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Highlights

Catena xxx (2011) xxx–xxx

Dendrochronological and geomorphological investigations to assess water erosion and mass wasting processes in the Apennines of Southern Tuscany (Italy)

I. Bollati [a,*], M. Della Seta [b], M. Pelfini [a], M. Del Monte [b], P. Fredi [b], E. Lupia Palmieri [b]

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► Tree growth anomalies allowed to reconstruct spatio-temporal evolution of relief in a calanchi area. ► Comparable erosion rates have been obtained using dendrogeomorphology and quantitative geomorphology. ► Erosion rates, compression wood and ring width anomalies are well correlated with thermo-pluviometric trends.

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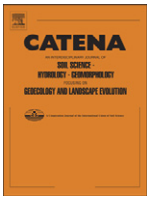

Dendrochronological and geomorphological investigations to assess water erosion and mass wasting processes in the Apennines of Southern Tuscany (Italy)

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ABSTRACT

The Tyrrhenian side of the Central Apennines is located in a lively geological context, in which uplift/denudation dynamics played a key role in landscape evolution. Intense water erosion and gravitational processes led to the development of spectacular badlands on the widespread clayey hillslopes. The Crete d'Arbia badlands (as part of the Crete Senesi of Southern Tuscany) represent one of the most beautiful examples of these landforms developed on Pliocene clays. On the other hand, these rapidly evolving landforms endanger the artistic heritage of the area, as with the Monte Oliveto Maggiore Abbey that was constructed on the top of a badland hillslope and confers additional value to the landscape.

In the perspective of monitoring and reconstructing some significant phases of the relief evolution of this area an integrated approach has been used, which is based on dendrogeomorphology and geomorphological monitoring techniques. In particular, the correspondence between the data from dendrogeomorphological indicators and the measured denudation rates on badland hillslopes was tested. The sampling for dendrogeomorphological analysis has been performed in two stages on 45 trees of the *Pinus pinea* L. species, on hillslopes affected by soil creep and shallow landslides, in order to identify annual ring growth anomalies, *compression wood* and root exposure. Trees' local behaviour is not homogeneous but some common trends have been detected on the basis of the *anomaly index* and *compression wood*. Since 1993 several monitoring stations at badland denudation "hot spots" have been equipped with erosion pins; quantitative data from monitoring stations, compared to pluviometric series, indicated critical phases of denudation that were supported by dendrochronological data. The integrated approach between dendrogeomorphology and geomorphological monitoring techniques allowed calibration of both tools in order to extend the analysis in the period preceding the field measurements. This kind of approach, capable of implementation in many contexts, could be particularly helpful in order to forecast the relief evolutionary trend.

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1. Introduction

The intensity of accelerated denudation represents one of the most studied topics in the geological and geomorphological field of research since these processes may cause significant landscape modifications during the time scale of a human life (Ananda and Herath, 2003). The damaging effects of slope denudation may be particularly serious when affecting geomorphosites (Bollati and Pelfini, 2010). Moreover, hazards and risks may be associated with these processes, even influencing tourist attendance, when they involve human settlements (Piccazzo et al., 2007).

The natural processes responsible for rapid landscape evolution act on different scales and at different velocities, so that different investigation techniques are needed to monitor and quantify relief evolution.

Accelerated erosion is likely to influence denudation rates on the catchment scale. Thus, understanding and monitoring the processes involved in their development are of crucial importance, especially with regard to distinguishing between the on- and off-site effects of denudation. Direct monitoring of accelerated water erosion processes has traditionally been performed on the hillslope scale on parcels of land or experimental catchments (Del Monte et al., 2002; Della Seta et al., 2007, 2009; Poesen et al., 2003; Richter and Negendank, 1977). Catchment scale erosion rates have been obtained through the quantification of the infill of artificial lakes or check-dams (Ciccacci et al., 1983; De Vente and Poesen, 2005; Romero-Díaz et al., 2004, 2007). In addition, multi-temporal analysis and hillslope monitoring are more and more frequently performed through photogrammetric techniques (Ries and Marzloff, 1997; Welch et al., 1983). Q6 Multidisciplinary approaches have recently been developed in order to enhance the results of the research on accelerated erosion processes (Guida et al., 2008).

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Plio-Pleistocene clayey landscapes of the Central Apennines, represent typical environments, where sheet wash, rill and gully erosion, along with shallow mass movements and soil creep have shaped spectacular badland scenarios (sharp-edged *calanchi* and rounded-edged *biancane*; Alexander, 1980; Ciccacci et al., 2003; Della Seta et al., 2009; Torri and Bryan, 1997), often associated with impressive artistic treasures. Nevertheless, the same lively processes responsible for amazing landscapes often endanger these regions with severe consequences on slope stability and on the preservation of cultural heritage (Bollati and Pelfini, 2010).

Finally, the strong morphodynamics on badlands often cause damage even to the field monitoring stations for denudation rate estimations. This happened, in particular, at Monte Oliveto Maggiore, where a monitoring station equipped with erosion pins was recently destroyed, causing loss of denudation data. In this frame, the integration of geomorphological monitoring techniques with the ones based on biological systems, like dendrochronology (Schweingruber, 1996), can be particularly useful, as already tested in different contexts such as for landslides (Guida et al., 2008) and debris flows (Pelfini and Santilli, 2008).

This paper is aimed at testing a multidisciplinary approach based on the integration of dendrogeomorphological and direct quantitative geomorphological techniques for the analysis of relief evolution of a badland test area in the Central Apennines, that is characterized by fast morphodynamics, as already reported in previous works on the same region (Alexander, 1980; Ciccacci et al., 2003, 2008; Del Monte, 2003; Del Monte et al., 2002; Della Seta et al., 2007, 2009; Moretti and Rodolfi, 2000). The integration between geomorphological and dendrogeomorphological techniques has focused on the reconstruction of the past relief modifications since the 1990s, with annual to seasonal resolution. The reconstruction of relief modifications is done through the analysis of the effects of hillslope processes on trees growth. In fact, dendrogeomorphological and geomorphological monitoring data are both strictly correlated to the rainfall data. For example, the extreme rainfall events speeding up water erosion and gravitational processes on clayey slopes (Della Seta et al., 2007, 2009) can produce local stresses to trees which establish conditions of instability. On the other hand, an extremely dry period may reduce the growth of some tree species (*P. pinea* L., Cherubini, 1993).

