in terms of initiation area and runout; 2) the understanding of the role of anthropogenic effects on the shallow landslides occurrence, distribution and propagation mechanism.

The development and the implementation of a new methodology for the shallow landslide susceptibility assessment in terms of initiation area and runout.

INITIATION AREA

The shallow landslides susceptibility assessment related to the initiation area was based on the application of a nonlinear regression technique, namely the Generalized Additive Models (GAM). In literature, data-driven methodology have been often applied in single areas, without investigating the predictive powerful of method in heterogeneous contexts (Guzzetti et al. 2006; Goetz et al. 2011; Galve et al. 2015). In this work, an innovative method for the evaluation of shallow landslide susceptibility of five different study areas was developed. In particular, the novelty of this work is to present a processing chain characterized by simplicity, reproducibility and predictive efficiency in the assessment of landslides susceptibility of different territories, despite the influence of different climatic conditions and environmental settings.

In particular, the investigated study areas are located in North-western Italy, in correspondence of the North-west Apennines sector (i.e. the Rio Frate, the Versa, the Pogliaschina, the Vernazza catchments).

This methodological strategy was able to identify the main geomorphological, hydrological, geological and land use parameters controlling shallow landslide occurrence, according to the characteristics of each investigated areas. The investigation of the most important predisposing factors allowed to improve the knowledge about mechanisms which regulate landslide occurrence in each study sites analysed.

In the Rio Frate catchment case, the parameter that mostly contributes to generate shallow instability was slope. It was selected 100 times in the bootstrap repetitions. By analysing the landslide-slope class distribution, it was notice that the majority of shallow landslides occurred on very steep slope, which can reach values higher than 35°. Also in the Versa catchment the most susceptible areas were located in correspondence of steep slope, in particular with slope angle higher than 17°. In addition, it was interesting to notice that the most susceptible slopes are exposed toward South-West/West. As observed by other authors (Van Westen et al. 2008; Demir et al. 2013), the slope direction reflects differences in rainfall amount, solar radiation and soil moisture conditions, which could favor differently the landslide triggering.

In the Versa catchment, in addition to the geomorphological parameters, also the cultural practices, related to the land use, were influent in shallow landslides occurrence. In particular, the vineyards were the land use class most affected by the highest probability to landsliding. This fact was confirmed by the landslide inventory related to the 27-28 April 2009, where the majority of shallow landslides were located within cultivated areas (mostly vineyards; 55%).

In the Vernazza catchment, land use played an important role on shallow landslide susceptibility.

As already observed by Cevasco et al. (2014) and Galve et al. (2015), the shallow landslides susceptibility tends to increase in abandoned terraces (with poor vegetation cover) and thus also for terraces which have been abandoned for a long time (with dense vegetation cover).

In the Pogliaschina catchment, despite the land use resulted important during the GAM application, the influence of geomorphological parameters and the geology on the GAM predictive performance is high. Slope and planform curvature are the most relevant parameters.

The use of landslide inventories referred only to a single event has represented the major limitation. In absence of multi-temporal landslide databases, we randomly partitioned the entire dataset into two parts (testing and test subsets) within a 100-fold bootstrap procedure. The model accuracy was carried out for each bootstrap sample comparing results of train subset and test subset (landslide pixels not used to fit the model).

Despite this limit, a good forecasting capability were reached in all the study areas analysed. In fact, the GAM performance was characterized by a good forecasting capability, as demonstrated by the accuracy and AUROC values of the 100 different iterations. In particular, a good predictive overall accuracy was underlined by AUROC measure, with values ranging from 0.76 and 0.82 with the mean accuracy reached by the model, ranging between 70-75%.

The worst results were obtained in the Rio Frate catchment (AUROC = 0.76 and mean accuracy = 70%). In this case the GAM wasn't completely able to identify roto-translational slides developed in correspondence of road cut scarps. This is due to the spatial resolution of data source used for the analysis. In fact, working with a cell size of 10 m the model is not able to obtain enough detail at the building scale.
Moreover, the utilization of input data simply derived from DEM allow to obtain good level of accuracy and predictive efficiency also in case of lack of exhaustive information.

RUNOUT

For what concern the run-out analysis, a geomorphometric index, namely the index of connectivity (IC), for the spatial characterization of sediment connectivity, based on the methodology developed by Cavalli et al. (2013), was applied. The novelty of the work was the application of this method to landslide typologies not yet analyzed with this approach, as the shallow landslides. Moreover, the IC was usually utilized to evaluate the potential connection between hillslopes and channels network and basin outlet. Whereas, in this is case it was tasted also to analyse the connectivity with roads network.
Moreover, also in this case, all the input data useful for the IC calculation were simply extracted by the LIDAR DTM allowing to assess connectivity using only topography-based information, ensuring easy applicability.
The performed analysis allowed obtaining maps of sediment connectivity that permit the characterization of the main sediment transfer processes variation as a result of landscape modification of two different study areas (i.e the Rio Frate and the Versa catchments) due to human activities. In addition, the use of shallow landslides as major sediment source areas, allowed to evaluate the sediments supply to the channel network and roads in response to slope instability phenomena.
The Rio Frate catchment was characterised by a high percentage of areas with medium-high values of IC, in most of the case localized in correspondence of the highest slope gradients included between 25°-35°. In the Versa catchment a high percentage of territory was characterised by disconnected areas, showing low and medium-low values of IC distributed along the territory. The differences obtained in the two basins are also strongly related to the different morphological characteristics and extension of the two areas. In fact, the Versa catchment, being characterised by higher extension and lower

average slope gradients with respect to the Rio Frate, tends to be characterised by the presence of a greater number of sediment storage areas. Moreover, the use of shallow landslides as major sediment source areas, allowed to evaluate the sediments supply to the channel network and roads in response to slope instability phenomena. In addition, the instability phenomena characterised by the highest connectivity were identified, in both the study areas represented by complex landslides. This provided useful information for land planning since this analysis allowed determining those areas where the mobilized sediment from shallow landslides can potentially reach roads and stream network, causing extensive damages.

The understanding of the role of anthropogenic effects on the shallow landslides occurrence, distribution and propagation mechanism

In the first parte of the analyses, the shallow landslides susceptibility assessment performed by means of the GAM, showed as the land use, in some areas, was the most significant predisposing factor. Thus, the result highlighted the important role of human activities in the predisposition, of certain territories, to shallow landsliding. This led to the development of an in-depth analysis on the role of anthropogenic effects, included the land use modification, on the shallow landslides occurrence, distribution and propagation mechanism.

MULTITEMPORAL LAND USE ANALYSIS

At first, the role of the land use changes on the shallow landslides distribution was investigated. A multi-temporal land use change analysis were performed in order to evaluate the geomorphic responses to land use changes. Specifically, the land use modifications that occurred in three shallow landslide-prone areas, characterizing the peculiar land use settings of the northern Apennines (i.e. the Rio Frate, the Versa and the Alta Val Tidone catchments) were investigated. The historical land use change profiles were evaluated. In particular, pronounced land abandonment and important modifications to agricultural practices were observed. These land use changes most influenced the shallow landslide susceptibility of the three study areas.

Specifically, abandoned cultivated lands such as vineyards and arable areas that gradually recovered through natural grasses, shrubs and woods were the land use classes that were most susceptible to instability. Moreover, the negative qualities of the

practiced maintenance activities intensified erosion processes and subsequent instability phenomena.
Thus, the present work showed the negative role of the abandonment of cultivated lands on the shallow landslide susceptibility of certain territories, highlighting the need to improve and increase maintenance activities in agricultural areas to guarantee greater land conservation. Furthermore, the achieved results underlined that sustainable management techniques within land management strategies should actually be implemented in the territory to reduce instability phenomena.

ROOT REINFORCEMENT ASSESSMENT

In addition, detailed analysis on the role of the vineyards on shallow landslides were performed. The analysis, carried out through the application of root reinforcement modelling of cultivated grapevines, allowed to highlight the positive effects that the grapevine roots can have on the soil reinforcement. The results showed that the root reinforcement in cultivated vineyards was variable between different sites, due to the variability of the grapevine root density. The maximum values were reached between 0.2 and 0.6 m and a significant decrease was evident below 0.9 m from ground level. Root density was lower in the steepest slopes (slope angle > 20°) than in the gentler ones. Moreover, the low permeable soils, in particular Calcic Gleysols soils, were characterized by a lower root density and, then, by a lower root reinforcement.
In the first 0.9 m of the soil profile, the roots were widespread, thus the average values of total root reinforcement were high (7.3-11.9 kPa) and significantly decreased from 1.0 m from ground. This allowed to underline that the grapevine roots can give a good reinforcement on soil, usually in the first 0.9-1.0 m from ground where the roots are more abundant, and can guarantee a positive role in the slope stability.
Thus, the obtained results represent fundamental tools for identifying the best agricultural practices which could lead to improve the root penetration in soil profile, promoting the increase in root reinforcement and preventing slope instability.

