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MULTITEMPORAL DENDROGEOMORPHOLOGICAL ANALYSIS OF SLOPE INSTABILITY IN UPPER ORCIA VALLEY (SOUTHERN TUSCANY, ITALY)

Abstract: Bollati I., Vergari F., Del Monte M. & Pelfini M., *Multitemporal Dendrogeomorphological Analysis of Slope Instability in Upper Orcia Valley (Southern Tuscany, Italy).* (IT ISSN 0391-9839, 2016)

The Upper Orcia Valley (Southern Tuscany, Italy) is a key site for the comprehension of denudation processes typically acting in Mediterranean badlands (*calanchi*) areas, thanks to the availability of long-lasting erosion monitoring datasets and the rapidity of erosion processes development. These features make the area suitable as an open-air laboratory for the study of badlands dynamic and changes in geoheritage due to erosion (i.e. active geomorphosites).

Decadal multitemporal investigations on the erosion rates and on the geomorphological dynamics of the study area allowed to highlight a decrease in the average water erosion rates during the last 60 years. More in detail, a reduction of bare land and, consequently, of erosion processes effectiveness and a contemporary increasing frequency of mass wasting events were recorded. These trends can be partly related to the land cover changes occurred in the study area from the 1950s onwards, which consist of a significant increase of reforestation practices and important other forms of human impacts on slopes, mainly land levelling for agricultural exploitation.

In order to better identify the most significant phases of geomorphological instability occurred in this area during the last decades, an integrated approach based on multitemporal geomorphological mapping and dendrogeomorphological analysis on specimen of *Pinus nigra* Arn. was used. In detail, trees colonizing a denudation slope located in the surrounding of the Radicofani town (Tuscany, Italy) and characterized by *calanchi* and shallow mass movements deposits, were analyzed for the 1985-2012 time period. The analysis of the growth anomaly indexes and of compression wood allowed to determine a spatio-temporal differentiation along the slope and respect to an undisturbed reference site. The negative anomaly index results to be more pronounced in the trees located on the investigated slope with respect to the ones sampled in a non-disturbed area. Compression wood characterizes trees on slope sectors mainly affected by runoff and/or mass movements with a different persistence. Erosion rates were finally calculated through dendrogeomorphological analysis on tree roots exposure (0.31-3 cm/y, runoff prevailing; 5.86-27.5 cm/y, mass movements prevailing). Dendrogeomorphological results are in accordance with those obtained in the investigated areas with multitemporal photogrammetric and geomorphologic analyses.

Key Words: Calanchi, Shallow landslides, Dendrogeomorphology, Dynamic geomorphology, Multitemporal analysis, Active geomorphosites, Orcia Valley (Tuscany, Italy).

Riassunto: Bollati I., Vergari F., Del Monte M. & Pelfini M., *Analisi dendrogeomorfologica multitemporale della stabilità di versanti in Val d'Orcia (Toscana, Italia).* (IT ISSN 0391-9839, 2016)

La Val d'Orcia (Toscana meridionale, Italia) rappresenta un sito chiave per la comprensione dei processi di denudazione dei versanti caratteristici delle zone Mediterranee in cui sono diffuse le aree a calanchi (badlands), grazie alla disponibilità di una lunga serie di dati riguardanti il monitoraggio della superficie topografica. I dati disponibili e la rapidità dei processi di erosione rendono queste zone calanchive laboratori a cielo aperto per lo studio delle dinamiche dei versanti nonché siti chiave nell'ambito della valorizzazione e geoconservazione del patrimonio geomorfologico e, in particolare, dei geomorfositi attivi.

Indagini multitemporali decennali sulla dinamica geomorfologica dell'area di studio hanno permesso di evidenziare una diminuzione dei tassi di erosione durante gli ultimi 60 anni. Più in dettaglio sono stati registrati una riduzione delle superfici interessate da suolo nudo e, di conseguenza, dell'efficacia dei processi di erosione, e un contemporaneo incremento nella frequenza degli episodi di dissesto gravitativo lungo i versanti. Queste tendenze possono essere in parte ricondotte ai profondi cambiamenti nell'uso del suolo occorsi nell'area di studio a partire dagli anni '50, principalmente dovuti all'aumento delle pratiche di riforestazione e all'intenso rimodellamento delle superfici incolte a fini agricoli.

Al fine di identificare le più significative fasi di instabilità geomorfologica che hanno caratterizzato l'area di studio negli ultimi decenni, è stato utilizzato un approccio multidisciplinare basato sulla cartografia geomorfologica multitemporale e su indagini dendrogeomorfologiche applicate a campioni di *Pinus nigra* Arn.. Sono stati analizzati, relativa-

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mente al periodo 1985-2012, gli alberi che colonizzano un'area situata nel Comune di Radicofani (Toscana, Italia), caratterizzata dalla presenza di calanchi e di depositi derivanti da movimenti in massa superficiali. L'analisi degli indici di anomalia di crescita e del legno di compressione ha permesso di identificare una differenziazione spazio-temporale nell'ambito dei fenomeni di dissesto stessi lungo il versante e rispetto ad un sito di riferimento indisturbato. L'indice di anomalia negativo sembra essere più marcato negli alberi che colonizzano il versante analizzato in confronto a quello misurato negli alberi di riferimento, ubicati in un'area geomorfologicamente stabile. Il legno di compressione mostra una differente persistenza negli alberi caratterizzanti le diverse aree del versante interessate da prevalente dilavamento o da movimenti in massa. I valori dei tassi di erosione sono stati misurati attraverso l'analisi dendrogeomorfologiche sulle radici esposte, nelle aree caratterizzate da prevalente dilavamento (0.31-3 cm/y) e/o da movimenti in massa (5.86-27.5 cm/y). I dati derivanti dalle indagini dendrogeomorfologiche sono risultati paragonabili con quelli ottenuti nella medesima area tramite le analisi multitemporali geomorfologiche e fotogrammetriche.

Termini Chiave: Calanchi, Frane superficiali, Dendrogeomorfologia, Geomorfologia dinamica, Analisi multitemporale, Geomorfositi attivi, Val d'Orcia (Toscana, Italia).

INTRODUCTION AND AIMS

In the framework of scientific research regarding soil erosion, a huge sector is devoted to investigate denudation processes on clayey bedrocks being them particularly prone to erosion (e.g. Della Seta & *alii*, 2009). Since the Italian region is characterized by wide outcrops of this kind of lithology (see map in Buccolini & Coco, 2013), badlands landscape are widespread and several are the studies conducted regarding these areas since the beginning of the XXth century. The first one reported is by Bombicci (1881). Especially common is the mapping, for the Italian territory, of both clayey outcrops (e.g. Buccolini & Coco, 2013) and *calanchi* landscapes (i.e. local name for badlands) deriving from water erosion on clay (e.g. Bucciante, 1922; Alexander, 1982; Del Prete & *alii*, 1994; Phillips, 1998). From a general overview, Tuscany and Basilicata, and immediately after Abruzzo, are the Italian regions with a greater number of scientific researches on badlands and where the *calanchi* landscapes are more famous. Nevertheless on the Italian territory "calanchive" landforms characterize different substrates (e.g. glacial deposits) widening the research towards the badlands landscape developing on the whole mountain relief (Bollati & *alii*, 2016). Different topics are object of scientific researches on badlands and different approaches have been proposed especially about the Italian region: landforms description and classification (e.g. Bucciante, 1922; Castiglioni, 1933; Rodolfi & Frascati, 1979; Moretti & Rodolfi, 2000; Alexander, 1982;), mineralogical, grain size and chemical analysis on sediments (e.g. Sfalanga & Vannucci, 1975; Vittorini, 1977; Summa & *alii*, 2007; De Santis & *alii*, 2010; Pulice & *alii*, 2013; Vergari & *alii*, 2013a), morphometric and topographic studies (e.g. Buccolini & Coco, 2013), geomorphological mapping (e.g. Bentivenga & *alii*, 2015; De Waele & *alii*, 2012), dynamic geomorphology measurements for erosion rates and multitemporal analysis of their evolution (e.g. Ciccacci & *alii*, 2008; Capolongo & *alii*, 2008; Della Seta & *alii*, 2009; Clarke & Rendell, 2010; Piccareta & *alii*, 2011; Vergari & *alii*, 2013b; Aucelli & *alii*, 2016; Neugirg & *alii*, 2016), interaction with vegetation (e.g. Del Prete & *alii*, 1997; Maccherini & *alii*, 1998; Phillips, 1998; Pirone & Frattaroli, 2011; Bollati & *alii*, 2012a; Ballesteros-Canovas & *alii*, 2013; Gallart & *alii*, 2013; Torri & *alii*, 2013), human influence on their evolution (e.g. Dramis & *alii*, 1982; Phillips, 1998; Clarke & Rendell, 2000; Torri & *alii*, 2013), geomorphological hazards (Vergari, 2015). Most of these researches are aimed at evidencing also the relation existing between intensity of denudation processes and climate (e.g. Della Seta & *alii*, 2009; Bollati & *alii*, 2012a; 2016).