Hence, both in the first case (indirect influence) and the second case (direct influence), climatic induced stresses may influence the tree ring growth (Fig. 1): the increase in intensity of water erosion and/or gravitational processes as a consequence of even annual variations in meteorological conditions (i.e. increase of rainfall, extreme events) can result in a mechanical stress on trees that, in turn and at the same time, are also directly influenced by the background climatic conditions (dryness). Thus, the final tree ring record is the result of the combination of both climatic/meteorological and mechanical inputs. In this sense it is important to separate the thermo-pluviometric input, which influences the growth of the majority of trees of the same species both on stable and unstable slopes from the one locally produced by slope instability in the *calanchi* areas.

In detail, the main goals referring to the major phases of relief evolution since the early 1990s are: 1) discriminating whether some growth anomalies can be associated with extreme thermo-pluviometric conditions (i.e. dryness) rather than geomorphic processes through the analysis of pluviometric series; 2) defining the spatio-temporal distribution of tree growth anomalies as indicators of geomorphic processes affecting trees; 3) making a comparison between dendrochronological and geomorphological erosion rate estimations.

Moreover, in the case of dendrogeomorphological analysis of tree growth disturbances (indicators) the principal aims are: i) identifying the effects of soil creep on trees; ii) estimating the erosion rate; iii) verifying the contribution of piping to slope instability; iv) analysing the contribution of soil creep and shallow landslides to accelerated slope denudation.

2. Study area

2.1. Location of the study area

The study area is located on the Tyrrhenian side of the Central Apennines and it is known as *Crete d'Arbia* (Southern Tuscany), one of the Italian SIC (Community Important Site) (IT5190005). It is also named as *Calanchi of Monte Oliveto Maggiore*, which is one of the most famous abbeys of the Benedectine Congregation, which confers additional value to the landscape (Reynard et al., 2010). The study Q7 area lies within the Ombrone Basin, which is strongly affected by water erosion and gravitational movements acting on widely outcropping Pliocene clays (examples in Fig. 2).

2.2. Geological and geomorphological setting

The major NW–SE striking horst-and-graben morphostructures of the region originated during the Apennine orogenic wedge collapse (Late Miocene). NW–SE striking normal faults cut sedimentary sequences (Umbria–Marche sequence, Tuscan Nappe, Ligurian and Subligurian Nappe) previously overthrusted towards the NE. The system of graben (Baldi et al., 1994; Carmignani et al., 1994), cut by SW–NE transfer faults (Liotta, 1991), experienced marine transgression that led to the deposition of the Plio-Pleistocene sequence of clays, sands and conglomerates within the major depressions (Radicofani Graben, Val di Chiana Graben and Tevere Graben; see Barberi et al., 1994; Bigi et al., 1992; Funiciello et al., 1981). Since the Late Pleistocene, these deposits have been uplifted up to several hundred of metres above. Since the Late Pleistocene, the marine present sea level, with the highest rates along a NW–SE elongated zone. This uplift is linked to pluton emplacement and widespread Quaternary volcanic activity (Lazzarotto, 1993; Liotta, 1996).

The variety of outcropping lithologies and the tectonic influence determined the development of structural landforms, such as morphostructural ridges bounded by NW–SE trending fault scarps, dipping towards the graben depressions, and minor morphotectonic alignments (e.g., straight channels, saddles, and straight ridges) following the structural patterns. The present day hilly landscape, with elevations rarely higher than 1000 m above sea level, is the result of both fluvial erosion and slope denudation on the widespread outcrops of soft sediments. Pervasive erosion by surface running water is favoured as well by present-day climate conditions and rapid uplift that leads to high suspended sediment load. Sheet erosion, especially on the flattish hill tops, causes the exposure of roots, while colluvium is frequently accumulated at the foot slope. Where the hillslope is even slightly steeper, rill and gully erosion, along with shallow landslides, especially mudflows, lead to badland development (*calanchi* and *biancane*) and soil degradation (ephemeral gullies; Foster, 1986), often associated with locally developed piping phenomena (Faulkner et al., 2004; Torri and Bryan, 1997).

Apart from processes acting on badland slopes, rock falls, slumps and slides occur on relatively steeper slopes while, on gentler slopes, mudflows, soil creep and solifluction are widespread (Fig. 2).

2.2.1. Geomorphic processes related to anthropic activity

Anthropic activities have strongly contributed to the landscape evolution of this region: deforestation, grazing and farming, land-use changes, especially cropland abandonment, are the most important triggers for accelerated water erosion, tillage erosion and gravitational movements on hillslopes (Calzolari et al., 1997; Torri et al., 1999). It is worth noting that some proposals for the adoption of hydraulic and reforestation techniques to slow down denudation on *calanchi* hillslopes had been made several years ago just for the area of the Monte Oliveto Maggiore Abbey (Gabbrielli, 1960).

The remoulding of badland slopes for agricultural purposes, often through heavy machinery reaching the head of *calanchi* areas, caused