GAM SCENARIOS

After that, to examine in depth the relationships between the land use change and the shallow landslides occurrence, the GAM methodology, defined in the first phase of the research activity, was used. In particular, different land use scenarios were realized and implemented in the GAM calculation in order to evaluate the effects of the land use changes on the shallow landslides susceptibility distribution. The analysis allowed to appreciate important modification in the shallow landslides susceptibility in territories characterized by a relevant land abandonment. In particular, in the Pogliaschina catchment, a low increasing of medium-high and high landslide susceptibility classes was observed in case of gradually abandonment of agricultural areas.

Whereas, in the Vernazza catchment, where the land use was seen by the GAM as the most significant predisposing factor, it was observed an evident increasing of the areas with high susceptibility, with the increasing of abandoned terraced areas. While, the increasing of wood areas led to the decreasing of high susceptibility, representing a land use class able to enhanced the slope stability, probably in relation to the root mechanical reinforcement.

IC SCENARIOS

Whereas, to better understand the influence of anthropogenic effects on the sediment delivery dynamics, the sediment connectivity analysis, developed during the first phase of the research activity, was exploited . Three scenarios, intended to represent the main landscape changes occurred in two different study areas (i.e the Rio Frate and the Versa catchments) due to anthropogenic activities, were analyzed. In particular, the drainage system variation with the gradual reduction of the minor network and the increase of road network due to urbanization and land use changes were represented. These scenarios were used to model the sediment transfer processes in order to understand how the changes that occurred on the landscape may have influenced the behaviour of sediment connectivity within the investigated catchments.

The Rio Frate catchment was the study area characterised by the highest values of connectivity evenly distributed across all the catchment. The reduction of the minor drainage network and the increase of road network over the years led to a general increase of the connectivity values in correspondence of hillslopes located within the mean distance of 50 m from river and roads network. By the use of shallow landslide inventories, as sediment source areas, it was possible to highlight these areas as the most affected by surface instability phenomena during the event that hit the Rio Frate catchment in 2009. Furthermore, the analysis allowed also to identify the shallow landslide typologies characterised by the highest connectivity (complex landslides) and that have effectively reached streams roads during the instability phenomena occurred in the 2009.

In the Rio Frate catchment, it was also observed a relationship between the main land use modification occurred in the last 60 years and the changes in the sediment connectivity distribution. In particular, the pronounced phenomenon of land abandonment, occurred after the 1980, contributed to a slightly decreasing of the connectivity of shallow landslide with the main stream network due to the increase of vegetation along the hillslope after the gradual transformation of areas cultivated with vineyards into abandoned vineyards and woods.

The Versa catchment was instead characterised by a high percentage of disconnected areas with medium-low and low value of connectivity, despite the effects produced on the territory by the main anthropogenic changes. Very few sectors of the Versa catchment showed medium-high values of connectivity and were concentrated on the areas affected by shallow landslides in 2009 and 2013, located within a mean distance of 500 m from the river network.

In this case, analysing the effects of land use change on the sediment connectivity, not changes were observed, since in this area the land use modification did not lead to important changes of sediment flux impedance.

In addition, the role of the landscape complexity in coupling/decoupling upstream sediment sources, such as shallow landslides, from the main channel network and roads was highlighted. Moreover, the assessment of the sediment connectivity in response to slope instability phenomena allowed to provide useful information for the improvement of land planning and management strategies. In particular, the understanding of the degree of connection between sediment sources and roads or rivers will permit to implement a detailed monitoring of those areas in which the mobilized sediment could damage the road network or cause flooding induced by aggradation or obstruction of the riverbed.

Lesson learnt and perspective

The research activity performed allowed to developed and implement an objective and innovative methodological strategy for the shallow landslide susceptibility assessment in terms of initiation area and runout. The simplicity, reproducibility and predictive efficiency ensured by the method allowed to provide a unique technique able to correctly assess the landslides susceptibility of different environmental contexts.

Therefore, their integrated use with the landslide-triggering rainfall thresholds, may provide an innovative tool useful for the improvement of spatial planning and early warning systems. In addition, the in-depth analysis, of the effects of anthropogenic factors on the shallow landslides occurrence, distribution and propagation mechanism provided important information for the improvement of land management and conservation strategies.

Nevertheless, one aspect still remains poorly investigated: the role of the landslide inventory. Specifically, it is not yet well known if the predictive performance of statistical models can be influenced by the type of landslide inventory used and, more specifically, if it can be related to the adopted classification rules and the way in which it is implemented as a response variable. In this context, future perspective will be the implementation of detailed investigations to evaluate the importance and the influence of the landslide inventory in the landslide susceptibility analysis.

APPENDIX

Research paper concerning a work to which I have collaborated:

Bordoni M., Meisina C., Vercesi A., Bischetti G.B., Chiaradia E.A., Vergani C., Chersich S., Valentino R., Bittelli M., Comolli R., Persichillo M.G., Cislaghi A. 2016. Quantifying the contribution of grapevine roots to soil mechanical reinforcement in an area susceptible to shallow landslides. Soil & Tillage Research. 163, 195-206.

Quantifying the contribution of grapevine roots to soil mechanical reinforcement in an area susceptible to shallow landslides

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ABSTRACT

Hilly slopes cultivated with vineyards are often affected by rainfall-induced shallow landslides that cause destruction and loss of the cultivations. For this reason, the assessment of mechanical contribution from grapevine roots is fundamental for slope stability analyses and consequently for the slope preservation.

In this context, our work aims to quantitatively evaluate the soil reinforcement given by grapevine roots.

The selected study area (13.4 km^2), located in the region of Oltrepò Pavese in Northern Italy, is characterized by a high shallow landslides density and is constituted by vineyards in steep slopes. The tested soils are Haplic Calcisols, Petric Calcisols and Calcic Gleysols, with silt loamy or silty clay loamy textures, from high to very high carbonate content and low organic carbon and nitrogen contents. The rootstock of the grapevine is a combination of Vitis berlandieri and Vitis riparia with root systems, which reach average depths of up to 1.5 m. The grapevine root density (number of roots and Root Area Ratio) is rather variable and is strongly correlated to soil permeability. In fact, the results show that low permeable soils have small number of roots and occur near recent shallow slides. Despite the differences of soil features, type of bedrock, grapevine plants age, vineyards row orientation and season collection, a unique

relationship between root diameter and root tensile strength has been identified. Root reinforcement, related to the grapevine root system and evaluated using Fiber Bundle Model, shows the lowest values in correspondence of sites characterized by the lowest soil permeability, as in the study case Calcic Gleysols.
The sites with these soil features, actually, are also those most affected by shallow instability in the past, indicating that their great susceptibility to shallow landslides. The results of this study also highlight the role played by different amounts of grapevine root reinforcement on the slope stability during rainfall conditions, which could lead to triggering, on the study area.

1. Introduction

Slope instability is very common in steep terrains cultivated with vineyards, as testified by numerous recent events in many areas traditionally devoted to wine production. In Northern and Central Italy, these phenomena occurred in the Marche region (Gentili et al., 2006), Langhe (Tiranti and Rabuffetti, 2010), Oltrepò Pavese (Zizioli et al., 2013; Bordoni et al., 2015a), Cinque Terre (Cevasco et al., 2014), Valtellina (Camera et al., 2015), and the Prosecco area. Furthermore, widespread landslides affected cultivated vineyards also in other European countries such as Slovenia (Komac and Ribicic, 2006), Spain (Ramos et al., 2007), Germany (Grunert, 2009) and France (van den Eeckhaut et al., 2010). Rainfall-induced shallow landslides frequently occur on landscapes with vineyards. They cause additional effects such as damages to adjacent structures and infrastructures (buildings, roads, railways, etc.), or even injuries and loss of human life, which are commonly observed. Such events, furthermore, generally destroy the cultivations with a great impact on the local economy (loss of plants and soil, need to reshape the fields and new plantation or abandonment).
Shallow landslides usually develop in the first 2 m of soil and are often triggered as a consequence of very intense and concentrated rainfalls. Such types of rainfall events cause a sudden increase in soil water content and a decrease in soil suction, which is responsible for the reduction in soil shear strength and for the initiation of the landslide phenomenon (Montrasio and Valentino, 2008).
In spite of the diffusion, the persistence, and consequences of shallow landslides on vineyards slopes, no significant studies have been carried out so far to investigate the role played by grapevine plants on preventing or promoting landslides triggering.
At the same time, the beneficial effect of plants in preventing slope instabilities is well known and vegetation is often used as an effective tool to decrease landslide susceptibility, in particular for shallow landslides (Tosi, 2007; Wu, 2012). In the last few decades, a significant body of literature has been published showing and quantifying the role exerted by the root systems on soil strength, Mainly for forest trees (e.g. Abe and Ziemer, 1991; Schmidt et al., 2001; Norris et

al., 2008; Stokes et al., 2008; Bischetti et al., 2009; Schwarz et al., 2010; Mao et al., 2012) or shrubs and grass (e.g. Tosi, 2007; Giadrossich et al., 2016).

Generally, the literature has mainly focused on effects of vegetation in terms of mechanical root reinforcement to be used in slope stability models. Quantifying the effects played by plants in slopes prone to shallow landslides, then, is considered as an important tool in the assessment of shallow landslides susceptibility and in the development of both hazard and risk mitigation strategies (Schwarz et al., 2010; Vergani et al., 2012).