Badlands s.s. may be defined as "deeply dissected erosional landscapes formed in soft rock terrain, commonly but not exclusively in semi-arid regions. Badlands processes are dominated by overland-flow erosion. Badlands usually have a high drainage density of rill and gully systems, and at most they support sparse vegetation" (Harvey, 2004). Anyway, at their upper margin they can be characterized by the presence of trees which lifetime can be controlled by regressive erosion (e.g. Bollati & *alii*, 2012a). The term *calanchi* is used to refer to "heavily dissected terrain with steep, bare slopes and channels which rapidly incise and extend headwards" (Alexander, 1982). Alexander (1982) specified also that *calanchi* present "a more internal disorder and do not respect the principle of constant of channel maintenance (Schumm, 1956) because there are landslides and piping interaction".

Rodolfi & Frascati (1979) and Moretti & Rodolfi (2000) proposed, for a sample area in Tuscany, a classification of *calanchi* typologies based on the features of landforms: i) type A, due to of the action of concentrated water runoff on clayey substrata and characterized by sharp and dissected landforms, referable to the classic "knife edged" type, with a very dense drainage pattern with channels having a deep V-shaped cross profile (sensu Scheidegger & *alii*, 1968); ii) type B, mainly due to recurrent superficial slides of soil on the un-weathered substratum, slopes are gentler, the drainage pattern less dense and slides may evolve like mudflows; iii) type C, characterized by a higher frequency of small mass movements, the typical *calanchi* ridge are destroyed and the sediment fill up the bottom of the small valleys. A spatio-temporal evolutionary trend from type "A" to type "C" was individuated by Ciccacci & *alii* (2008) for Tuscany badlands in particular. They detected also the important contribution of landslides especially for the type C category, as already highlighted by Alexander (1982). This evolution trend was attributed by the Authors to climate change or human impact.

Such studies and definitions show that the attention paid towards *calanchi* landforms is mainly due both to positive and negative features (table 1). These features are somehow correspondent to the attributes (e.g. Panizza, 2001 and Bollati & *alii*, 2012b) usually taken into consideration during the quantitative assessment of the values of sites of geomorphological interest of a region (i.e. geomorphosites sensu Panizza & Piacente, 2003), elements of geoheritage of a region.

Badlands are positively considered "chiefly important because to the geomorphologist they demonstrate that permanently disordered drainage system exist" (Alexander,

TABLE 1 - Positive and negative roles of *calanchi* landforms according to different authors.

POSITIVE ROLE	
Model of geomorphological evolution (meaningfulness as open-air laboratory)	e.g. Alexander, 1980; Campbell, 1982; Faulkner, 2008; Gallart & *alii*, 2012; Aucelli & *alii*, 2016
Ecologic support role	e.g. Maccherini & *alii*, 1998
Aesthetic value	e.g. Clarke & Rendell 2006; Del Prete & *alii*, 1994, Alexander, 1982
Cultural value	e.g. Farabegoli & Agostino, 2000; Bucciante, 1922; Alexander, 1980
NEGATIVE ROLE	
Erosion hotspots	e.g. Della Seta & *alii*, 2009; Aucelli & *alii*, 2016
Source of hazard and threats, and soil loss	e.g. Almagià, 1907, Alexander, 1982; Vergari, 2015
Importance in generating extreme water and sediment yields	e.g. Nadal-Romero & Regüés, 2010, Gallart & *alii*, 2002; García-Ruiz & López Bermúdez, 2009
Disturbance towards vegetation	e.g. Del Prete & *alii*, 1997; Bollati & *alii*, 2012a; Ballesteros-Canovas & *alii*, 2013; Gallart & *alii*, 2013

1980) so they may be considered a model of geomorphological evolution (sensu Panizza & Piacente, 2003 and Bollati & *alii*, 2012b). Also Campbell (1982) considers them as "near ideal opportunity for study of processes and rates of weathering, erosion and the associated patterns of change in surface morphology". In this sense badlands are expressively considered "open-air laboratories" (e.g. Faulkner, 2008; Gallart & *alii*, 2013; Aucelli & *alii*, 2016) with a high educational exemplarity. Moreover they are often associated with cultural assets s.s., as it happens in the Central Italian landscape (e.g. Bollati & *alii*, 2012a), conferring to badlands a cultural value s.s.. The geohistorical importance and cultural value (sensu Bollati & *alii*, 2012b) of these sites increase if we consider that one of the term most used within the international scientific community to refer to these landforms (i.e. *calanchi*), was born especially concerning the Italian case (from the Latin *Chalare* - to come down Alexander, 1980; or from the name of a specific locality where they are widespread "I *calanchi*" Bucciante, 1922). Moreover, in some cases the *calanchi* landscape was used as suggestive and enriching background for literary works (e.g. Calvino, 1972) contributing to the increase of the cultural value of these landforms too. Finally these landscapes are surely famous for their aesthetic value (e.g. Clarke & Rendell, 2006; Del Prete & *alii*, 1994, Alexander, 1982).

Considering all these positive features, badlands landscape are meaningful as complex geomorphosites (sensu Reynard & Panizza, 2005) and, hence, as a part of the geomorphological heritage and cultural heritage in general (Panizza & Piacente, 2003).

However, in the framework of scientific research, the attention put towards *calanchi* landscapes as site of geo(morpho)logical interest is still limited (e.g. Castaldini & *alii*, 2005; Bollati & *alii*, 2012a; Bruno & Perrotta, 2012)

On the other side, from a negative point of view, badlands are considered "Forme di sfacelo" (i.e. break-up landforms) (Castiglioni, 1933) and erosion hotspots (Della Seta & *alii*, 2009; Aucelli & *alii*, 2016) that may become source of hazard, threats and soil loss (e.g. Almagià, 1907, Alexander, 1982; Vergari, 2015). Their negative role is also highlighted considering their importance in generating extreme water and sediment yields (Nadal-Romero & Regüés 2010, Gallart & *alii* 2002; García-Ruiz & López Bermúdez 2009).

A further attention regards the relation between badlands and vegetation. Such landforms may host important endemic species (e.g. Maccherini & *alii*, 1998; Torri & *alii*, 2013) (i.e. ecologic support role; Panizza, 2001 and Bollati & *alii*, 2012b). Moreover vegetation is considered a stabilizing tool to slow down erosion (e.g. Bucciante, 1922; Gabbrielli, 1960; Gallart & *alii*, 2013; Ballesteros-Cánovas & *alii*, 2013) and an agent reducing the rain splash effect (e.g. Ballesteros-Cánovas & *alii*, 2013). Nevertheless the process shaping badlands may provoke disturbance towards other components of the ecosystem like vegetation (e.g. Chiarucci & *alii*, 1995; Bollati & *alii*, 2012a; Ballesteros-Cánovas & *alii*, 2013), including trees, which in turn may become a powerful tool for recording the environmental changes (Schweingruber, 1996), in particular those due to geomorphological processes (Alestalo, 1971; Stoffel & Bollschweiler, 2008). As already demonstrated specifically for badlands, growth anomalies in the annual tree rings pattern and the exposition of roots as a consequence of erosion document the intensity of denudation processes, allowing to calculate erosion rates, and slope processes in general, and to date the years of particular suffering (e.g. Chiarucci & *alii*, 1995; Maccherini & *alii*, 1998; Bollati & *alii*, 2012a; Ballesteros-Cánovas & *alii*, 2013).

All these considerations led to the present research which main aim is to analyse an exemplar badlands area of the Central Italian Apennine (Orcia Valley, Tuscany Italy) in order i) to define a methodology to assess the evolution rates of badlands and the influence of active processes on these landforms, based on different techniques and ii) to emphasize the importance of investigations about morphological changes in *calanchi* areas considering their importance as component of the local and regional geoheritage. The integration of the data coming from the analysis of the biotic (i.e. vegetation) and abiotic components of the landscape had been already demonstrated to be efficient in detailing the relief evolutionary phases (e.g. Gärtner, 2007; Guida & *alii*, 2008; Bollati & *alii*, 2012a; 2016; Ballesteros-Cánovas & *alii*, 2013;Stoffel & *alii*, 2013).

Moreover the Orcia Valley, where the study site is located, has been studied for a long time (at least 20 years) using different tools and long datasets on erosion are available.