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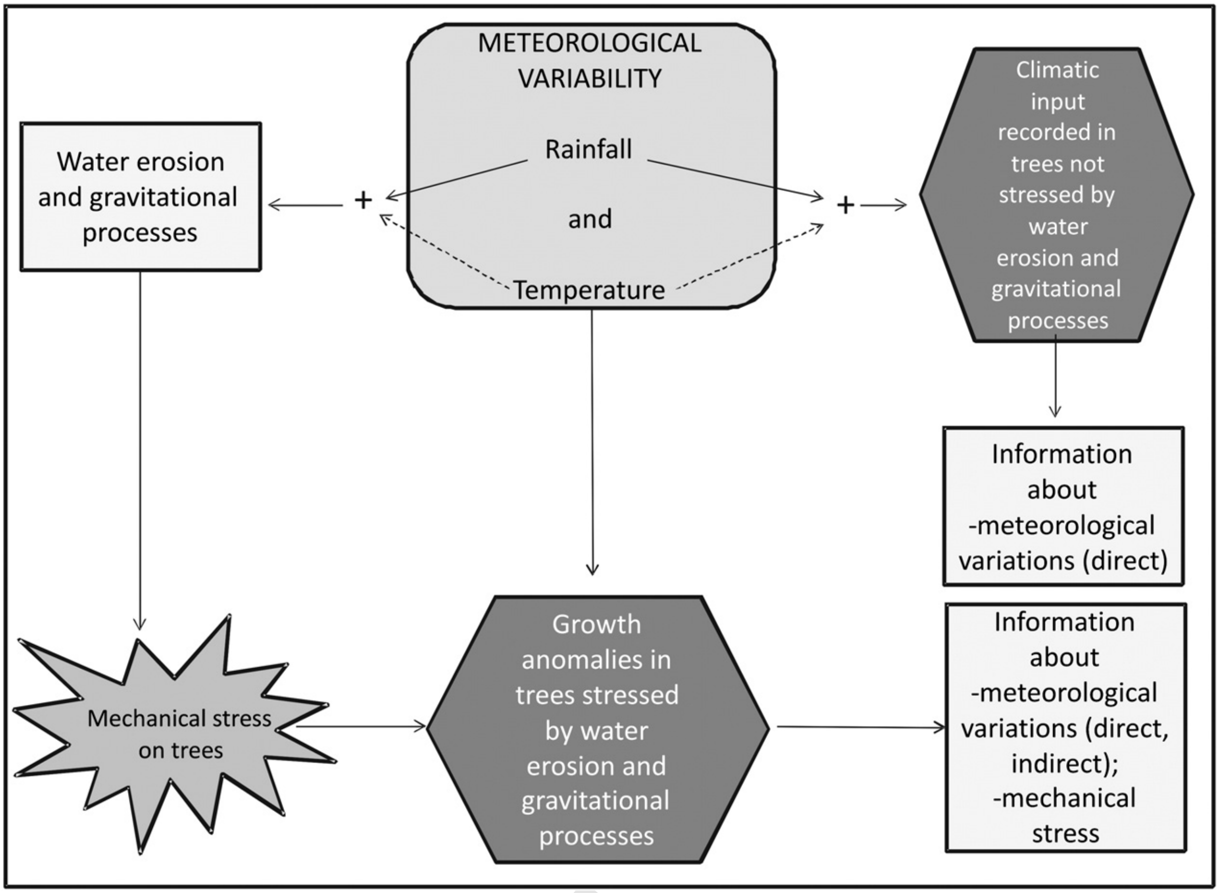

Fig. 1. Sketch of the relationship among thermo-pluviometric inputs, hillslope processes and tree growth.

preferential deep infiltration tracks, which favoured the development of landslides. The result is the rapid destruction of their typical knife-edge ridge-lines, due to increased gravitational processes over time. In particular, Ciccacci et al. (2008), using field monitoring and photogrammetric techniques, outlined that over the past 50 years *calanchi* badlands have progressively changed from type A (with sharp edges and narrow and deep gullies), to type B (with trough-floored small valleys, separated by smaller convex ridges, affected by noticeable mass movements) and then to type C (characterized by a higher frequency of mass movements, which almost completely destroy the *calanchi* ridge and fill up the bottom of the small valleys) (Rodolfi and Frascati, 1979). Salvini (2008), as a result of a landscape evolution study based on remote sensing techniques, reported a noticeable reduction of the badlands from 1954 to 2000 in the Crete Senesi area due to levelling practices.

2.3. Climatic setting

The Fiume Ombrone Basin climate, from the 1951–1996 Hydrological Year Books' data is characterized by mean annual rainfalls of $696\ \text{mm a}^{-1}$ (below the national average of $970\ \text{mm a}^{-1}$), although single total annual rainfalls during this time-span have been discontinuous. The rainfall regime shows a maximum in November and a minimum in July and the greatest number of consecutive rainy days is recorded in the autumn. Mean annual temperature is around 13 °C and the thermal regime indicates an annual range of about 18 °C, with a maximum in the summer months (July–August). Over the period 1961–2001 the average rainfall trend (mm/100 years) showed a minor decrease in the winter and summer seasons (−1.18 and −0.85, respectively; M. Fazzini, personal communication) and a minor increase in spring and autumn seasons (+0.29 and +0.64, respectively; M. Fazzini, personal communication). Over the period 1954–2004, extreme rainfall events per hour showed a mean intensity of 35 mm, with a quite constant trend, while the extreme rainfall events per day showed a mean intensity of 60 mm, with a small decreasing trend (M. Fazzini, personal communication). Rainfall data over the last 10 years indicate a slight decrease of the total annual rainfall (mainly due to changes relative to the spring season; Brunetti et al., 2006). Nevertheless, it is worth noting that an increase in the frequency and intensity of extreme rainfall events, as well as of the number of consecutive dry days, was recorded (Vento et al., 2004).

In general, and in particular during the recent years, marked semi-arid conditions during the summer period followed by heavy rainfall in the autumn are probably ideal factors for effective water erosion on clayey slopes.

3. Brief state of the art

The severe denudation processes that have been rapidly shaping the clay slopes of the Crete Senesi area have been studied over several decades through indirect estimations of suspended sediment yield from catchments (Ciccacci et al., 1986) and implemented techniques of field monitoring. Both direct and indirect quantitative geomorphic investigations, widely applied in Central Italy (Alexander, 1980; Ciccacci et al., 2003; Del Monte, 2003; Del Monte et al., 2002; Della Seta et al., 2007, 2009; Farabollini et al., 1992; Lupia Palmieri et al., 1995; Moretti and Rodolfi, 2000), define the *calanchi* and *biancane* badlands as erosion “hot spots” (Della Seta et al., 2007, 2009).