Since this work has been carried out for forest landscapes, it is clearly it is important to develop analysis in cultivated areas similar to that done in forest landscapes, especially for the plants of great economical relevance, such as grapevine. As a contribution to filling about the knowledge gap, the relationship between vineyards and shallow landsliding, in this work a sample hilly area of Oltrepò Pavese has been considered. This area represents the bigger Controlled Origin Denomination (C.O.D.) wine zone of Lombardy Region, with about 13,000 ha of vineyards and is among the top ten areas for the production of Italian wine. Moreover, the viticulture is the most important branch of the local economy. This sector belongs to the so called “Buttafuoco dell'Oltrepò Pavese” C.O.D. zone and it represents the area with the highest shallow landslides density of all the Oltrepò Pavese region (Zizioli et al., 2013). In particular, our objective is to quantify the soil strength contribution in terms of additional root reinforcement by: (i) providing the grapevine root distribution patterns within the soil profile by considering different features of the vineyards and the slopes; (ii) measuring the grapevine root tensile strength; and, (iii) quantifying the grapevine additional root reinforcement to the soil.

2. Methods

2.1 The study area

The study area is located in the north-eastern sector of Oltrepò Pavese which belongs to the north-western Italian Apennines (Fig. 1).

All the data needed to estimate the grapevine root distribution patterns and the related root reinforcement were collected in some test sites located between the medium traits of Versa River and Scuropasso River basins that belongs to north-eastern Oltrepò Pavese (Fig. 1).

The 13.4 km^2 sector is a hilly area characterized by slopes with medium-high topographic gradient (ranging from 18 to 37) elevation ranging between 59 and 323 m above sea level (a.s.l.).

The climatic regime is temperate/mesothermal according to Koppen's classification of world climates, with a mean yearly temperature of 12C and mean yearly rainfall of 684.4 mm.

The bedrock is composed of arenaceous conglomeratic deposits (Monte Arzolo Sandstones, Rocca Ticozzi Conglomerates) overlying silty-sandy marly deposits and evaporitic chalky marls and gypsum (Sant’Agata Fossili Marls, Gessoso-Solfifera Formation) (Fig. One; Bordoni et al., 2015b).

Above the bedrock levels, the soils, derived from the bedrock weathering, have a prevalently clayey-silty or silty-sandy texture.

The soil thickness ranges between a few centimetres to 2.5–3.0 m and it generally increases from the top to the bottom of the slopes (Zizioli et al., 2013).

The land use was obtained from an automatic interpretation of very high resolution (<1 m) Pleiades satellite images, acquired on 17 April 2013.

The land use thus constructed can be considered substantially equal to the situation present in 27–28 April 2009, when the most significant shallow landslides occurred in the study area. The vineyards (VN) cover 31.3% of the study area, representing the most widespread land use class (Table 1). The most common type of vineyard is the one with rows oriented parallel to the maximum slope gradient (Par VN), with a slightly lower diffusion of vineyards with row orientation perpendicular to the slope gradient (Perp VN). Approximately 24.9% of the study area is also characterized by the presence of vineyards abandoned in the last 20–30 years (Ab VN). The grapevine plants remain in these sectors, but they are progressively substituted with grasses, shrubs and other plants, especially black locust trees (Robinia pseudoacacia L.). In vineyards abandoned for more than 30 years, natural vegetation has completely colonized the slopes forming grasslands and shrub lands (S) and woodlands (W). The woodlands cover 12.0% of the study area.

Several rainfall-induced shallow landslides were triggered in the study area in the last 6 years. These phenomena affected the superficial soils with failure surfaces located at depths ranging between 0.7 and 2.0 m from ground level, and occurring at the contact between the soil and the bedrock or at the interface between soil layers with different hydrological and physical properties.

The first and most significant event in terms of number of triggered phenomena occurred on 27–28 April 2009. This event, characterized by an extreme rainfall event of 160 mm in 62 h (Zizioli et al., 2013), caused the triggering of 384 landslides in the study area, with a density of about 51 landslides per km^2.

Further shallow landslide events occurred successively, as reported by Bordoni et al. (2015a): (a) in the period between March and April 2013, after some rainfall events with a cumulated rainfall amount higher than 40 mm lasting between 30 and 50 h (23–25 March, 4–5 April, 20–22 April); and (b) between 28 February and 2 March 2014 as a consequence of an event of 68.9 mm in 42 h. These events caused the triggering of a limited number of shallow landslides (17 and 20 respectively) due to the more limited rainfall amount.

Most shallow landslides occurred in the study area can be classified as complex landslides, which start as shallow rotational-translational failures and then evolve into earth-flows (Cruden and Varnes, 1996). Recent movements affected vineyards (40.7%), abandoned vineyards (22.8%) and woodlands (22.0%) as shown in Table 1.

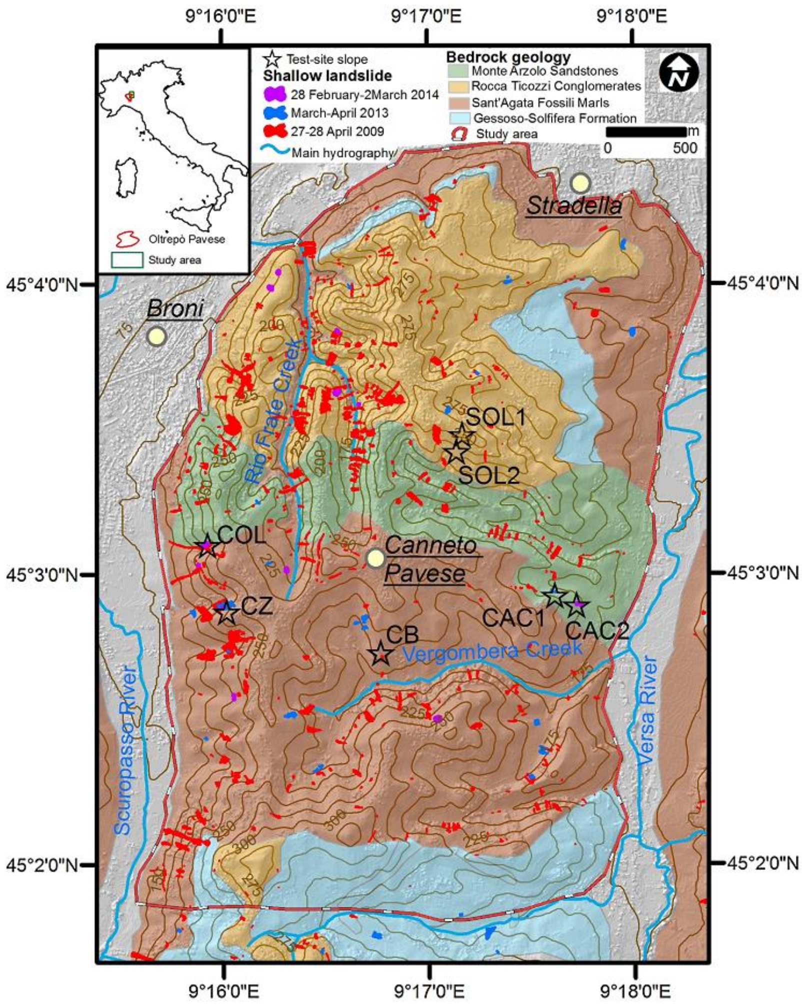

Fig. 1. Location and geological sketch map of the study area.

Table 1. Percentage of the study area occupied by the different land use classes and frequency of shallow landslides for each class: Ab VN) abandoned vineyards; VN) vineyards; (W) woodlands; (Sh) shrub lands; (B) bare soils; (S) sowed areas; (U) urban areas.

Land use classes	Area occupied by the class (%)	Frequency of shallow landslides (%)
Ab VN	24.9	22.8
VN	31.3	40.7
W	12.0	22.0
Sh	8.2	4.8
B	6.2	6.5
S	9.8	2.8
U	7.6	0.4

2.2 Choice of the test sites

A multidisciplinary (geological, pedological, soil physical, geotechnical, agronomical) study was carried out to select vineyard test-sites and to identify relationships between root density and mechanical properties and the main features of the test-sites. Test-site slopes (black star symbols in Fig. 1) were selected according to Table 2: age of the grapevine plants, row orientation of the vineyard plantations, presence or absence of previously triggered shallow landslides, type of bedrock and soil features. The studied grapevine plants were between 5 and 30 years old and the vineyards had the row orientation parallel (Par VN) or perpendicular (Perp VN) to the maximum slope gradient In the study area, grapevine cultivation has been documented since the Roman Age. Considering aerial ortho-photos acquired since 1954, in CB, COL, CAC1 and CAC2 test sites, grapevine cultivations carry on since those years. SOL1 and SOL2 vineyards were not cultivated only between 1994 and 2007, while CZ vineyards were not cultivated only in the period 1994–2003. Distance between plants along the same row ranges between 0.8 and 1.9 m, while distance between two adjacent rows is, in every test-site, between 2.1 and 2.4 m. The rootstocks used in the test-sites are the 420A and the SO4, both with the same combination of Vitis berlandieri and Vitis riparia. The grapevine cultivars are Croatina, Uva Rara and Barbera. The soil is usually fertilized, with mineral fertilizers, especially in spring months, and/or with organic and pellet fertilizers in autumn. In the analyzed slopes previously affected by shallow landslides, the failure surface was located at a depth of 0.85–0.90 m
From the ground level.