More detailed goals of the present research are: i) to determine the different evolution stages of an active geomorphosite using a dendrogeomorphology approach; ii) to calculate the erosion rates that affect it by means of roots exposure; iii) to compare data obtained by using different techniques and to evaluate the contribution of the different technologies for a better comprehension of the badlands relief evolution.

STUDY AREA

The Orcia Valley landscape, and in particular the area surrounding Radicofani (Siena), was chosen for the present research since it is highly representative as a sub-humid temperate Mediterranean area characterized by badlands. They are famous for both cultural and aesthetic values, being inserted in the UNESCO World Heritage List since 2004 in the category of the "cultural landscapes". Their progressive geomorphological changes, represented by a rapid change from type "A" to type "C" *calanchi* was investigated by Ciccacci & alii (2008) in relation to land use change and climatic factors, as mentioned above. More recently Aucelli & *alii* (2016) and Neugirg & *alii* (2016) applied photogrammetric methods to detect landforms changes during time in this area. Finally, long lasting datasets concerning monitoring of erosion rates are available (e.g. Ciccacci & *alii*, 2008; Della Seta & *alii*, 2009; Vergari & *alii*, 2013a). In the Radicofani area, specific studies were also conducted on the influence of geomorphic processes on herbaceous vegetation dynamics (Chiarucci & *alii*, 1995; Maccherini & *alii*, 2000). Concerning arboreal vegetation currently colonizing the Radicofani surroundings areas, trees derived mainly from reforestation practices performed during the 1960-1970 time interval. The dominant species are black pine (*Pinus nigra* Arn.) and Arizona cypress (*Cupressus arizonica*) (Castaldi & Chiocchini, 2012). They are species quite sensible to summer droughts that may induce them to produce density fluctuations within the annual growth rings. Such trees are used to stabilize the substrate but they are interested too by slope processes (fig. 1).

Fig. 1 - Overview of the different features of the study area. *Calanchi* landforms are dominant on the rear but locally, in the front of figure (a), a shallow landslide is dismantling them. The influence of mass wasting processes on trees growing along the slope is timely dependent and regressive propagation of erosion involved, in the gravitative processes at first the trees located on the main landslide body (a) and, only in a second, time the trees located in the newly activated upper part of the slope, where trenches are opening (b, c) (photos of 2013).

GEOLOGICAL SETTING

Outcrops of lithological units prone to denudation are widespread on Upper Orcia Valley (fig. 2). They mainly consist of clayey Plio-Pleistocene marine deposits that infilled a NW–SE-striking graben (Baldi & *alii*, 1994; Carmignani & *alii*, 1994). During Quaternary, these deposits were uplifted to several hundreds of meters above the present sea level (Liotta, 1996) due to pluton emplacement and to widespread volcanic activity along the Tyrrhenian side of Central Italy (Acocella & Rossetti, 2002), underlined by the alignment of many volcanic complexes. Quaternary uplift has been particularly strong along the southern margin of the Radicofani Graben, where marine deposits outcrop locally at 900 m a.s.l., from the Amiata-Radicofani Mt. neck, on the western side, to Cetona Mt., on the eastern slope of the study area.

GEOMORPHOLOGICAL SETTING

The geological evolution of the area led to the development of peculiar structural landforms. The major landforms are represented by morphostructural ridges bounded by NW-SE-trending fault scarps, dipping towards the graben depressions. Minor morphotectonic elements (e.g. straight channels, saddles, straight ridges) are aligned along (and controlled by) the other structural patterns.

Fluvial erosion, together with slope denudation, contributes significantly to the morphogenesis. Many slopes are rapidly evolving, and the rivers show high suspended sediment load. Water erosion is pervasive, due to extensive clayey outcrops as well as to the current climatic conditions and the rapid uplift, leading to typical sharp- and rounded-edged badlands, locally called *calanchi* and *biancane* respectively.

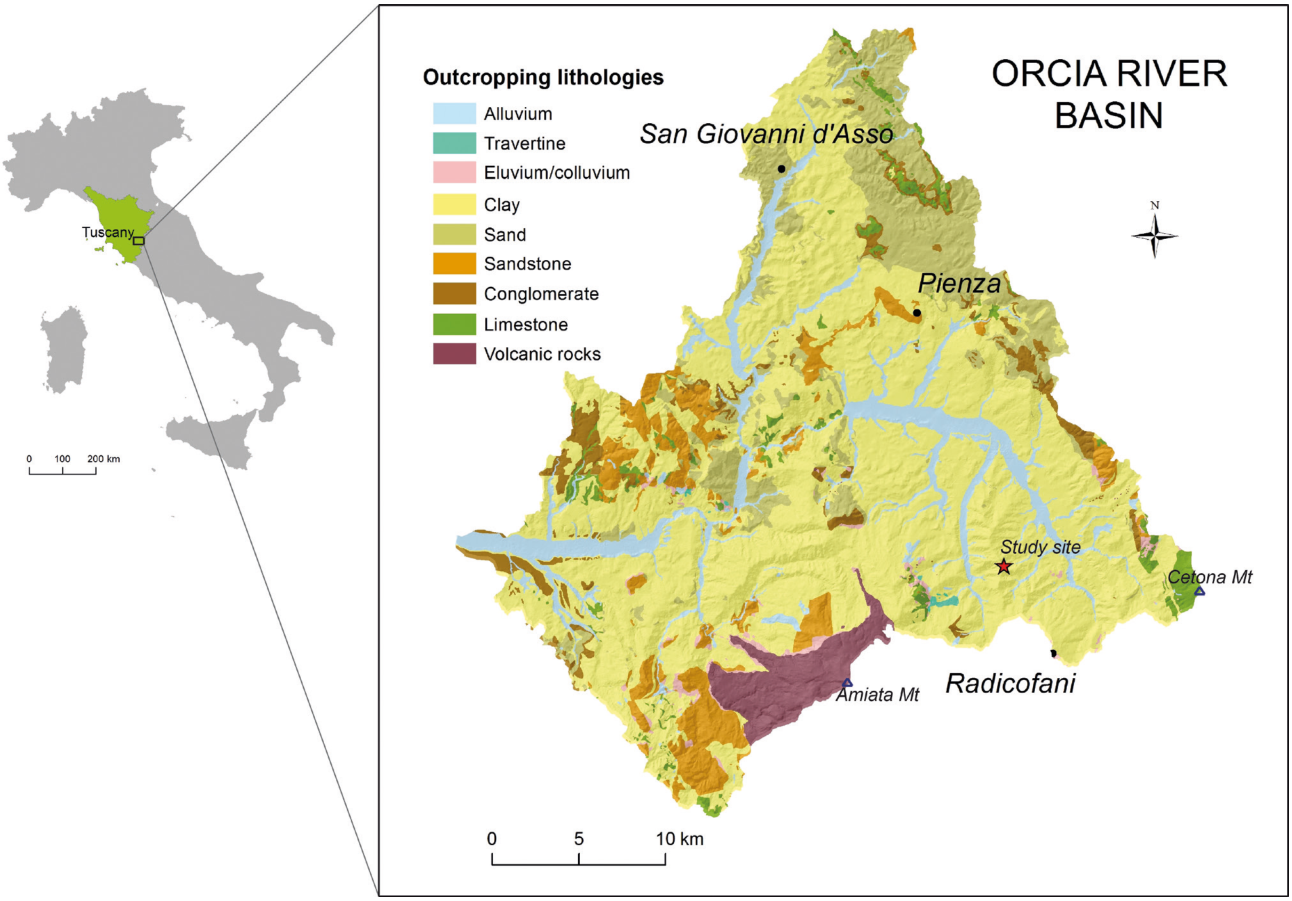

FIG. 2 - Location and geological sketch of the study site, where dendrogeomorphological investigations were performed, within the Upper Orcia Valley.

These hot spots of erosion are characterized by a wide variety of landscapes. A smooth hilly landscape marks the northern portion of Upper Orcia Valley, where typical *biancane* landforms are frequent, although often reshaped due to local crop-growing activities. These features are small clay domes up to approximately 10 m high, mostly bare of vegetation on the typically steeper southern slopes, where rill erosion is particularly strong. Towards the South (where the sampling sites are located), the presence of horst structures and/or volcanic structures led to the raising of the Pliocene marine deposits to several hundred meters above sea level. The landscape in this area is much rougher, and the typical landforms on clayey slopes are represented by *calanchi* (fig. 1a). In this portion of the area, the slopes are generally steeper, often dampening human activities; thus, the morphosculptures are less reworked than those in the *biancane* zones.