Della Seta et al. (2009) observed, in particular, noticeable space–time variability of indirectly estimated and monitored denudation rates on the catchment and hillslope scales. Despite the time- and

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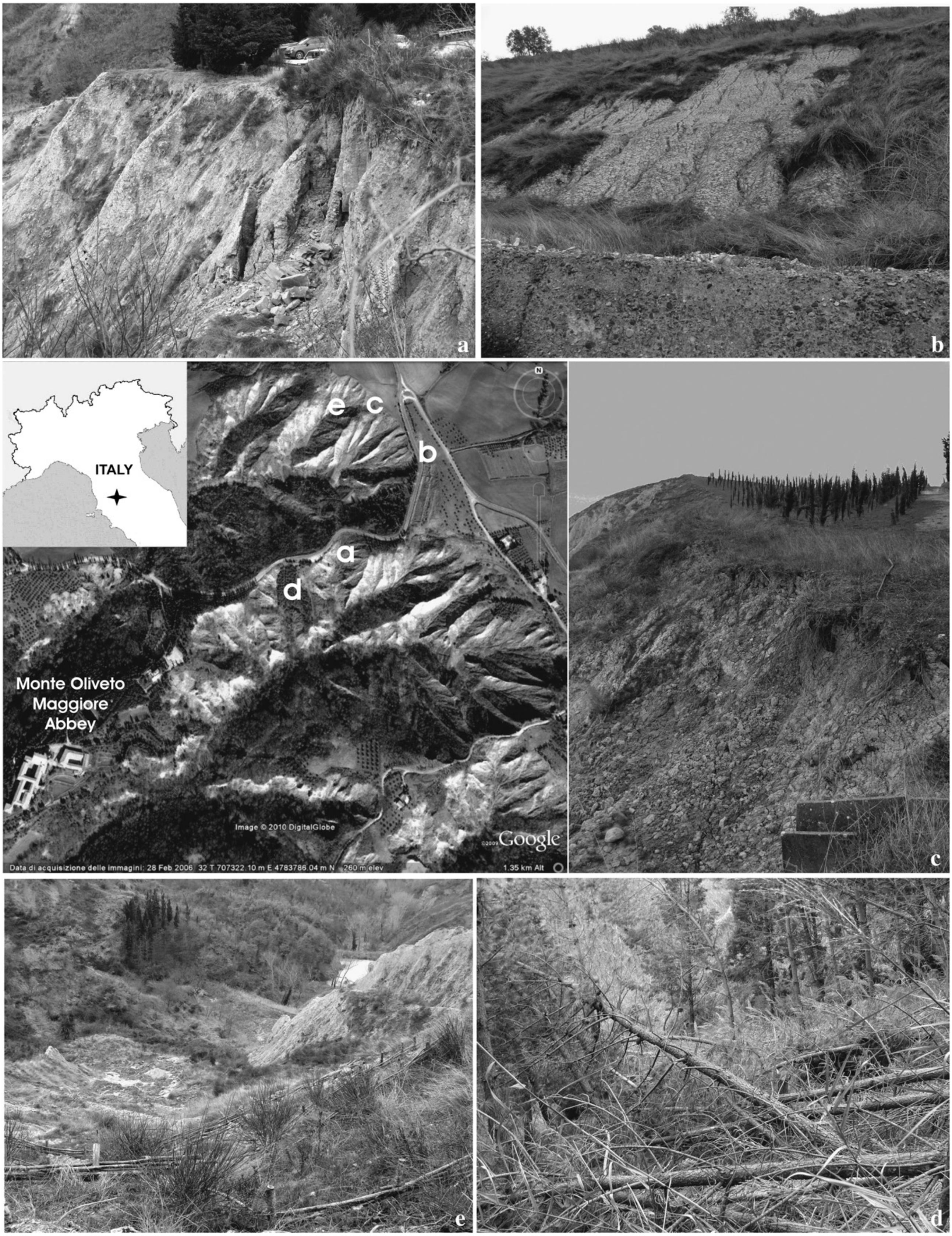

Fig. 2. Badlands of the Crete d'Arbia, close to the Monte Oliveto Maggiore Abbey. The most significant examples of the fast morphoevolution and anthropic interventions are reported: *a*. lateral spread and fall of clay pillar immediately below the road to the Abbey, causing significant slope retreat; *b*. incipient sheet and rill erosion close to the road to the Monte Oliveto Maggiore Abbey; *c*. reforestation with *Cupressus sp.* and one of the several drainage ducts used for the stabilization of the head of *calanchi* hillslopes; *d*. trees fallen on the examined hillslope during the time-span between two sampling surveys (June 2009–March 2010); *e*. soil barriers on a *calanchi* hillslope.

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spatial-scale effects they observed that water erosion has strong off-site effects on the catchment sediment yield through extreme denudation events, triggered by rainfall several days long. This pulsating trend of hillslope process off-site effects reflects the step-like trend of denudation graphs (Della Seta et al., 2007), with critical denudation periods possibly triggered by extreme rainfall events.

Ciccacci et al. (2008), using field monitoring and photogrammetric techniques, evaluated the *calanchi* typology changes, as described above, while Salvini (2008), using remote sensing techniques, calculated the badland area reduction in the Crete Senesi region in the second half of 20th century (see Section 2.2.1).

As mentioned above, some important stations for the monitoring of denudation processes in the Crete Senesi area were damaged due to strong water erosion and shallow landsliding on hillslopes, such as the ones at Calanchi of Monte Oliveto Maggiore, which are added of additional cultural as well as geomorphological value (Reynard et al., 2010). Due to this additional value, the partial loss of denudation data, the presence of reforested hillslopes affected by soil creep, shallow landsliding and water erosion (Fig. 2), and the contribution of dendrogeomorphological data may be particularly useful in reconstructing the recent relief evolution, especially if cross-checked with denudation and rainfall data already available for the studied region described below.

As outlined by Della Seta et al. (2007, 2009), denudation graphs show step-like trends, with critical erosion/accumulation periods, triggered by extreme rainfall events several days long, especially if occurring just after the dry summer season (Della Seta et al., 2009). However, single-day events, even strong events, are generally not followed by drops in the denudation graphs.

Point measurements of denudation at "hot spots" provided mean erosion rates (without the contribution of piping) of about 4.5–5.0 cm a^{-1} over the period 1993–2007. Nevertheless, considerable spatial variability of erosion rates was observed, with *biancane* experiencing the strongest inter-rill erosion, attaining up to 7.7 cm a^{-1} and no evidence of accumulation. Erosion/accumulation phases alternate within rills, where rainfall-triggered mudflows occasionally occur, especially on *calanchi* slopes (see also Ciccacci et al., 2008). Due to episodic mudflow deposits, the measured net denudation rate within rills may locally be significantly lower. Pins placed on micro-pediments recorded a slope retreat of up to 7.4 cm a^{-1}.