2.3 Soils characterization

The soils were described and classified in each site according to the WRB system (IUSS Working Group WRB, 2014). The humus forms was classified according to Jabiol et al. (1995). For this procedure, the following pedological properties of the soil were determined, according to Violante (2000): pH in water, total nitrogen, organic carbon content (SOC), organic matter content (SOM), active lime, cation exchange capacity (CEC), grade of saturation of the exchange complex (BS).
Geotechnical laboratory tests, performed according to American Society for Testing and Materials (ASTM) procedures (1988), allowed for determining the particle size distribution curve, the Atterberg limits and the quantity of calcium carbonate content (CaCO3), on disturbed soil samples. Moreover, on undisturbed soil samples, unit weight (g) and dry unit weight (gd) were determined.
The saturated hydraulic conductivity (Ks) was determined in laboratory for each test site from undisturbed soil samples using a Wind Schindler Method (WSM; Peters and Durner, 2008)

technique (Hyprop, UMS GmbH, Munich, Germany). These samples were collected below the most superficial soil horizons, usually in B or C levels, at depths ranging between 0.3 and 0.9 m from ground. In the sites affected by shallow landslides, they were taken at the depth of the sliding surface.

2.4 Root density evaluation

A trench was excavated to collect grapevine root samples for mechanical properties measurement and for evaluating root density and root size distribution with depth at distances from the plants between 0.10 and 1.26 m (Table 2; Bischetti et al., 2009), in trenches of 1 m – 2m.

Root samplings were performed between spring 2013 and autumn 2014, as shown in Table 2. In the test sites affected by shallow landslides in the past, the trench was excavated slightly uphill with respect to the shallow landslide source area. Root density was quantified by counting the number of roots per root diameter class by means of the root-wall technique (Bischetti et al., 2009).

Root diameter and position were measured by the manual digitization of each root located in a frame of known size (0.30 - 0.30 m) that was moved along all the soil profile in correspondence of the considered trench wall. For the digitization of the roots, a Geographical Information System (GIS) software (MapWindow 4.6) was used. The number of roots per diameter class was determined in increments of 0.10 m in depth, considering the following diameter classes: 0.5–1 mm, 1–2 mm, 2–5 mm, 5–10 mm, and >10 mm, as suggested by literature (e.g. Bischetti et al., 2009; Bischetti et al., 2016). Together with the number of roots, root density was quantified also by means of Root Area Ratio (RAR), which is the ratio between the cross sectional area of the roots and the soil area in the frame of known size (0.30 - 0.30 m). The RAR was estimated at depth increments of 0.10 m.

2.5 Root mechanical properties evaluation

Several grapevine roots were collected in each excavated trench for the tests of root mechanical properties. To protect the sampled roots from deterioration, they were preserved in plastic containers with a 15% alcohol solution until the root tensile resistance tests were performed (e.g. Bischetti et al., 2005). To investigate the effect of seasonality on root mechanical properties, two samplings were collected in different seasons of 2014, respectively namely in winter and summer for COL and in summer and autumn for CZ. Grapevine roots mechanical properties were measured through laboratory tensile strength tests using the MTS Criterion Model 44 (MTS Systems, Eden Prairie, MN, USA) device with the speed range between 0.005–

3000 mm/min. Roots were attached to specifically clamping devices that avoid root damage at the clamping points.

Table 2 Test-site slopes main features. Perp VN: vineyard with row direction perpendicular to the maximum slope gradient; Par VN: vineyard with row direction parallel to the maximum slope gradient.

Site	Age (y)	Land use	Shallow landslides triggering (sliding surface, m)	Altitude (m a.s.l.)	Slope angle (°)	Slope aspect	Type of bedrock	Soil thickness (m)	Season of root samplings	Distance of sampling trenches from plants (m)
SOL1	10	Par VN	-	280.2	17.5	SSW	Rocca Ticozzi Conglomerates: poorly cemented conglomerates	0.9	autumn	0.10, 0.50
SOL2	10-15	Par VN	-	238.0	21.9	SSW	Rocca Ticozzi Conglomerates: poorly cemented conglomerates	1.5	autumn	0.10, 0.50
CB	20-30	Perp VN	-	177.8	21.3	E	Sant'Agata Fossili Marls: sandy marls	2.1	spring	0.50
COL	5-6	Perp VN	1 March 2014 (0.90)	223.0	24.8	W	Monte Arzolo Sandstones: sand	> 1.2	winter, summer	0.20
CZ	13-15	Par VN	27-28 April 2009 (0.90)	185.0	37.0	NW	Sant'Agata Fossili Marls: sandy marls	1.0	summer, autumn	0.65, 0.80, 0.95
CAC 1	20-25	Par VN	27-28 April 2009 (0.85)	165.0	22.0	N	Monte Arzolo Sandstones: sand, sandy marls	> 1.0	summer	0.42, 0.81, 1.26
CAC 2	5-6	Par VN	1 March 2014 (0.85)	155.0	15.0	E	Monte Arzolo Sandstones: sand, sandy marls	> 1.0	autumn	0.20, 0.71, 0.88

The tensile force, applied to the root at a rate of 10 mm/min, was measured by a load cell in N (Full Scale F.S. of 500N, accuracy of 0.1% F. S.) until the rupture. Only specimens that broke near the middle of the rootswere included in the data to ensure that the rupture was due to the

tension and not structural damage to the root or concentration of stress near the clamps. The diameter of the root (mm) was measured as the average of three values taken with an electronic caliper at three points near the potential breaking point.
The results of tensile strength tests are then expressed as a power law relationship between the tensile force at rupture (f) and diameter (D) of the tested root (e.g. Tosi, 2007; Vergani et al., 2012) (Eq. (1)):

$$f = aD^b \tag{1}$$

where a and b in Eq. (1) are fitting parameters of the power-law function. The suitability of these regressions were evaluated using the coefficient of determination (R^2) and the coefficient of significance (p-value) obtained from Fisher's Test, with a significance level of 0.01.
The use of tensile force vs. diameter is probably preferable to the use of stress, which tends to necessarily amplify the uncertainty involved in the determination of diameters (Vergani et al., 2012).

2.6 Root reinforcement evaluation

Force-diameter (f-D) relationship and root density were the input data used to estimate root reinforcement in the soil profile through the application of the Fiber Bundle Model, FBM, described
in details by Pollen and Simon (2005). Based on the pioneering work of Waldron (1977), this model simulates a progressive failure of a bundle of fibers under increasing load. This model takes into account simple rules: (i) an initial load is added and equally distributed between all the parallel fibers (roots) inside the bundle, (ii) the load is continuously increased until a root breaks (when the distributed load is greater than the single root tensile resistance) and then the load is redistributed to the remaining roots, (iii) if the redistribution causes a further rupture, the redistribution occurs once again, (iv) the process is repeated until all of the fibers have been broken. In this study, the FBM was implemented under the static fiber bundle approach and equal load sharing (Bischetti et al., 2009; Schwarz et al., 2010; Mao et al., 2012).
The FBM model allowed for assessing total root reinforcement, c_{rtot}, at a certain depth in soil as the sum both of the resistance due to those roots crossing the basal shear surface (basal root reinforcement, crbas) and the resistance due to those roots intersecting the vertical plane at the detachment scarp (lateral root reinforcement, crlat). Differently from crbas, crlat provides the additional root reinforcement due to the roots located at higher soil levels along the lateral landslide scarp. Considering both crbasand crlatis preferable because, in the case of shallow landslides, the sliding mass must exceed both the resistance due to roots crossing the basal and the vertical shear surface (Schmidt et al., 2001; Bischetti et al., 2009; Schwarz et al., 2010).

For the computation of root reinforcement, we considered only roots with diameter ranging between 1 and 10 mm (e.g. Tosi, 2007; Bischetti et al., 2009). Roots with a diameter less than 1 mm are disregarded because their role in reinforcing the soil is questionable in view of the length necessary to keep them from slipping rather than breaking (Waldron, 1977).

2.7 Statistical analyses

To evaluate the differences in terms of root distribution and root tensile strength in the different vineyards, analysis of covariance, ANCOVA, was used, taking into account the depth and diameter as covariate factors, for root distribution and root tensile strength, respectively. To verify the assumptions of ANCOVA, KolmogorovSmirnov's and Levene's tests were used to check the normality and the variance homogeneity of the residuals. All statistical analyses were performed with a significance level of 0.01 and using the software R (R Core Team, 2014).
To evaluate the correlation between soil features and grapevine root density, the Pearson product-moment correlation coefficient (ρ) was applied.