Landslides provide the major contribution to slope denudation (fig. 1a), together with water erosion (Della Seta & *alii*, 2009; Ciccacci & *alii*, 2008; Vergari & *alii*, 2011), so that they supply a considerable amount of material to be transported by the major rivers. Apart from some rock falls, earth slumps and earth slides occur on steep slopes. However, the influence of gravity is also evident on gentler slopes, where mud flows, soil creep and solifluction are widespread. Due to these prevailing morphogenetic processes, gently undulating slopes characterize the landscape.

Human activity has significantly affected the landscape for a long time. Deforestation, grazing and farming are among the most important triggers for accelerated water erosion, tillage erosion, and gravitational movements on slopes. Moreover, the effects of farming may become stronger if there are land-use changes related to cropland abandonment (Calzolari & *alii* 1997; Torri & *alii* 1999, 2013; Vergari & *alii* 2013b).

CLIMATE SETTING

The Radicofani region has a temperate warm climate depicted by the typical Mediterranean temperature and rainfall variability. The average annual precipitation in the Upper Orcia Valley is about 700 mm and the mean annual temperature is around 14°C or lower at the higher altitudes. Annual rainfalls recorded at Radicofani station (i.e. National Center for Aeronautical Meteorology and Climatology) varies between 500 and 1200 mm and presents two main peaks (Giaccone & *alii*, 2015): i) a greater one during Autumn, following summer semiarid conditions; ii) a minor one during Spring. The most rainy month is November, while the minimum of precipitation is recorded in July.

MATERIALS AND METHODS

The first step of the research was the multitemporal geomorphological mapping of the sampled hillslope through the interpretation of the available aerial photographs (dated to 1976, 1994, 2001, 2006, 2012, 2013).

Then, a field survey was carried out in 2013 in order to collect samples from trees and exposed roots mostly stressed by processes of runoff and shallow landsliding. Samplings from trunks were taken using a Pressler increment borer. The cores extracted from the trunks were collected at the standard height of the trunk of 1.30 m (breast height). Moreover, disks were cut from exposed roots. More in detail, during the sampling activities specimens from 40 trees of *Pinus nigra* Arn. were collected in the area disturbed by denudation processes (fig. 3). Other 15 trees of the same species, located about 4.5 km far away from the disturbed slope and not involved in active geomorphic processes, were sampled in order to build a reference chronology. The chronology and features of reference trees were compared with those of disturbed trees to detect the possible differences due to the affecting geomorphic processes. Moreover, in the disturbed area, the analysis was performed at level of sub-sites where locally differences in active geomorphic processes were observable. In particular, as shown in figure 3, two subsites were distinguished (each site is named as "Group" referring to all the analysed trees included): Group 1 is affected mainly by water erosion; Group 2 is located on a landslide body as delimited in 2013, where shallow landslides re-profile the slope.

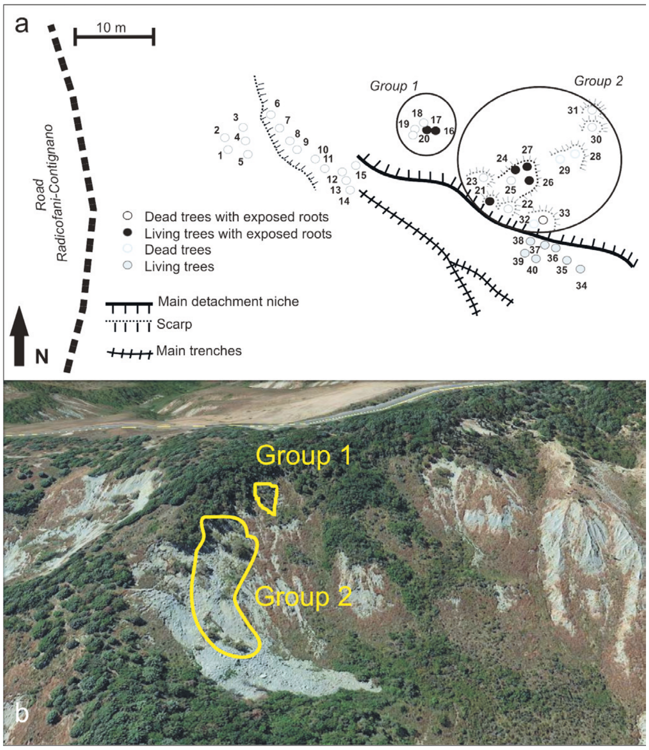

FIG. 3 - General overview of the investigated slope. a) A geomorphological sketch of the study slope with trees' location reported respect to the main geomorphological elements characterizing the slope. The subsite Group 1 includes those trees involved mainly by runoff processes and the subsite Group 2 trees located on the landslide body; b) Groups are reported on a Google Earth 3D-image of the slope (2013).

For all dendrochronological investigations, tree rings widths were measured (accuracy of 0.01 mm) using the LINTAB and TSAP systems (Rinn, 1996) and image analysis was performed with the WinDENDRO software (Régent Instruments Inc., 2001). The cross dating of the dendrochronological series was performed visually with TSAP and using COFECHA (Holmes & *alii*, 1986). Cross dating procedures (Alestalo, 1971; Heikkinen, 1994) allowed the establishment of the date of each individual annual ring through matching patterns of rings among different cores and, consequently, the identification and interpretation of growth disturbances after the building of a chronology for each tree covering the time interval 1985-2012.

After dating each annual ring, dendrogeomorphological indicators for different investigation purposes were considered.

Growth Anomaly Index (e.g. Pelfini & *alii*, 2007 and reference therein) is an indicator useful for analysing abrupt growth changes (i.e. release and suppression) and it is based on the yearly percentage growth variation with respect to the mean of the four previous years, with threshold values (positive and negative) at 40%, 55% and 70%. Particular attention was paid towards growth suppression that was referred to and quantified as Negative Anomaly Index (NAI). The NAIs were analysed for both disturbed and reference trees in order to detect their origin: if anomalies are common to all the series they can be related to one or more common actors (e.g. climate conditions), while, if not, they should be due to local conditions (e.g. local and specific geomorphic processes);

- Compression Wood (CW) (Timell, 1986) is the second indicator considered. It is a particular, denser kind of wood; it was described and dated, being a response to mechanical stress. The space-time distribution of CW among the trees of an unstable slope was used for localizing stress sources and defining their space-time contribution.

Combining these two indicators (NAI and CW) and analysing their space-time distribution, yearly event-response maps (e.g. Pelfini & Santilli, 2008) were built; they allow the localization of growth anomalies in specific years, based on trees position respect to the geomorphological features of the study area. The maps allow to understand and better communicate the temporal and spatial evolution of the disturbances along the investigated slope and the portions of its surface affected by the denudation processes (i.e. mass wasting and runoff).

To complete the range of dendrogeomorphological information, exposed roots were analysed. Roots exposure is useful for estimating the erosion rate derived mainly from water erosion (e.g. a recent review by Stoffel & *alii*, 2013 and reference therein). Morphometric analysis was performed on roots since the change in their micromorphology, from the production of root type wood to a trunk type wood, with the distinction in earlywood and latewood, is a consequence of the exposure (Gärtner, 2007; Stoffel & *alii*, 2013; Pelfini & Santilli, 2006). The equation proposed by Hupp & Carey (1990) (E=D/A), allowing to obtain the erosion rate by dividing the distance (D) between the actual ground surface and the tree root top, by the age (A) of the micromorphologic change in root, is one of the most frequently used. Recently Bodoque & alii (2015) refine the methodology, in the specific case of roots connected with the substratum, considering micromorphological issues due to secondary roots growth. Local Erosion Rates (LERs), in correspondence of single trees, and Average Erosion Rates (AERs) over long periods (e.g. Bollati & *alii*, 2012a; 2016; Ballesteros-Cánovas & *alii*, 2013) for the two Groups (1 and 2) were calculated.

The data obtained were compared with data overlapping the study time interval, deriving from iron pins monitoring (Ciccacci & *alii*, 2008; Della Seta & *alii*, 2009; Vergari & *alii*, 2013a, 2013b), multitemporal geomorphological surveies and erosion rate estimations available for the surrounding areas by digital photogrammetric analysis (Aucelli & *alii*, 2016).

RESULTS

In general different annual rings patterns were observed in trees located on the active slope respect to the undisturbed area. A detailed analysis on the different indicators is here given. The temporal resolution of the indicators were compared with the most important denudation events due to mass wasting processes that characterized the Radicofani area during the considered period (1993-1994, 1997, 2000, 2005, 2011), as emerged from previous studies and from the geomorphological maps drawn in the framework of the present research (fig. 4). The further detailed geomorphological analysis of the specific hillslope by means of multitemporal aerial photographs, allowed in fact the identification of the main instability processes affecting the area during the last 40 years. As shown in figure 4, the hillslope was interested by rill erosion during the whole time span considered for the geomorphological analysis (i.e. 1976-2013). In the site including trees of Group 2 repeated landslides (mainly earth flows) occurred, in particular starting from 2001.