Dendrogeomorphological investigations (Alestalo, 1971; Schweingruber, 1996; Strunk, 1997) are based on the response of the trees to the environmental changes, mainly correlated with the change in the mechanical stress field. The anomalies recorded in the tree rings are different depending on whether they are due to thermo-pluviometric or mechanical factors (as described above; Fig. 1). Thus, discrimination of the stress factor is one of the main purposes of dendrogeomorphologists. Ring width anomalies and growth anomalies in trees affected by geomorphic processes should be compared to the ring pattern from reference trees growing outside of the influence of geomorphic processes. Significant stress indicators are *compression wood* (Timell, 1986), trunk eccentricity (Baylot and Vautherin, 1992; Braam et al., 1987) and root exposure (Gärtner, 2007; Hupp and Carey, 1990; Malik, 2008; Pelfini and Santilli, 2006; Pelfini et al., 2004; Vandekerckhove et al., 2001). The presence of scars on the trunk is more strictly related to mass movements involving large debris affecting tree trunks. In the study area, no evidence of this kind of effect on trees was detected, even if, as outlined by recent works, mass movements contribute significantly to hillslope denudation (Ciccacci et al., 2008; Della Seta et al., 2007) (Fig. 2d).

In the literature erosion rates have been examined through dendrogeomorphological techniques and in particular through exposure of roots in different geomorphic contexts, using different species, and the results are different in terms of millimetres of sediments eroded per year (Chartier et al., 2009; Gärtner, 2007; Gärtner et al., 2001; Hupp and Carey, 1990; La Marche, 1966; Malik, 2008; Malik and Matyja, 2008; Pelfini and Santilli, 2006). A review of the methodology has recently been proposed by Gärtner (2007). Different authors examined root exposure in some cases focusing on gully erosion contexts (Malik, 2008; Vandekerckhove et al., 2001).

The calibration between denudation monitoring data and dendrogeomorphological data for the overlapping period of time is expected to provide the base for deriving information for the time intervals preceding the set up of the erosion monitoring stations.

In fact, while geomorphological field monitoring implies periodical surveys (ideally recording monthly over several years), the dendrogeomorphological investigations work on samples collected simultaneously and, in addition, allow looking at the past for many years or decades. Despite the possibility of sampling during only one survey, the periodical geomorphological survey of the study area is anyway fundamental given the lively morphodynamic context.

4. Material and methods

4.1. Geomorphological monitoring techniques and thermo-pluviometric analysis

Since 1993, an increasing number of monitoring stations (Fig. 3) have been equipped and geomorphological surveys performed in some significant denudation "hot spots" within the eastern Ombrone River Basin (Del Monte, 2003; Del Monte et al., 2002; Marini, 1995). In order to record changes on the topographic surface, iron pins have been used and placed at different depths to cross the weathered horizon (Del Monte, 2003; Della Seta et al., 2007). Both at *biancane* and *calanchi* denudation "hot spots" uphill, downhill and lateral changes in the ground level (Δy) have been measured at rill and inter-rill positions (Fig. 3). In some cases, slope retreat (Δx) has been measured at pins placed on pediments. Since the contribution of piping to denudation is hardly measurable, even if considerable, pins are placed where piping is absent.

Denudation graphs have been obtained from the measures of change on the topographic surface. They show the erosion/accumulation trend and allow the estimation of short-term erosion rates. Denudation data were compared to those obtained by daily rainfall records from meteorological stations close to the sites (Fig. 3), providing data up to 2009. Over the field monitoring period, the analysis of meteorological data provided total annual and monthly rainfall, maximum and minimum monthly rainfall, as well as showing seasonal rainy days.

Moreover the *annual aridity index* was calculated using the equation by De Martonne (1926; *aridity index* $= R/(T+10)$, based on total annual rainfall (R) and mean annual temperature (T)). In addition, a *seasonal aridity index* has been calculated using a modified equation based on seasonal rainfall (Rs; over 3 months) and mean seasonal temperature (Ts) data for each considered year (*seasonal aridity index* $= 4Rs/(Ts+10)$). The above indices can help in considering the dry conditions that represent a limiting factor for the growth of *P. pinea* L. (Cherubini., 1993).

4.2. Dendrogeomorphological investigations

Two different dendrogeomorphological surveys were performed in June, 2009 and March, 2010 on a hillslope surrounding the Monte Oliveto Maggiore Abbey, which is affected by soil creep processes, water erosion and shallow landsliding.

A detailed survey has been carried out in order to collect samples from trees mostly stressed by processes that entail erosion. Some samples have been taken from exposed roots. During the sampling activities, specimens from 45 trees of *P. pinea* L. have been collected and the results obtained will be illustrated. The small amount of samples derives from the scarce availability of trees of this species in the investigated area.

Samplings from trunks have been taken using an increment borer. The cores extracted from the trunks were collected at the