3. Results

3.1 Soils properties

Main pedological features of vineyards test site soils were shown in Table 3. All the studied soils have a deep calcic horizon starting from about 0.6 m from the ground, with typical values of $CaCO_3$higher than 15% and of active lime around or higher than 6%. CZ and CAC1 soils are Calcic Gleysols (Siltic), with gleyic properties due to the presence of saturated conditions along the year which cause the development of reducing conditions. The other tested vineyard soils are Calcisols. Haplic Calcisols (Siltic) are detected in SOL1, CB and COL sites, while SOL2 and CAC2 soils are Petric Calcisols (Siltic) due to the presence of a cemented or hardened calcic horizon at depth greater than 1.0 m from the ground. Also in the Calcisols, the presence of reddish concretions demonstrates a seasonal water logging in the deeper horizons till about 0.4 m above the contact between soil and bedrock. Most of these soils are moderately well drained, except for CB and CAC2, which are well drained. Furthermore, all the soils are characterized by: Eumull humus; alkaline pH (7.8–8.4); low SOM and total N contents (0.3–1.9% and 0.003–0.012%, respectively); low ratio of organic carbon to nitrogen contents (C:N) (between 3.4 and 8.9); CEC with narrow range of values (lower than 18.2 meq/100 g); BS of 100%. In addition, the geotechnical features were shown in Table 4.
All the tested soils have silt loamy or silty clay loamy textures, with high silt content (51–64%). SOL2 and COL test-sites are characterized by a sand content higher than 13.6%, and by a clay content ranging between 21 and 27%.

In the other study slopes, the soils have a lower sand content (3–12%) and a higher clay content (24– 41%). Gravel amount is low in all the tested soils, ranging between 0 and 11%. No significant trends can be identified on the distribution of the particle size along depth in the soil profiles. According to USCS classification, all the tested soils can be classified as low medium plastic soils (CL), with liquid limit (w_L) values ranging between 30.5 and 50.0%, and plasticity index (P_I) values that range between 15 and 29.0%. Total unit weight (γ) and dry unit weight (γ_d) of soils keep also quite steady along depth in all the test-site profiles. SOL2 and CB test-sites are characterized by g values between 15.2 and 17.2 kN/m^3, which are generally quite lower than in the other test-sites, where g usually ranges between 17.7 and 19.3 kN/m^3.

Table 3. Main pedological features of vineyards test-site soils: (SOM) organic matter content; total (N) total nitrogen content; (C:N) ratio between organic carbon content and total nitrogen content; (CaCO3) calcium carbonate content; (Active lime) active calcium content; (CEC) cation exchange capacity; (BS) grade of saturation of the exchange complex.

Site	Soil type (WRB, 2014)	Position on the slope	Superficial drainage	pH (H_2O) (-)	SOM (%)	total N (%)	C:N (-)	$CaCO_3$ (%)	Active lime (%)	CEC (meq/100 g)	BS (%)
SOL1	Haplic Calcisol (Siltic)	top	moderately well drained	7.8-8.4	0.2-1.3	0.004-0.010	3.4-8.0	41.7-82.7	16.3-18.1	3.6-14.4	100
SOL2	Petric Calcisol (Siltic)	medium	moderately well drained	8.0-8.2	0.9-1.2	0.007-0.008	7.6-8.5	21.5-24.0	5.6-7.2	11.9-13.9	100
CB	Haplic Calcisol (Siltic)	top	well drained	7.9-8.3	0.5-1.9	0.007-0.013	4.6-8.4	22.3-35.7	8.8-11.1	12.9-16.6	100
COL	Haplic Calcisol (Siltic)	medium	moderately well drained	7.9-8.3	0.4-1.2	0.003-0.009	7.0-8.9	6.5-26.3	2.5-12.0	13.2-16.6	100
CZ	Calcic Gleysol (Siltic)	top	moderately well drained	8.0-8.2	0.3-1.6	0.003-0.012	5.2-7.8	22.7-35.2	6.8-11.1	11.1-18.1	100
CAC1	Calcic Gleysol (Siltic)	top	moderately well drained	7.8-8.1	0.6-1.4	0.006-0.010	4.0-8.2	21.9-25.9	6.4-10.1	8.1-10.4	100
CAC2	Petric Calcisol (Siltic)	medium	well drained	8.1-8.3	0.5-1.1	0.005-0.008	7.4-7.9	27.9-34.0	12.3-13.3	12.4-15.2	100

This feature characterizes also gd, which is quite lower in SOL2 and CB (12.5–14.2 kN/m^3) than in the other soil profiles (14.3–16.3 kN/m^3).

Ks values are in the order of 10^{-6}–10^{-7} m/s. It is interesting to note that in sites not affected by shallow landslides (SOL1, SOL2,CB), Ks values are higher of one order of magnitude than in sites with shallow landslides.

3.2 Root density

The number of grapevine roots shows great variations between the different sites. The highest amounts of roots were found between 0.2–0.6 m below the ground level, and, as expected, the number of roots decreased with depth in the soil and in some cases they disappeared above the contact between soil and weathered bedrock. The maximum rooting depth ranged between 0.7 m (CZ test site) and 1.5 m (SOL2 test-site). Moreover, no roots were observed at the bedrock levels, regardless the depth of the soil limit.

At SOL1 and CB test-sites the roots are more abundant than the others. Only roots with diameter between 1.0 and 5.0 mm were generally observed at all the soil depths, at different distance from plants. In particular, roots with diameter ranging between 1.0 and 2.0 mm are prevalent with respect to other root size at distances from the stem greater than 0.5 m.

The RAR follows the trends of the grapevine roots number. Moreover, it is possible to highlight a high variation of RAR among the different test sites as shown in Fig. 2. The mean RAR values obtained for a soil depth until 2.0 m showed that considering all test sites until 0.9 m from the ground RAR ranges between 0.06 and 0.18%. A negligible average value was observed starting from 1.1 m of depth, even if locally RAR values higher than zero were detected, until a depth of 1.5 m (SOL2 and COL test sites) as shown in Fig. 3a.

It is worth noting that in the vineyards where shallow landslides occurred, at the same soil level the average RAR values are 0.10–0.15% lower than the average values of the vineyards where no shallow landslides have been triggered (Fig. 3b, c). At a depth of 0.85 and 0.9 m from the ground, mean RAR value is of 0.08–0.09%, where the sliding surfaces were observed. We considered as indicator of the root density, the mean RAR measured till 0.9 m from ground (depth where RAR is averagely lower than 0.05%) at a distance ranging between 0.20 and 0.65 m from the plant trunk.

Concerning the different measured soil properties, the soil hydraulic conductivity K_s and the bulk density gd are the soil features, which were characterized by the highest variation among the different test sites.

The mean RAR of the soil profile is strongly correlated to the Ks measured in correspondence of the B or C horizon of the soil ($\rho = 0.83$), although the number of the studied soils is rather limited. Increasing the soil K_s the mean RAR of the soil profile also increases, passing from 0.07–0.11% in the order of 10^{-7} m/s to 0.22-0.27% in soil with K_s in the order of 10^{-6} m/s (Fig. 4a). The lowest mean RAR values are found in Calcic Gleysols (CZ and CAC1), and in the slopes with Calcisols characterized by a young age of the grapevines (5–6 years old; COL and CAC2).

Moreover, the test-sites with low permeable soils and, thus, lowest values of root density, are also the sites affected in past by shallow landslides.

Only a partial relationship (ρ = 0.42) seems to link the mean RAR with the mean γ_d (Fig. 4b) in the tested vineyards. SOL1 has the highest mean RAR value (0.24%) but also a very high gdvalue (15.8 kn/m^3), similar to that one measured in COL and CAC1, where mean RAR values are significantly lower (0.07–0.13%). For the other sites, the decrease in gdis coupled with an increase in mean RAR.

3.3 Root tensile strength

Diameters of the tested roots ranged from 0.55 to 4.73 mm, with 75% having a diameter lower than 3.00 mm. The force at failure of the tested grapevine roots ranged between 1.45 and 219.55 N. Table 5 shows that the force-diameter power laws for the studied vineyards are comparable. Similar relationships are highlighted in COL (ANCOVA: $F_{1.57}$ = 0.02 and p-value = 0.89 for parallelism and $F_{1.57}$= 1.05 and p-value = 0.31 for intercept) and CZ (ANCOVA: $F_{1.60}$= 0.05 and = 0.82 for parallelism and $F_{1.61}$= 4.71 and p-value = 0.05 for intercept) test-sites by considering roots taken in different seasons.

Table 4. Main geotechnical features and soil saturated hydraulic conductivity of test-site soils: (w_L) liquid limit; (P_I) plasticity index); (γ) soil unit weight; (γ_d) soil bulk density; (K_s) saturated hydraulic conductivity.