Negative anomaly index (NAI)

The trees located on the slope disturbed by runoff and landslide present in general greater NAI values (fig. 5) than trees used as reference. The persistence of negative growth trend is more evident along the slope with respect to the reference trees especially during specific periods (1985-1990; 1992-1997; 2005-2012).

The suffering in trees is different in some specific periods at sub-sites or groups (see location in fig. 3 and fig. 4). This result may be related to the differentiation in processes characterizing the same slope. In this sense the NAI is variable in time in connection with geomorphological processes variation. In particular, Group 1 (B in fig. 5), including trees affected by evident runoff, records greater NAI values during the 1985-1998 time interval. The Group 2 (C in fig. 5), including all the trees located on the landslide body as delimited in 2013, underwent a negative growth trend from the middle of the '90s, when the landsliding began to involve the area, till the end of the series in 2012. A worst negative trend could be masked by the positive anomaly index that accompanies usually the formation of CW.

Compression wood (CW)

In the analysed trees, growing on the instable slope, the CW is concentrated in specific time intervals: 1985-1990 and 2009-2012. This indicates possible periods of substrate instability. More in detail, the trees of Group 1 (fig. 3; fig. 4) are intensely characterized by CW mainly during 1985-1991 till 1999. The trees of Group 2 (fig. 3; fig. 4) are characterized by CW during the last years of the investigated time span: 2002-2012, even if trees numbered 26, 31 and 32 (see fig. 3) are also characterized by CW during the first period of investigation, suggesting a suffering also prior to the main landslide events, when the area had undergone mainly runoff.

The different spatio-temporal distribution along the slope is reported in figure 6.

The persistence of CW is different from a tree to another. The trees in the different groups show different percentages of years characterized by CW along the investigated time interval: i) trees of Group 1, from a minimum of 7% to 96% and among them, the 40% of the trees shows CW in more than 50% of the investigated time interval; ii) trees of Group 2, two trees (31 and 26 see fig. 3) are characterized by CW quite along all the investigated period (96-100%) while all the other trees for 0-43% of the years; iii) trees located in the disturbed area but not included in these groups, except for particular cases (e.g. 8 see fig. 3), do not show particular CW trends.

Spatio-temporal analysis combining NAI and CW

In the figure 7 the spatio-temporal maps illustrating the disturbance along the slope during the 1985-2012 time interval are reported. Combining the NAI and CW, a differentiation on trees suffering along the slope is detectable. The thicker contour of specific years in figure 7 indicates when important landslide events happened along the slope (i.e. 1993-1994, 1997, 2000, 2005, 2011). During the 1985-mid '90s time interval the disturbance seems to be concentrated continuously in the area where runoff is prevailing (trees of Group 1; fig. 3; fig. 4). During the same time interval, trees located on the landslide body (Group 2; fig. 3; fig. 4) do not show evident or continuous signals of disturbance even if local presence of CW was recorded, as already described. During the mid '90s till 2012 trees, that moved together with the substrate during landslide events (Group 2), show quite continuous signals of suffering. After 1993, but especially after the year 2000, characterized by an important mass wasting event, instability is particularly continuous (i.e. presence of CW for several consecutive years) involving the greatest part of trees of Group 2.

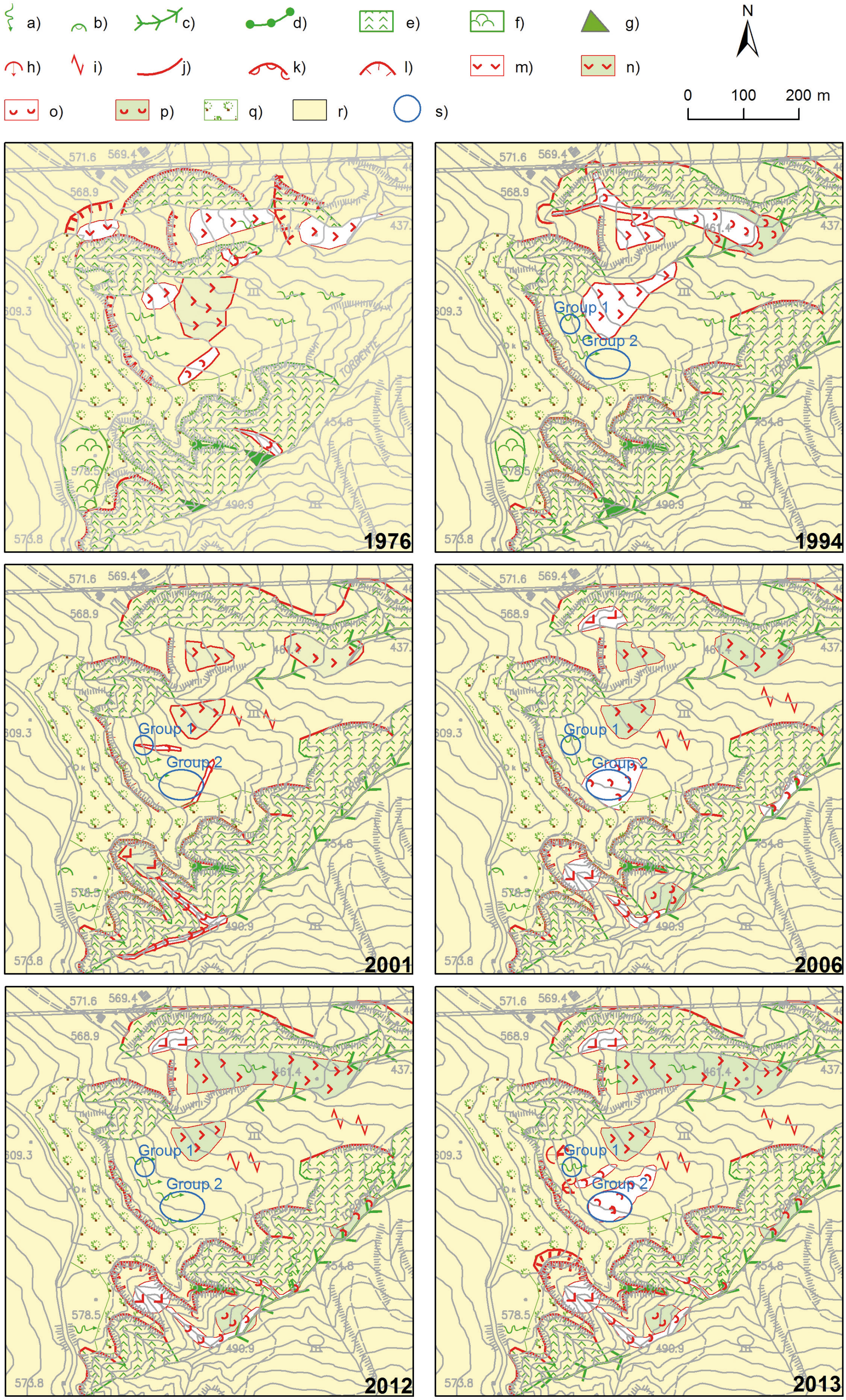

FIG. 4 - Geomorphological sketches of the hillslope investigated through dendrogeomorphological analysis. a) rill erosion; b) single *biancana*; c) V-shaped valley; d) sharp ridge; e) area affected by *calanchi* badlands; f) area affected by *biancane* badlands; g) small fluvial erosion facet; h) small landslide; i) soil creep; j) polygenic scarp; k) earth flow scarp; l) earth slump scarp; m) earth slump body; n) vegetated earth slump body; o) earth flow body; p) vegetated earth flow body; q) forest cover; r) clayey and sandy clayey (Pliocene) outcrop; s) sampled trees groups, in the 1976 map they are not reported because all the trees are younger.