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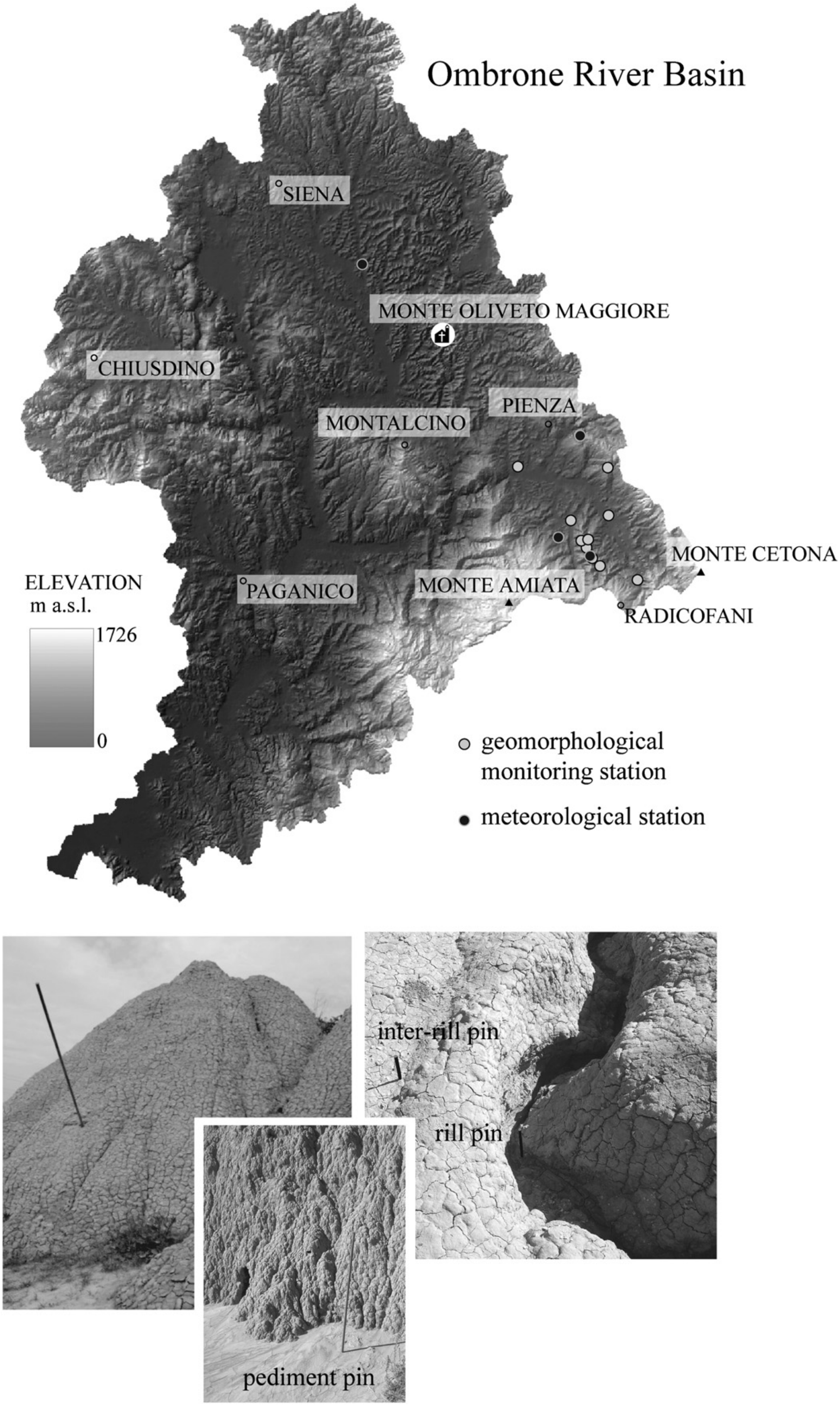

Fig. 3. Location of the geomorphological monitoring station and meteorological stations within the Ombrone River Basin and examples of the erosion pin setting.

standard height of the trunk of 1.30 m (breast height). Moreover, disks have been cut from exposed roots. Where scars were present, samples have been taken to correspond to the damaged portion of the root (Schweingruber, 1996) with the aim of dating the damaging events, particularly meaningful for the analysis of root exposure.

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The most important dendrogeomorphological indicators have been considered for different investigation purposes:

i) *anomaly index* (Pelfini et al., 2007; Rolland et al., 2001; Schweingruber et al., 1991) is related to growth reductions consequent to the variation of geomorphic processes and climatic conditions;
ii) *compression wood* presence (Timell, 1986) and *eccentricity index* variations (Baylot and Vautherin, 1992; Braam et al., 1987) are related in particular to creep movements;
iii) root exposure is useful for estimating the erosion rate derived mainly from water erosion (Alestalo, 1971; Gärtner, 2007; Gärtner et al., 2001; Hupp and Carey, 1990; Pelfini and Santilli, 2006).

For all dendrochronological investigations, tree rings width has been measured (accuracy of 0.01 mm) using the LINTAB and TSAP systems (Rinn, 1996) and image analysis with WinDENDRO software (Régent Instruments Inc., 2001). The cross dating of the dendrochronological series has been mainly performed visually with TSAP because short chronologies do not permit an affordable degree of statistic correlation using COFECHA (Holmes et al., 1986). Cross dating procedures (Alestalo, 1971; Heikkinen, 1994) allow 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.

The *anomaly index* (Pelfini et al., 2007; Rolland et al., 2001; Schweingruber et al., 1991) is useful for analysing abrupt growth changes (growth release and suppression). 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%.

For a correct distinction between growth anomalies induced by geomorphic processes or thermo-pluviometric oscillations, it should be appropriate to have a reference chronology (Alestalo, 1971; Heikkinen, 1994) built on trees of the same species grown in an undisturbed context. The only chronologies available for *P. pinea* L. for the Italian peninsula in the ITRDB (International Tree Ring Data Bank; Grissino-Mayer and Fritts, 1997) were elaborated by Biondi (1992) but the time interval does not correspond to the one of the *Pinus* in the study area. In addition the majority of the trees in the sample area are disturbed and involved in geomorphic processes.

Hence, we have collected some samples from trees whose stems look almost undisturbed in order to obtain single reference samples to be correlated with the disturbed ones. These undisturbed pines were located in spot not yet sliding/creeping or strongly affected by erosion processes (e.g. far enough from unstable slopes, even if still in an area with clayey outcrops). In this sense, the presence of shared anomalies between the samples from the two areas has been ascribed to climate, or to any other cause, not exclusively affecting the badland hillslope, while the anomalies present only locally on the disturbed hillslope have been correlated with geomorphic processes (for the method see Pelfini et al., 2007).

The presence of *compression wood* (Timell, 1986) has been described and dated, as a response to mechanical stress. The space–time distribution of *compression wood* among the trees of an unstable slope allows the localization in space and time of stress sources and in particular of creep-like movements.