Site	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	w_L (%)	P_I (%)	γ (kN/m^3)	γ_d (kN/m^3)	K_s (m/s)
SOL1	2	9-10	55-57	32-34	44.4-45.1	23.0-24.5	19.0	15.6	$2.8\cdot10^{-6}$
SOL2	4-11	14	54-60	22	40.4-41.4	17.0-17.8	15.2	13.7	$2.9\cdot10^{-6}$
CB	0-1	3-7	60-63	33-34	39.6-42.7	17.9-21.6	15.4-17.2	12.5-14.2	$1.8\cdot10^{-6}$
COL	1-2	17-23	51-59	21-27	39.7-41.2	17.3-18.2	17.7-18.2	15.2-15.6	$8.0\cdot10^{-7}$
CZ	2-5	8-12	58-61	26-31	41.1-50.0	14.7-30.5	17.7-18.7	14.4-15.5	$3.2\cdot10^{-7}$
CAC1	1	4-12	61-64	24-33	36.9-45.9	15.1-23.0	16.3-18.6	14.3-16.2	$5.8\cdot10^{-7}$
CAC2	0-2	2-4	55-59	39-41	46.5-50.0	24.4-29.0	17.9-19.3	15.7-16.3	$1.4\cdot10^{-6}$

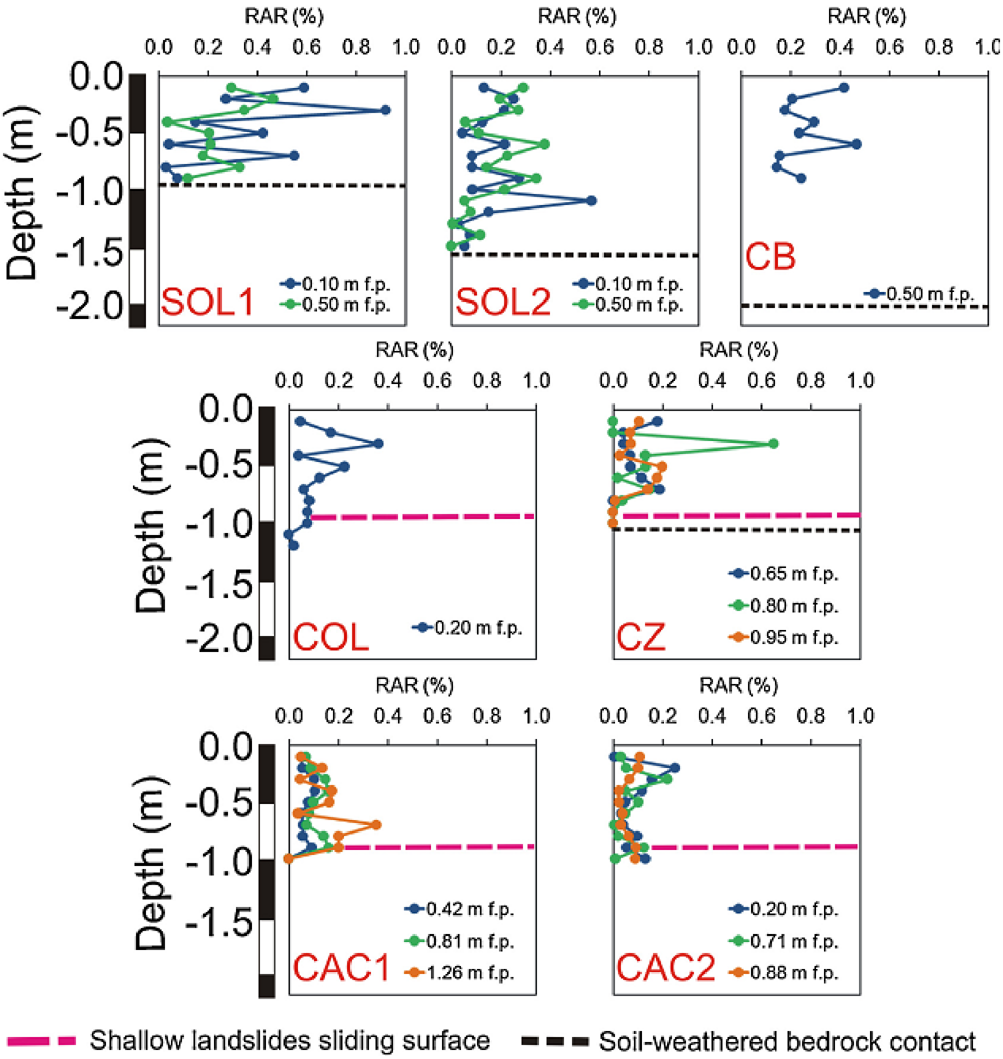

Fig. 2. RAR distribution in tested vineyards site at different distance from plant (f. p.).

Considering all test sites, after ANCOVA verified the parallelism of the power laws ($F_{6.278}$= 1.23 p-value = 0.29), it also confirmed the f-D relationships were statistically not different $F_{6.284}$= 0.57, p-value = 0.02) Moreover, no differences in terms of mechanical properties can be statistically observed between sites with or without landslides (ANCOVA: $F_{1.289}$ = 5.73 and p-value = 0.02 for intercept). Thus, it is possible to identify a unique force-diameter relationship for tested grapevine roots in the study area.

3.4 Additional root reinforcement

According to the statistical homogeneity on root mechanical properties in different vineyard sites and as already observed in previous works concerning forest species (Schmidt et al., 2001; Bischetti et al., 2009), grapevine root reinforcement was estimated using a unique f-D relationship specifically determined for this species.

The difference in additional root reinforcement values at the different test-sites are therefore related only to the peculiar root density of a site. Accordingly, the total root reinforcement c_{rtot} showed great variations on the different analyzed pits, as shown in Fig. 5. The differences were more significant in the first 0.9–1.0 m within the soil profile.

Where a local increase of c_{rtot} along depth is observed, it is related to a local increase of the root density, as observed in CAC1 test-site between 0.8 and 1.0 m from the ground.

The highest values of c_{rtot} have been observed at a depth between 0.1 and 0.6 m from ground level, where it attained average values of 12.6 and 20.1 kPa (Fig. 5, Fig. 6). c_{rtot} also decreased along the soil profile, with an abrupt decrease immediately above or at the contact between soil and weathered bedrock.

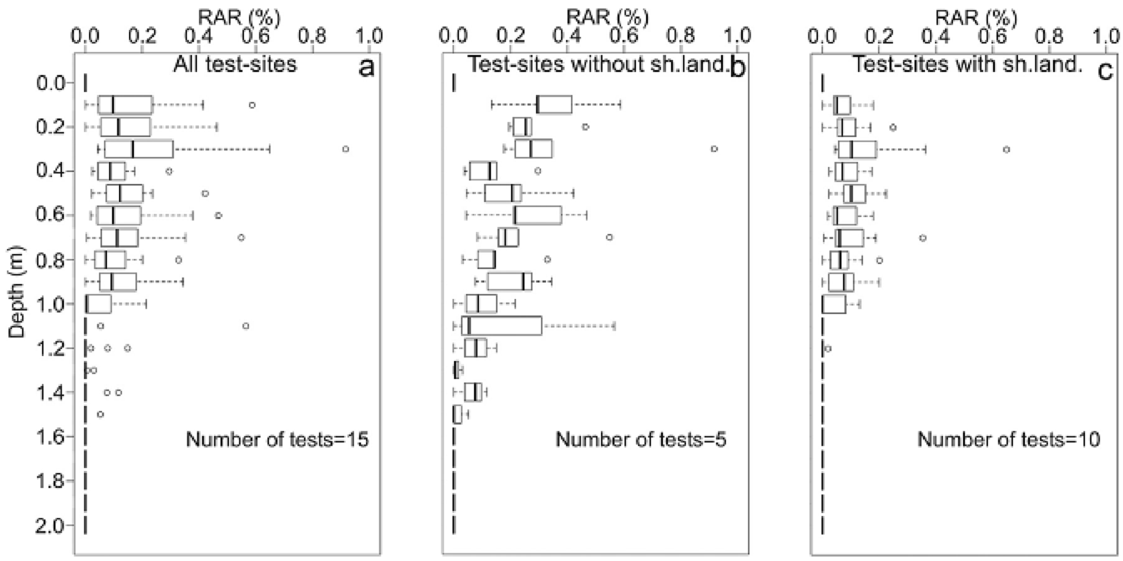

Fig. 3. RAR trends with depth in the test-site slopes: (a) all test-site slopes; (b) slopes without shallow landslides; (c) slopes affected by shallow landslides.

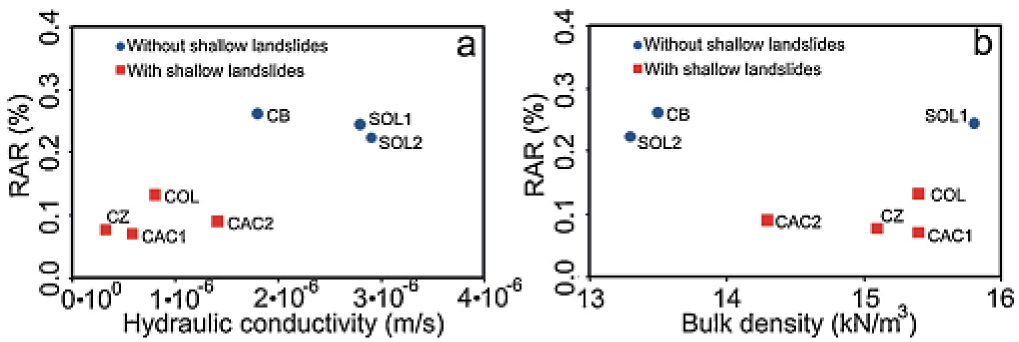

Fig. 4. Mean RAR value of the soil profile (distance from plant between 0.20 and 0.65 m from plant) compared with (a) saturated hydraulic conductivity (Ks) and (b) bulk density (gd) for vineyards test-sites.