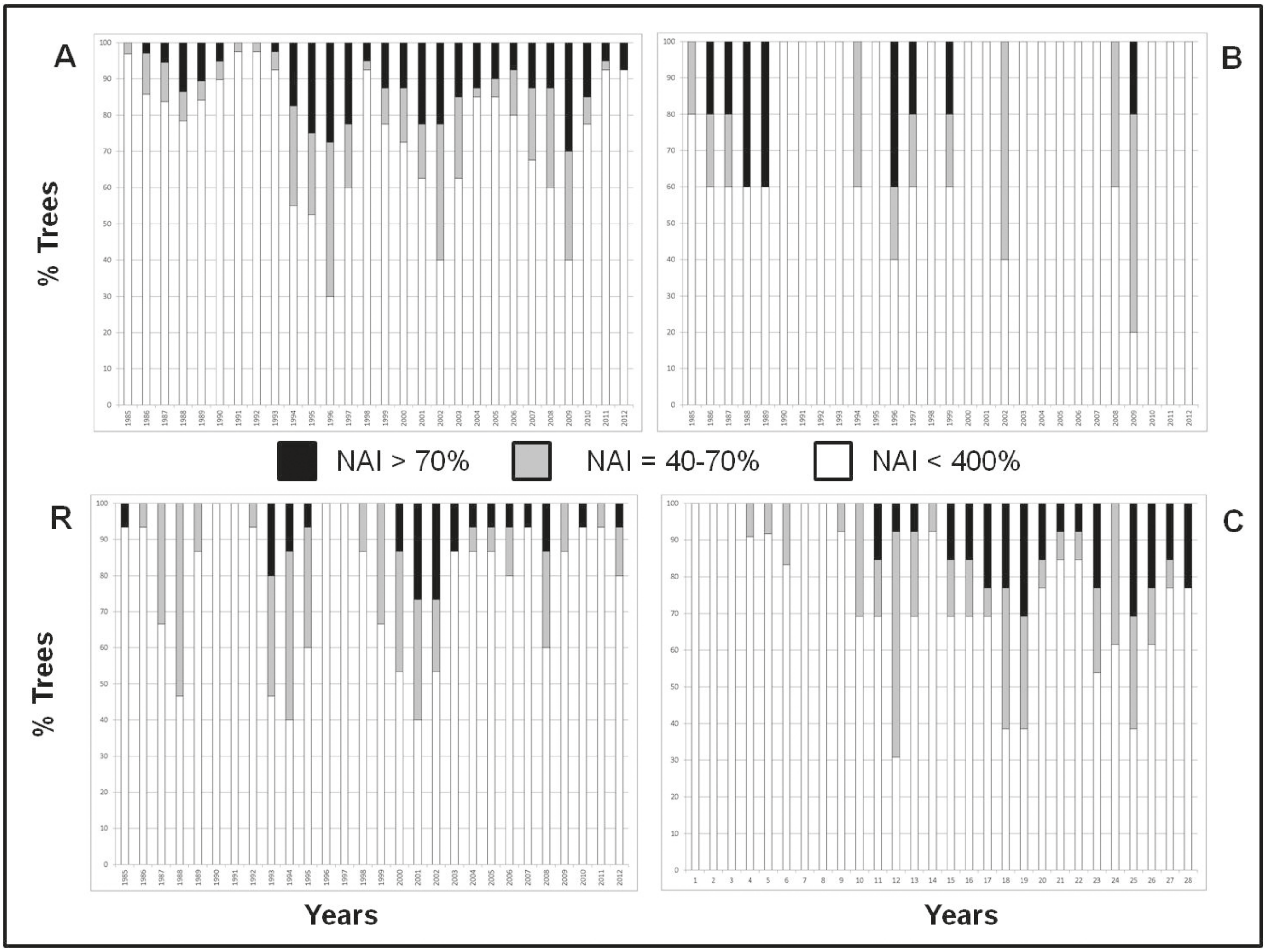

FIG. 5 - Comparison between the NAI of different groups of trees. a) NAI of trees located along the entire slope interested by landslide and runoff; b) NAI of trees located in the runoff prevailing area (Group 1, fig. 2); c) NAI of trees located on the landslide body (Group 2, fig. 2); R) NAI of trees located in an undisturbed area used as reference. The NAI are reported for each year considering the percentage of trees presenting a NAI greater than 70% (black), comprised between 40% and 70% (grey) or lower than 40% (white).

Erosion rates

Exposed roots were found only in trees of Group 1 and 2 since they are interested by evident denudation processes. Different roots exposure conditions were surveyed. Where runoff prevails (trees of Group 1; fig. 3; fig. 4), the values of removed sediment are lower (4-10 cm) (fig. 8, a), while trees located on the landslide body (Group 2; fig. 3; fig. 4), and moving together with portions of it, show higher values (30-100 cm) (fig. 8, b).

The trees of Group 1 show roots exposed since the end of the '90s with an AER of 1.65 cm/y, while roots of the trees of Group 2 resulted to be exposed since 2006 with an AERs of 14 cm/y. The calculated values of erosions are spatially variable and reported in detail in table 2 and in figure 9.

DISCUSSIONS

This study, together with the analysis of the available previous data, allowed to reconstruct and to detail the morphoevolution of a slope located near Radicofani, a sub-humid temperate Mediterranean badlands area, characterized by highly active denudation processes driven by both surface runoff and gravity action. In general, in fact, dendrogeomorphology combined with other investigation techniques is used to provide additional information with a different temporal resolution and spatial distribution (e.g. Stoffel & Bollschweiler, 2008; Bollati & *alii*, 2012a; 2016; Ballesteros-Cánovas & *alii*, 2013).

According to Vergari & *alii* (2013b) and Giaccone & *alii* (2015), the two main rainfall peaks favour differently slope processes: i) the greater one characterizing Autumn and following summer semiarid conditions, seems to favour a strong runoff erosion; ii) the minor one, characterizing the

TABLE 2 - Local Erosion Rates (LERs) and Average Erosion Rates (AERs) measured by means of exposed roots.

LOCATION	LERs (cm/y)		AERs (cm/y)	TIME PERIOD
GROUP 1 – Runoff prevailing	2.00	3.00	1.65	2007-2012
	0.31			1999-2012
GROUP 1 – Landslide body	15.00		14	2010-2012
	5.83			2006-2012
	6.00			2007-2012
	16.00			2007-2012
	27.50			2010-2012

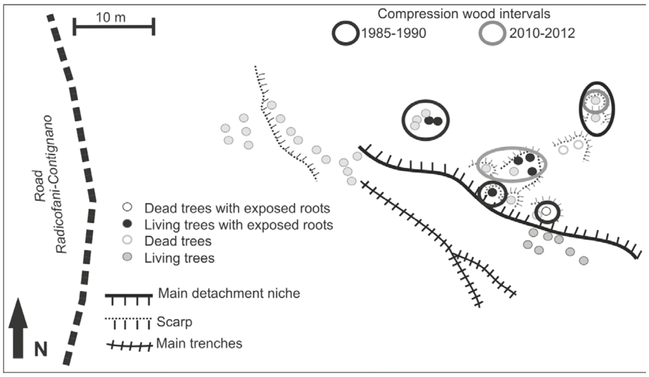

FIG. 6 - The compression wood presence in the landslide trees. Two main time intervals were individuated (1985-1990; 2009-2012) in different portions of the slope.

Spring period and insisting on a bedrock already saturated from the Autumn and Winter rainfall seasons, favours shallow landsliding.

Starting from the data coming from previous geomorphological and digital photogrammetric analyses and according to multitemporal geomorphological mapping of the sampled hillslope, the different stages of evolution of the relief were detailed using a dendrogeomorphological approach for the time interval 1985-2012. The combination of the techniques allowed a higher definition in space and time (e.g. Ballesteros-Cánovas & *alii*, 2013) as highlighted in the comparison sketch of figure 10.

A first main result is the subdivision of the investigated time interval into two main time periods: 1985-middle '90s and middle '90s -2012 corresponding roughly to the period when runoff and landslides events became respectively more relevant (fig. 4). This result is in accordance with the outcomes achieved independently by Ciccacci & *alii* (2008) and Aucelli & *alii* (2016), for the 1976-2004 time span. Ciccacci & *alii* (2008) described the evolution of the area using the typologies of *calanchi* suggested by Rodolfi and Frascati (1979): an evolution, starting from middle '50s, from type "A" *calanchi*, the more classic ones characterized by sharp edges and narrow and deep gullies, to type C *calanchi*, where the typical knife-edge ridges are dismantled as a consequence of increasing mass movements. The multitemporal photogrammetric analysis performed by Aucelli & *alii* (2016) also showed a slight decrease in the average water erosion rate during the last 60 years and a parallel increase in the frequency of mass wasting events. The shift from water to gravity driven processes could be due, according to Aucelli & *alii* (2016), to land cover changes and to the increasing frequency of extreme rainfall events combined with a greater number of consecutive dry days as triggering factor.

The present dendrogeomorphological analysis allowed to add more information about the space-time distribution of mass wasting events, detecting some landslide events along the slope (i.e. 1993-1994, 1997, 2000, 2005, 2011; fig. 4; 7), that provoked an intensification of suffering in trees recorded in term of NAIs and CW (see fig. 7). For what concerns the stress in term of CW, instability is generated by a combination of water and gravity processes. More in detail, after the 1993 event, and especially after the 2000 event, the CW started to characterize continuously the trees currently located on the landslide body. Since some trees of Group 2 (fig. 3; 4) are interested by CW all along the time interval, probably, before landsliding, runoff had generated instability within the entire area, as also confirmed by the multitemporal geomorphological sketches (fig. 4).