The *eccentricity index* as defined by Casteller et al. (2007) is used to quantify the changes in trunk eccentricity before and after a specific event. In this work the calculation was based on Braam et al. (1987) and Baylot and Vautherin's (1992) methods. They consist of a morphometric comparison between:

- external features that are the maximum and minimum dimensions of the trunk (Braam et al., 1987);
- internal features that are the annual ring widths along a parallel and orthogonal direction with respect to the slope (Baylot and Vautherin, 1992).

The space–time analysis of the indicators leads to the creation of yearly event–response maps (Pelfini and Santilli, 2008; Shroder, 1978; Stefanini, 2003) that allow the localization of growth anomalies in specific years, based on tree position in a morphological sketch of the study area. This technique can help in understanding the temporal and spatial evolution of the disturbances through time along the slope and the portions of its surface affected by the denudation processes.

Roots have been sampled to perform morphometric analysis (Alestalo, 1971; Gärtner, 2007; Gärtner et al., 2001; Hupp and Carey, 1990; Pelfini and Santilli, 2006) and to estimate the erosion rates due to surface running water. In fact, the change in root micromorphology from the production of root type wood to a trunk type wood, with the distinction in early and latewood, is a consequence of the exposure. Thus, applying the equation by Hupp and Carey (1990) ($E = D/A$) it is possible to obtain the erosion rate by dividing the distance (D) between the actual ground surface and the tree root collars, by the age (A) of the micromorphologic change in root. Each root growth curve has been compared to the corresponding tree growth curve in order to obtain the minimum exposure date and eventually the scar age, as accurately as possible (for detailed methodology see Pelfini and Santilli, 2006).

5. Results

5.1. Denudation field monitoring and thermo-pluviometric analysis

The most significant denudation data come from a *calanchi* monitoring station close to the town of Radicofani. We plotted the net annual denudation measured uphill and downhill of a pin that has been recording continuously since 1994 (Fig. 4). Then we compared these data with the seasonal rainfall depth and with the mean seasonal rainfall depth (Fig. 4). Critical net erosion occurred in 1996, 2002, 2005 and 2008. It can be noted that these years experienced high seasonal variability of rainfall, with summer and fall rainfall significantly above the mean. It is noteworthy that these critical years in most cases (i.e. 1996, 2002, 2008) follow years with particularly low seasonal variability of rainfall (i.e. 2001, 2007) and low total annual rainfall (respectively 260.5 and 366.6 mm). Unfortunately the rainfall record for 1994, 1995 and 1997 is incomplete, although denudation data suggest that 1994 could have been another critical year. The period 1998–2001 was marked by relatively low net denudation, or by values close to 0, alternatively uphill and downhill. This behaviour corresponded to years generally marked by strong contrast between summer (very low) and fall (very high) rainfall depths. In 2007 and 2009 net accumulation, and in 2006 strong differences between uphill and downhill net denudation, have been observed. These years **Q9** share a low seasonal contrast in rainfall depth and, above all, they experienced fall rainfall depth significantly below the mean.

The erosion rate obtained for the entire 14 years period is 1.65–1.96 cm a^{-1}. This value is quite low for the area and testifies that accumulation events occurred, thus affecting the net annual denudation value. In fact, it is likely that single (fast) accumulation events (mass movements) in some cases lead to rapid erosion on more erodible mobilized deposits.

In Fig. 5 the *summer aridity index values* are reported. These values follow mainly the rainfall trend because the mean summer temperature does not show any meaningful annual variation (mean summer temperatures range between 12.2 and 14.1 °C).

New data from more recently set up stations at *biancane* sites close to Pienza (2005–2010), confirmed the above results (Fig. 6),

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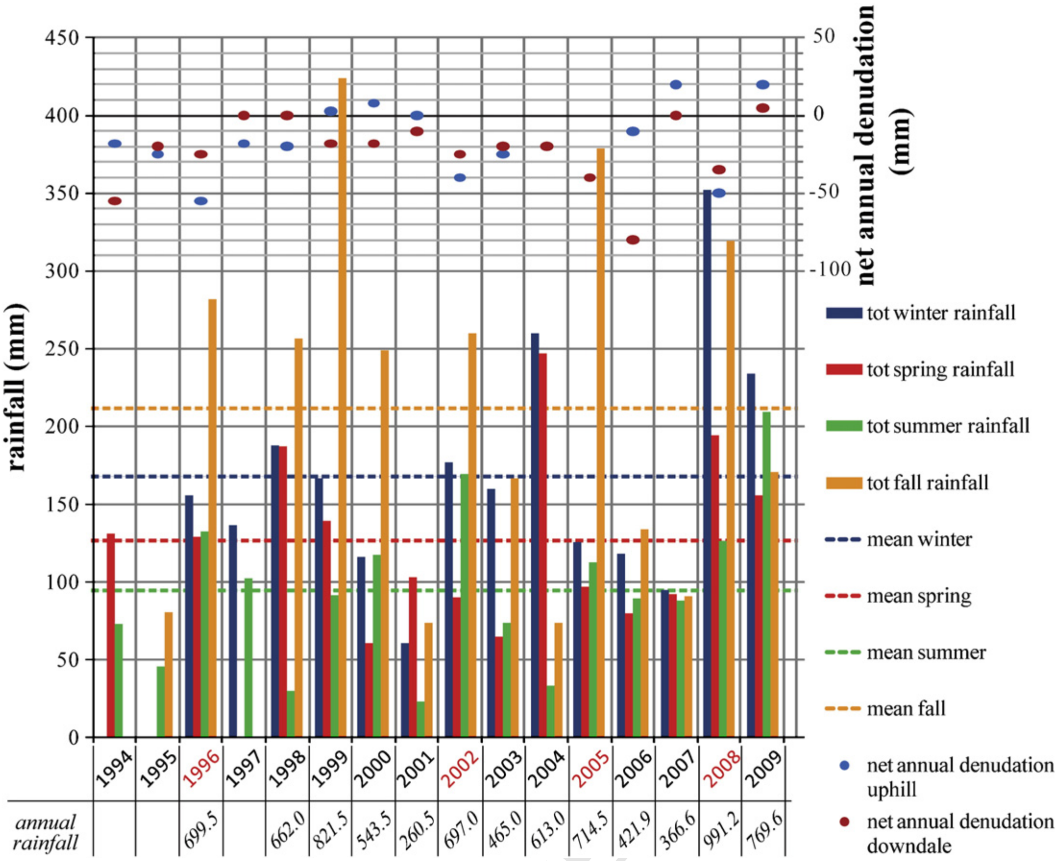

Fig. 4. Net annual denudation of a continuously monitored pin compared to the seasonal rainfall depth and to the mean seasonal rainfall depth. The measures at the pin have been taken both uphill (blue point) and downhill (red point). Critical years with net erosion are indicated in red on the horizontal axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

indicating 2008 as a critical denudation year in which both critical erosion and local accumulation have been recorded at several pins.