Table 2. Coefficients and statistical parameters of f-D relationships for vineyards test-sites: (a and b) fitting parameter of force/diameter relationship; (R^2) coefficient of determination; (se) standard error.

Site	Vineyards age (y)	Number of tested roots (-)	power law relationship				
			a	b	R^2	p-value	se
SOL1	10	35	8.68	2.05	0.77	<0.001	0.38
SOL2	10-15	39	10.97	1.65	0.80	<0.001	0.39
CB	20-30	31	9.31	2.10	0.76	<0.001	0.41
COL-Summer	1-6	30	9.00	1.93	0.85	<0.001	0.35
COL-Winter	1-6	31	7.60	2.12	0.93	<0.001	0.33
CZ-Summer	13-15	34	7.64	1.95	0.77	0.005	0.38
CZ-Autumn	13-15	30	8.85	2.02	0.77	0.005	0.38
CAC1	20-25	30	6.68	1.99	0.81	<0.001	0.34
CAC2	5-6	33	14.00	1.73	0.80	<0.001	0.35
Total		293	9.25	1.93	0.80	<0.001	0.39

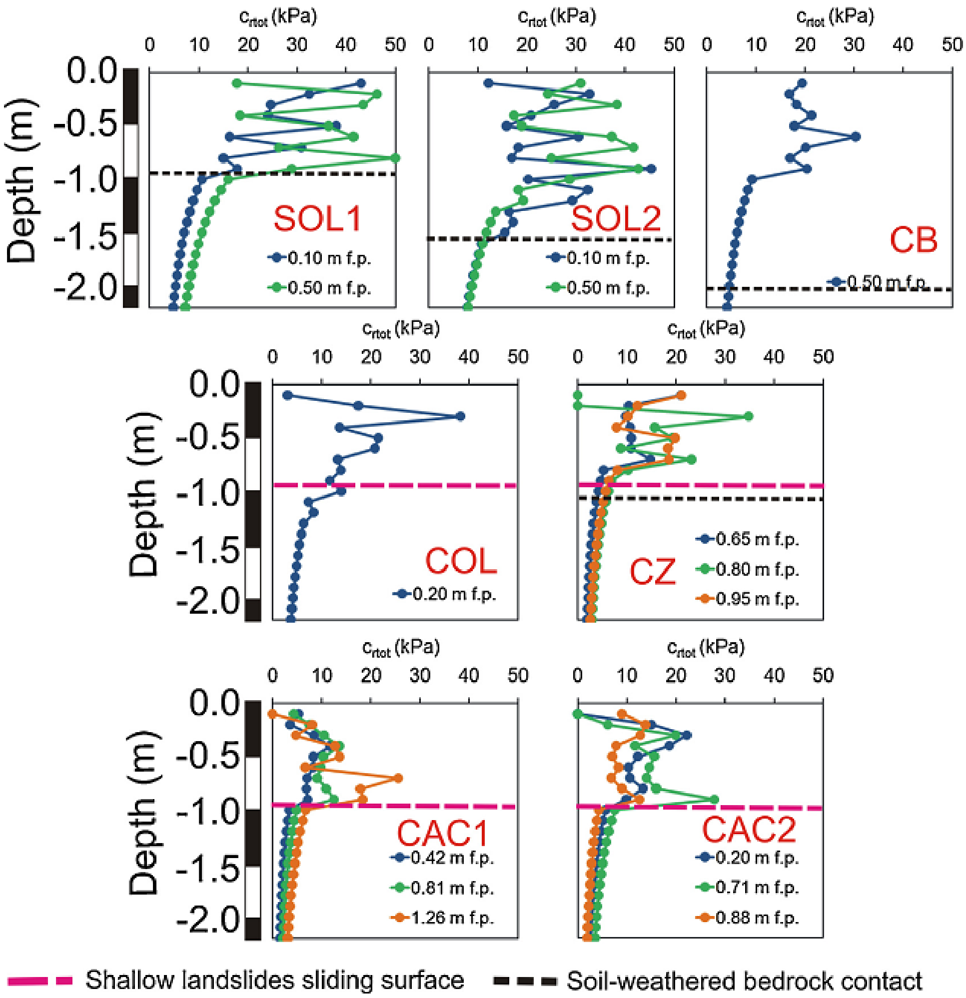

Fig. 5. Total root reinforcement c_{rtot} distribution in tested vineyards site at different distance from plant (f. p.)

Below 1.0 m from ground, grapevine c_{rtot} showed a slower decrease along depth, in the order of 0.3–0.5 kPa every 0.1 m increment in depth.

Moreover, as for root density, at different depths c_{rtot} was higher in slopes without landslides than the slopes affected by landslides.

Generally, the differences between unstable and stable slopes reached values of 14 kPa till 0.9 m from ground, while, below 0.9–1.0 m from ground, the mean value of c_{rtot} decreased in unstable slopes respect to stable ones to values of 3–9 kPa.
Furthermore, it is important to highlight that between 0.8 and 1.0 m from ground, where shallow landslides failure surfaces were detected in the analyzed vineyards, c_{rtot} is of 7.3–8.0 kPa.

4. Discussions

The grapevine root density, in terms of number of roots and RAR, in soil profile has a great variability with regard to different test-site location. This variability generally characterizes all the plant types investigated in the past and it is due to the spatial heterogeneity of root system development, which is dependent upon the interactions of genetic and very local environmental factors (Stokes et al., 2008).
RAR results strictly followed the trend of number of roots and, in spite of great average RAR values variability, general features of grapevine root density with depth can be identified.
The greatest amounts of roots were found between 0.2–0.6 m below the ground level, with a decreasing trend along the depth. This can be associated with the use of mechanical hoes and the trenching of the soil till 0.15 m from ground level during agronomic practices, which cause the partial destruction of the grapevine roots.
Grapevine roots can rarely reach depths greater than about 1 m from the ground (Fig. 2 and Table 4). This is in agreement with Swanepoel and Southey (1989) and Shange and Conradie (2012), who suggested that the maximum rooting depth of different types of grapevine rootstocks is between 0.6 and 1.2 m from ground in fine textured soils whereas it can be more than 2.0 m in coarse textured soils where sand is more than 50%.
Considering the lateral development of root system in the same profile, similar values of root density can be observed at distances between 0.10 and 1.26 m from plant trunks. This feature is consistent with previous works which highlighted, in different soils and environmental contexts, fairly high and constant root density up to 1.5 m from the plant trunk (Saayman and van Huyssteen, 1980; Morlat and Jacquet, 2003).
As regards the relations between root density and soil properties or agricultural practices, the mean RAR of the soil profile is strongly correlated with soil Ks, which is an indicator of the permeability and penetrability of soil material. Where Ks increases, the vertical root density in the soil profile also increases.
In particular, mean RAR is 0.12–0.20% higher in soils with K_s in the order of 10^{-6} m/s, than in soils with K_s in the order of 10^{-7} m/s. The lowest RAR values correspond to sites with Calcic Gleysols (CZ and CAC1). Low values of mean RAR are also typical of sites characterized by Calcisols and by the young age of the grapevines (5–6 years old; COL and CAC2). The reasons

of the lowest root density in Calcic Gleysols can be due to the development of completely saturated horizons, typical of soils with gleyic features, which cannot be crossed by the roots.
Less permeable soils cause water logging, which does not seem promoting the development of a high grapevine roots density (Smart et al., 2006). The difference of RAR values reflects on the distinction between the slopes affected or not by shallow landslides in the past. The selected vineyards affected in past by shallow landslides have average RAR values 0.10–0.15% lower than the average values of the vineyards where no shallow landslides occurred. Low permeable soils had a lower grapevine root density and appear more susceptible to shallow landsliding.
In vineyards affected by past shallow landslides, gdis generally higher than in stable slope too (except for SOL1). Instead, in respect with other observations of grapevine root density (Van Huyssteen, 1988; Smart et al., 2006), in the selected test-sites, the increase in gdis not always coupled with a decrease in mean RAR.
Statistical analyses on grapevine root tensile strength showed that in the study area this feature was not affected by location, type of soil and bedrock, grapevine plants age, type of vineyards and seasons of the year.
The existence of a unique root mechanical behaviour can be linked to the presence of the same combination of Vitis berlandieri and Vitis riparia rootstocks and to the similar environmental conditions everywhere in the study area, linked to its small size (13.4 km^2). Differences in tensile strength of the same species, in fact, can be partially associated with a difference in cellulose content (Genet et al., 2005) and such an effect can be appreciated only for very different environmental conditions, in terms of slope altitude, wind, air temperature, rainfall amounts.
The f/d relationship determined for grapevine plants of cultivated vineyards in the study area has been compared with the power law functions for forest species (Vergani et al., 2012). This comparison provided by the value of the force at failure for root with a diameter of 2 mm, which is the most common class of diameter we observed, shows that grapevines seems to be strong as most of the considered forest species (Table 6).