The NAI values show a differentiation too, among the two groups and respect to the reference trees. In this last group, instead, CW was not present at all. The suffering of trees of Group 1 (fig, 3; 4) was concentrated in the first part of the investigated time interval (1985-middle '90s) while during the middle '90s NAIs were more intense on landslide trees (Group 2; fig. 3; 4). The investigated species (*Pinus nigra* Arn.) fits quite well in this environmental context, even though an hydrological stress, for example as a consequence of a modification on the groundwater circulation following the landslide events, might have induced the detected stress on trees.

The analysis of the erosion rates measured by means of roots exposure, especially the AERs, provides values comparable with those coming from both geomorphological monitoring and digital photogrammetric analysis, taking into consideration the slightly different time interval (e.g. Bollati & *alii*, 2016; Ballesteros-Cánovas & *alii*, 2013). The erosion

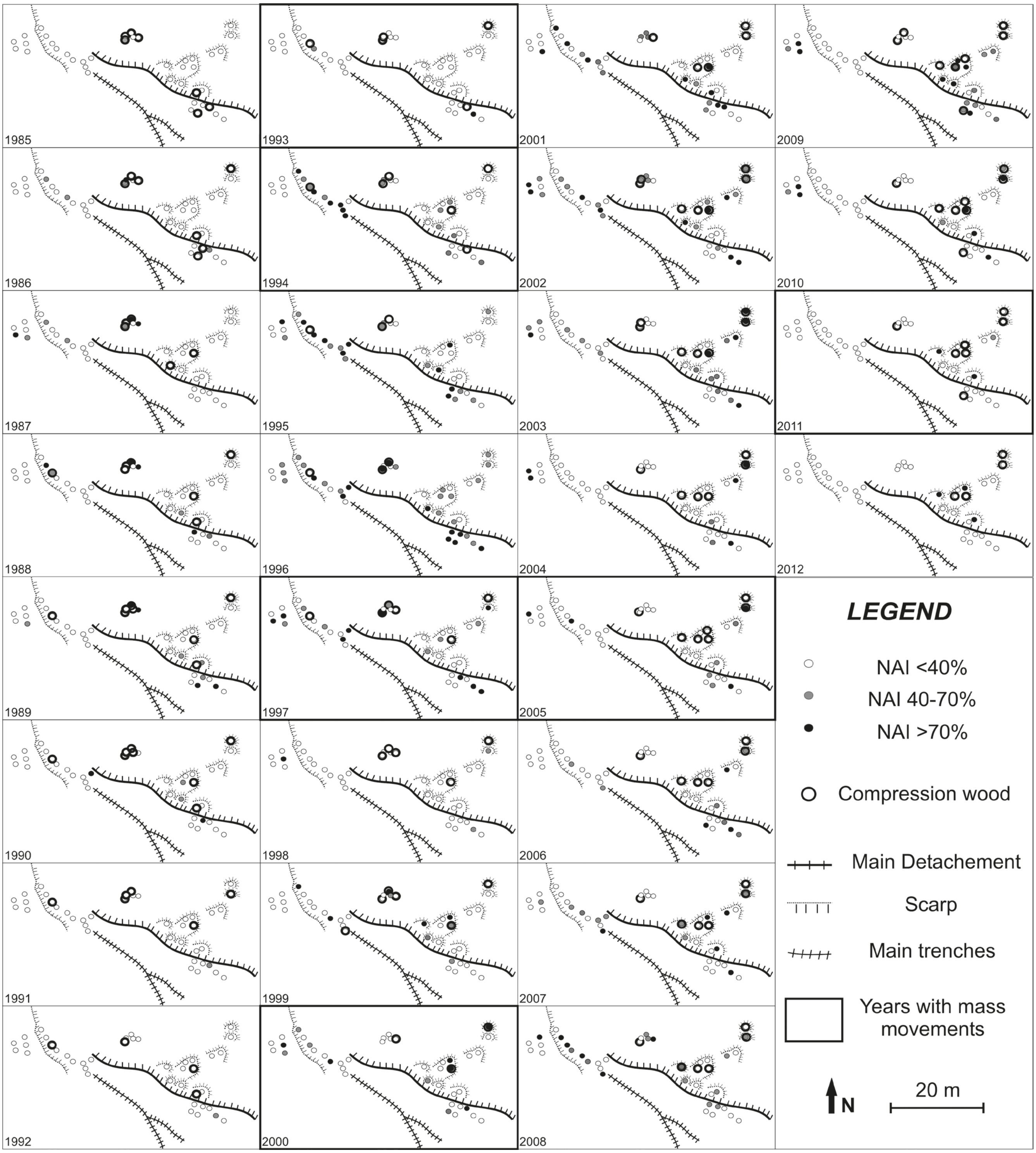

FIG. 7 - Spatio-temporal distribution of NAIs and CW in the trees located along the investigated slope. The phases of disturbance are differentiated along the slope and in a former stage (1985-middle '90s) the disturbance looks like to be concentrated where runoff processes prevail. In a following phase (middle '90s - 2012) the disturbance on trees is concentrated on the landslide body testifying a more important contribution to the disturbance from the gravity processes rather than exclusively from runoff.

FIG. 8 - Different typologies of exposed roots. a) Where runoff prevails the exposition of roots is relatively limited and it should be probable that erosion rates have been constant during time; b) where the trees move together with the landslide body portions, the roots are more distant from the topographic surface and sudden important events of sediment removal are expected to be linked to the landsliding phases (photos of 2013).

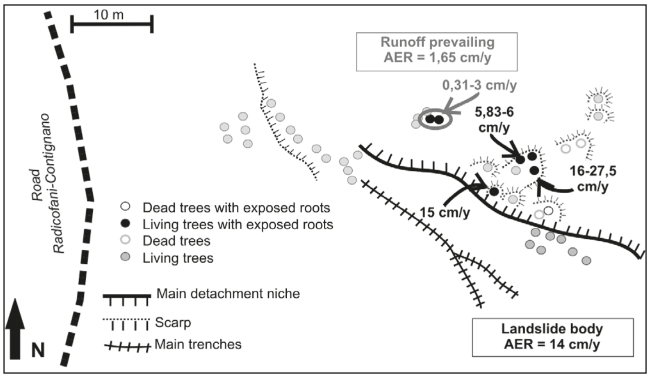

FIG. 9 - Distribution of the LERs along the investigated slope. The erosion rates obtained in the runoff prevailing area are lower (0.31-3 cm/y, AER 1.65 cm/y) than the values obtained for the trees located on the landslide body (5.83-27.5 cm/y, AER 14 cm/y).

processes are discontinuous in Mediterranean badlands contexts, as already testified by classical geomorphological techniques (Ciccacci & *alii*, 2008) or by dendrogeomorphology (Bollati & *alii*, 2012a; Ballesteros-Cánovas & *alii*, 2013; Bodoque & *alii*, 2015). The Mediterranean basins, where clayey outcrops occur, are characterized in general by mean erosion rates of 1.5-2.0 mm/y (Lupia Palmieri, 1983) and where specifically *calanchi* and *biancane* are the dominant landforms, this value increases at least by one order of magnitude (e.g. Alexander, 1982; Del Prete & *alii*, 1997; Clarke & Rendell, 2006). The calculated mean surface lowering rate due to runoff processes for *calanchi* in the areas surrounding the Radicofani study case (i.e. Orcia Valley) was calculated by Della Seta & *alii* (2009), by means of iron pins monitoring, to be 1-2.5 cm/y with an average of 1.65 cm/y, comparable with those calculated for the typical *calanchi* area (Type A and B *calanchi*; 1.5-3 cm/y; Ciccacci & *alii*, 2008; fig. 10). As shown in many studies, dendrogeomorphology analyses allow to show variable rates depending on the target morphoclimatic systems and the affected substrates. In particular Stoffel & *alii* (2013), in a recent review, indicate a range of values of erosion detectable by means of root exposure of 0.15-1.35 cm/y. The mean value obtained for runoff area by means of dendrogeomorphology in the present research is 1.73 cm/y (1999-2012; fig. 10). Bollati & *alii* (2012a), in a site located in Southern Tuscany about 35 km North of Radicofani, obtained an AER of 1.58 cm/y.