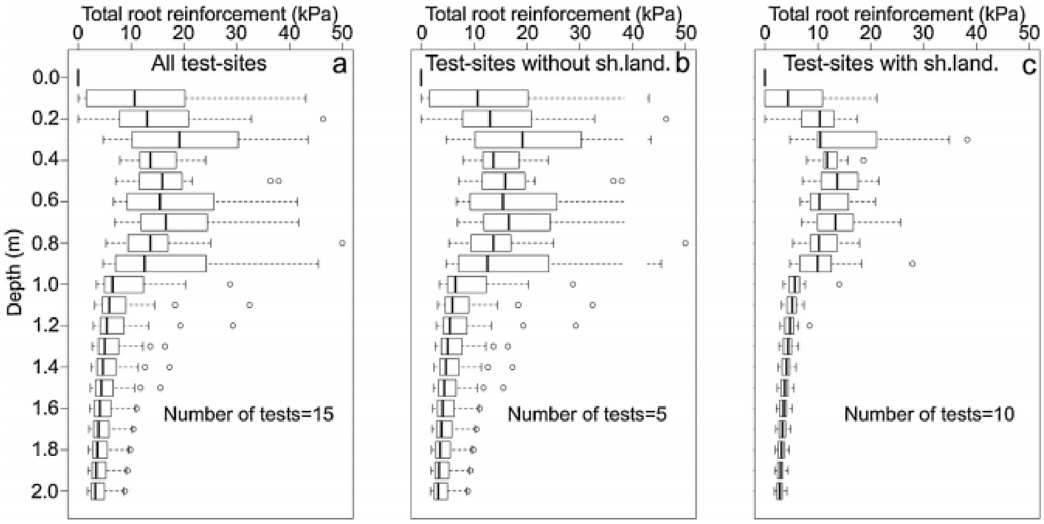

Fig. 6. Total root reinforcement c_{rtot} trends with depth in the test-site slopes: (a) all test-site slopes; (b) slopes without shallow landslides; (c) slopes affected by shallow landslides.

Table 6. Comparison between Oltrepò Pavese grapevines and some forest species f-D relationships: (a and b) fitting parameters of force/diameter relationship. The f-D relations of the forest species (identified with the asterisk) refer to data collected in Vergani et al. (2012).

Plant species	Parameters of f/d relationship		Root tensile strength (f) linked to a root diameter (d) of 2.0 mm
	a (-)	b (-)	(N)
Grapevine (combination of *Vitis berlandieri* and *Vitis riparia*)	9.25	1.93	35.2
European beech*	19.66	1.70	63.9
Spruce fir*	8.31	1.85	30.0
Sweet chestnut*	11.57	1.54	33.6
Ash*	10.63	1.74	35.5
Maple tree*	14.71	1.73	48.8
Hornbeam*	14.08	1.63	43.6
European larch*	12.31	1.49	34.6

Grapevine total root reinforcement (c_{rtot}), calculated through FBM model, follows root density trend of a soil profile. It is the highest value till 0.6 m from ground, where most of the roots are detected, and it decreases along depth, passing from average values of 18 kPa till 0.6 m from the ground to 10 kPa between 0.6 and 1.0 m from the ground.

At soil depths higher than 1.0 m, c_{rtot} shows an abrupt decrease, with values that fall down below 6 kPa. This abrupt decrease is due to the general absence of roots below 1.0 m from the ground. In these soil horizons, c_{rtot} is only due to the lateral root reinforcement, thanks to the roots located in most shallow horizons (Bischetti et al., 2009). Thanks to the presence of this lateral component, c_{rtot} is not completely nullified in each investigated levels (till 2.0 m from ground as shown in Fig. 5 and Fig. 6).

The tested vineyards affected in past by shallow landslides are characterized by a lower c_{rtot} than the stable ones. In correspondence of the depths where shallow landslides sliding surfaces formed (between 0.8 and 1.0 m from ground), c_{rtot} of unstable slopes is of 7.3–8.0 kPa, while in stable slopes average values range between 16.9 and 25.0 kPa.

Unstable tested vineyards have lower c_{rtot} and low permeable soils, as already observed for root density. This confirms that the cultivated slopes characterized by soil with low permeability are more prone to shallow landslides triggering.

The stability of cultivated slopes can be obviously also linked to the soil shear strength parameters, in particular soil friction angle and effective cohesion. As shown in previous works (Zizioli et al. 2013; Bordoni et al., 2015b), the soils of the study area have average values of shear strength properties distributed in a narrow range, in particular between 24 and 27 for soil friction angle and between 1.5 and 2.0 kPa for effective cohesion, respectively.

According to the similar values of soil shear strength, grapevine root reinforcement, and its variation in relation to root density in different soil contexts, controls the predisposition of cultivated vineyards of the study area to shallow landslides.

To summarize the key results, a schematic flow chart was presented in Fig. 7.

5. Conclusions

In this work, we presented analyses of grapevine root reinforcement toward slope stability in steep terrains adding new knowledge in this field.

Previous studies on vineyards did not deal with root mechanical properties of grapevine roots nor have previous studies on the mechanical properties of plant roots considered grapevine plants.

The results provided important information, which could further be extended to other viticulture areas prone to shallow landsliding, and support mapping and guiding vineyards management.

Grapevine root density, in terms of number of roots and RAR, shows a great variability in soil profile in the different analyzed test-sites. The highest values are reached between 0.2 and 0.6 m from slope surface, and a significant decrease is evident below 0.9–1.0 m from ground, where grapevine roots can rarely be found.

Soil permeability is the soil property, which seems to be most strongly associated with grapevine root density, controlling roots amount in soil. The low permeable soils, in this study case mostly Calcic Gleysols, have lower root density and were affected by shallow landslides in the past.

Grapevine root tensile strength appears not to be affected by location, type of soil and bedrock, grapevine plants age, type of vineyards, different seasons of sampling. Analysis of the f/d relationship showed that grapevine roots are strong as most of the forest species analyzed in past.

Grapevine roots can provide a good soil reinforcement, usually in the first 0.6 m from the ground where the roots are more abundant. At depths ranging between 0.8 and 1.0 m from the ground, where shallow sliding surfaces formed in the tested vineyards, c_{rtot} of unstable slopes reached 7.3–8.0 kPa, while in stable slopes average values range between 16.9 and 25.0 kPa for the same horizons. The contribution of the lateral root reinforcement makes the total root reinforcement always greater than 0.0 kPa.

The great variation of root reinforcement between different sites is essentially linked to root density. In slopes with low permeable soils, the root reinforcement is lower, making these slopes the most susceptible ones to shallow landslides.

The obtained results represent fundamental tools for land use planning. For example, it is fundamental to identify the best agricultural practices which could improve root penetration to deeper profiles in slopes with vineyards especially slopes with characterized by lower root density. The increase in root reinforcement within the soil profile will promote resistance to landslides and more sustained slope stability.

Future developments of this research will be the analyses of the effect of different agricultural practices on vineyards (e.g. management of the interrows) on grapevine root density and, then, on grapevine root reinforcement in soil. Grapevine root reinforcement will be also implemented in distributed physically-based stability models for assessing shallow landslides susceptibility at local and regional scales, considering different land use and rainfall scenarios.

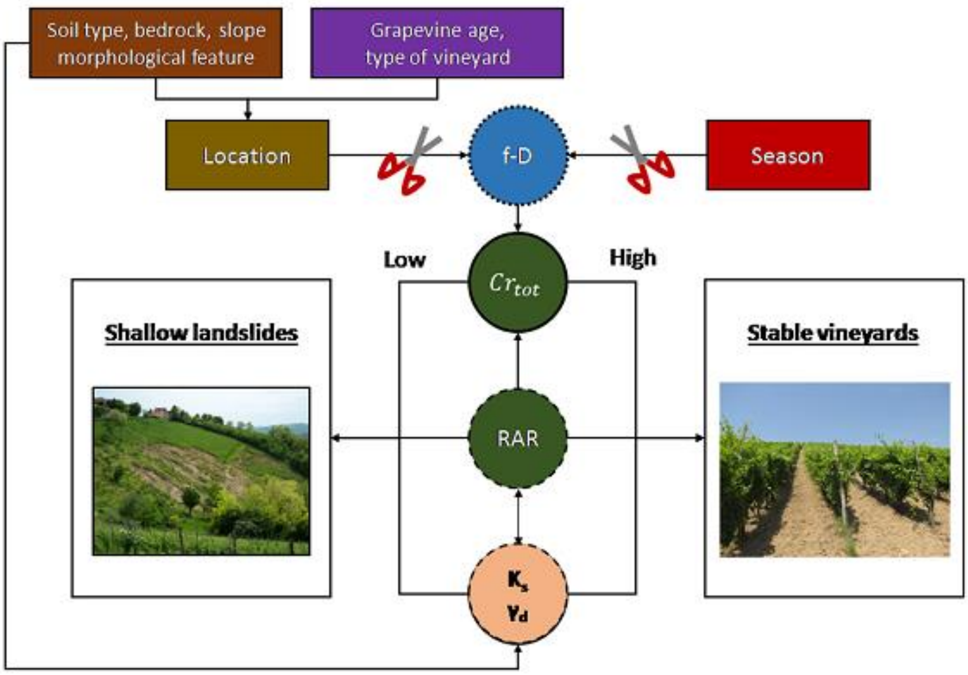

Fig. 7. Schematic flow chart of the main results of this research.

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