For what concerns AERs characterizing the slope where landslide dominates, calculated in the present research, the values become higher (i.e. 14 cm/y; 2006-2012; fig. 10), as expected by other authors using the same methodology (Vandekerckhove & *alii*, 2001; Ballesteros-Cánovas & *alii*, 2013). This result is in accordance also with that obtained by Aucelli & *alii* (2016) by means of digital photogrammetric analysis and indicated as value of head retreat (i.e. 10-15 cm/y; fig. 10).

Ciccacci & *alii* (2008) calculated the AERs for the entire Radicofani basin, including hence runoff and mass wasting: 7.5 cm/y by means of direct measurements and 5.5 cm/y for the time period 1976-1994 through indirect methods (i.e. DEM analysis). As highlighted by the Authors, the contribution of mass movements, meaningful for this area, justify these higher values at the Radicofani study site. Similar AERs for the entire basin by Aucelli & *alii* (2016) (i.e. 6.2 cm/y over about 30 years) and Neugirg & *alii* (2016) (i.e. 5.3 cm/y over 1 year). The AER for the entire study area, by means of dendrogeomorphology, for the period 1999-2012 herein calculated, is 7.82 cm/y (fig. 10), concordant with and of the same order of magnitude of those indicated in literature (fig. 10).

Bodoque & *alii* (2015) has recently analysed the possible source of errors affecting erosion rates calculation using roots. The Authors suggest to pay attention, during roots sampling, to microtopography variation due to roots secondary growth (i.e. to maintain a thresholds distance from the trunk, to sample roots growing parallel to the slope to avoid the dam effect for sediment). The roots

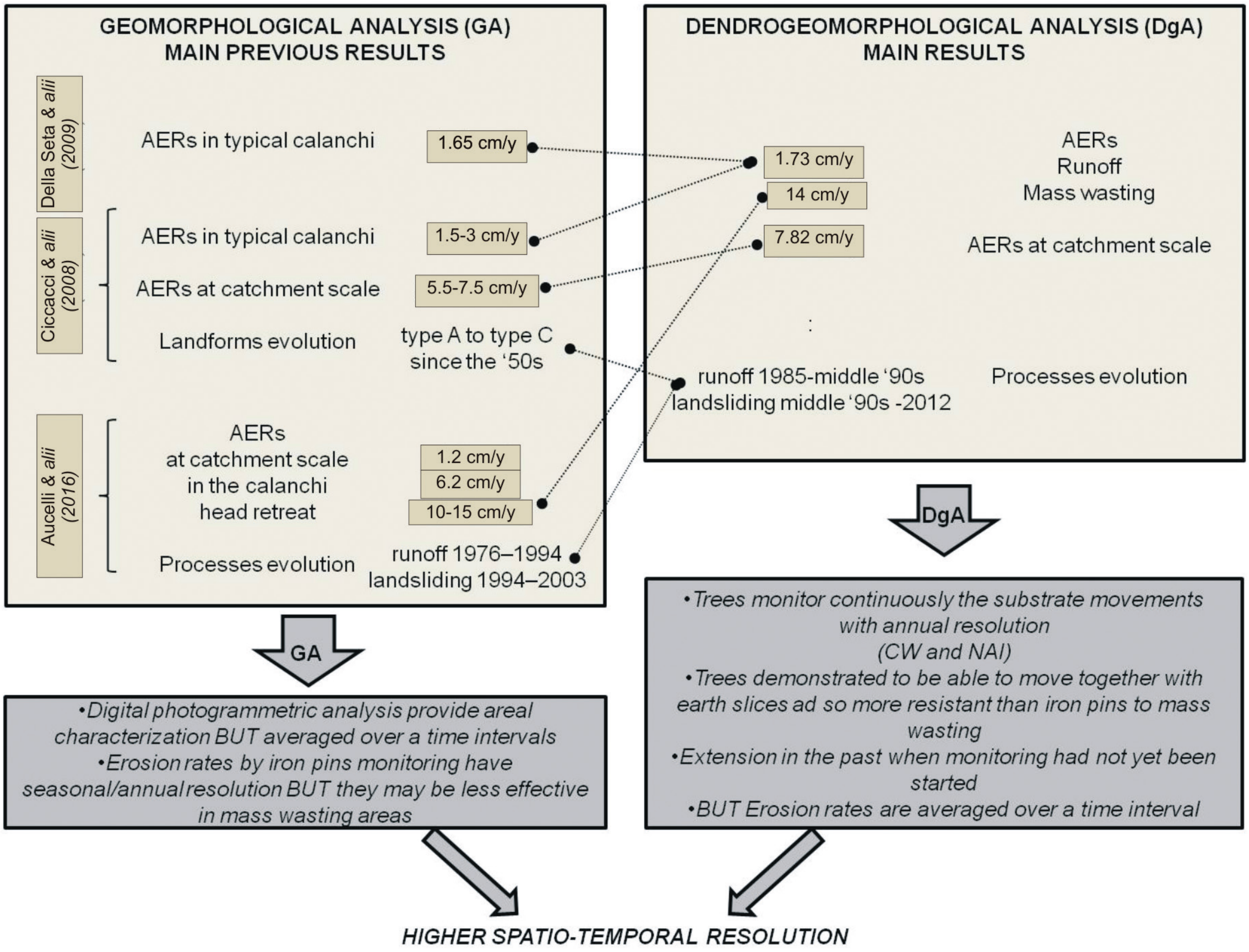

FIG. 10 - Comparison of the data and advantages deriving from the integration of different investigation techniques.

sampled in the framework of the present research were detached from the topographic surface, anyway the possibility of further detailed microtopographic analysis could be taken into account, especially considering roots present in the surroundings and connected with soil, incrementing the degree of detail for the investigated area.

Concerning geoheritage topics, the studied area can be considered not only a very representative of the changes in surface processes affecting clayey outcrops through time (i.e. model of geomorphological evolution), and consequently a high scientific valued spot, but also a key site for educational purposes. The morphological and vegetation evidences favour the increase of the educational exemplarity thanks to the presence, in a narrow area (fig. 1), of different and rapidly evolving water/gravity driven landforms. This feature represents an example of geodiversity (i.e. processes and landforms genetically and temporarily linked each other) that affects differently vegetation during its life-span having a meaning also in term of ecologic support role inducing changes in the global value of a potential geomorphosite (e.g. Bollati & *alii*, 2016). All these considerations endorse the investigated area, and the Orcia Valley badlands landscape in general, as a valuable complex geomorphosite.

More in detail this site is classifiable as an active geomorphosite, according to the most recent classification proposal for geomorphosites (Pelfini & Bollati, 2014 and previously Reynard, 2004) and also as a mixed active/evolving passive geomorphosite. It is the case where recently landslides dominate landforms evolution: here in fact the original water runoff action, responsible for the genesis of the *calanchi* landforms, has gradually left place to water driven gravity processes that generate mass movements.

From a negative point of view, the activity of processes are inducing the dismantling of type "A" *calanchi* landforms affecting the integrity of the site. At the same time, the formation of new landforms as geomorphosites (i.e. landslide morphological evidences) is inducing change in term of geodiversity and new bare surfaces are generating, on which, in future, new integer *calanchi* may be modelled depending on the dominating geomorphological process (more water or more gravity) (Bollati & *alii*, 2016).

CONCLUSIONS

The reconstruction of spatio-temporal evolution of a key-site in the surrounding of Radicofani (Tuscany, Italy) can be considered useful in the framework of changes of erosion landscapes (i.e. badlands areas in the Mediterranean morphoclimatic environment) and assessment of geoheritage undergoing evolution.

The integration of different methodologies of investigation (i.e. dendrogeomorphology, geomorphological mapping) and the comparison with previous data have allowed here to calibrate the contribute of each discipline involved in detailing the local evolution of slope during time (fig. 10), as successfully already tested in similar areas where runoff was the dominant process. More in detail, the results herein presented (i) highlight the different stages of evolution of the analyzed site, (ii) outline the comparability of erosion rate values obtained applying different methods and, at the same time, (iii) evidence the meaningful contribution of roots exposure analysis in calculating erosion rates and potentially soil loss through time where traditional monitoring is not suitable for. A specific research seems necessary for investigating in depth the response of the investigated trees species to hydrological stress deriving from these kind of slope processes (e.g. isotopic signals in tree rings).

Badlands landscapes, like the one analyzed, may be considered complex geomorphosites where changes in active processes responsible for their evolution should be considered in their assessment and management. The methodology applied in the study area, based on integration of techniques on abio- and biological components of the landscape, allowed to collect quantitative data to measure spatio-temporal changes of the whole landforms and of the vegetation (i.e. trees) system (i.e. ecologic support role). In the investigated site, in a very narrow area, an example of active and evolving passive complex geomorphosite may be proposed. These features allow to increase the scientific value especially in term of educational exemplarity, geodiversity and ecologic support role of the investigated landforms.

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