The *calanchi* landforms at the Monte Oliveto Maggiore site are represented by sharp-edged badlands, developed in rapidly evolving small catchments. Mass wasting contributes to hillslope denudation together

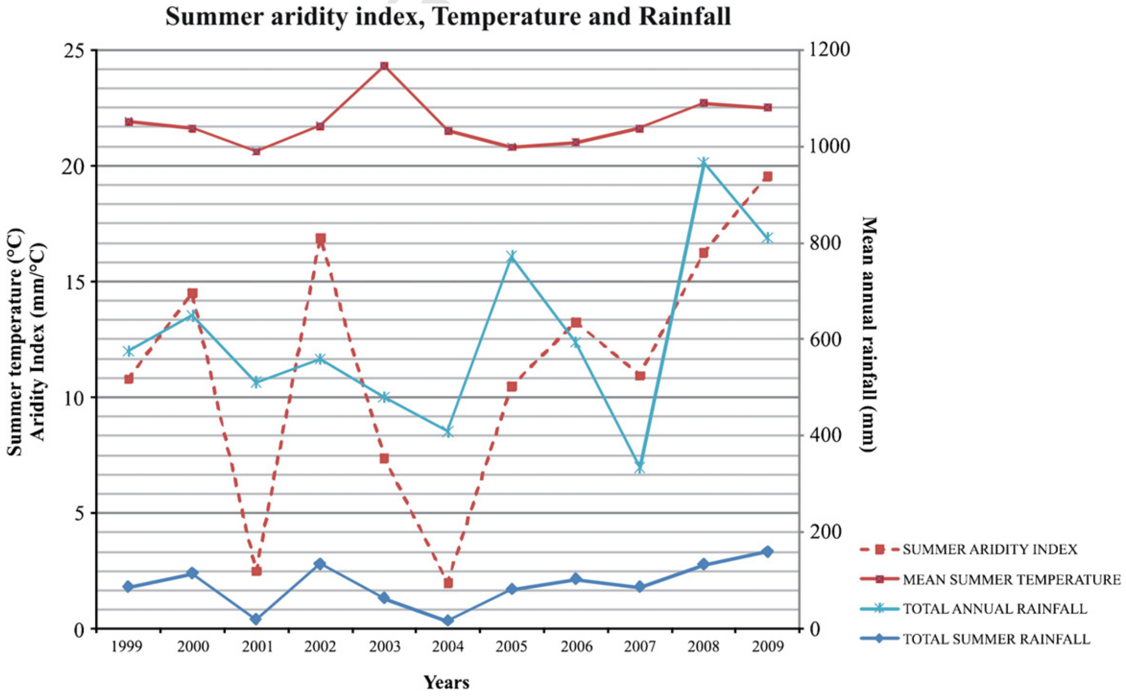

Fig. 5. Aridity index for the period 1999–2009. The trend follows the total annual and summer rainfall values because the temperature variations can be considered to be not so significant for the meteorological conditions of the region.

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with runoff, especially through localized landslides and widespread soil creep. Unfortunately, the monitoring station equipped on the *calanchi* hillslope close to Monte Oliveto Maggiore Abbey was destroyed, after having provided few data: erosion rates of about 1–1.5 cm over the 1998 winter period. Thus this site was chosen to perform dendrogeomorphological investigations.

5.2. Dendrogeomorphological investigations

Dendrogeomorphological analyses carried out on *P. pinea* L. cover the time period 1995–2008 and the data deriving are herein illustrated.

5.2.1. Comparison between thermo-pluviometric data and tree ring series from trees outside the unstable slopes

As mentioned above, it was difficult finding undisturbed trees in the study area, thus only some samples have been analysed. The most evidently negative values of the *anomaly index* are concentrated in a few years. They have been recorded in 1999 and 2007. In 1999, the value of the *anomaly index*, in 70% of the samples demonstrates a negative variation of ring width greater than 70%. The 2007 value shows a quite uniform behaviour of trees and the value of the *anomaly index* in 40% of the samples demonstrates a negative variation of ring width greater than 70%, in 60% of the samples it is greater than 40%.

In the pluviometric record, 1999 is not such an evidently dry year, while 2007 corresponds to a year of extreme dryness followed by a considerably rainy year (2008) (Fig. 7).

These data allow the link between the 2007 negative anomaly and the thermo-pluviometric unfavourable conditions: as Cherubini (1993) indicates, dryness is the main limiting factor for *P. pinea* L., as deriving strictly from climatic conditions, especially if concomitant with high temperatures.

Temperature values, as above mentioned, show no extreme variations; so the trees' behaviour response can be mainly correlated to the variation in rainfall regime (see also *aridity index*).

5.2.2. Anomaly index analysis in tree ring series from unstable slopes

As previously underlined, the critical years showing high monthly rainfalls occurring mostly in the autumn (i.e. 1996, 2002, 2008), preceded by years with particularly low seasonal variability of rainfall (i.e. 2001, 2007) and low total annual rainfall, represent the optimum conditions for the increase of water erosion rate. 2001 and 2002 represent the dry–wet couple of years that looks like having triggered increased water erosion processes. The *anomaly index* values calculated for the disturbed trees highlight periods of shared suffering for the trees (mainly 2002, 2007). These years show at least 40% of trees with negative anomalies greater than 70%, even if the values obtained are not so regularly distributed, as illustrated in the spatio-temporal maps of Fig. 8.

The 1999 anomaly, well evident in undisturbed trees, is present in the trees of disturbed area: 37% of trees have a negative anomaly greater than 70% and 7% greater than 40% (Fig. 8a).

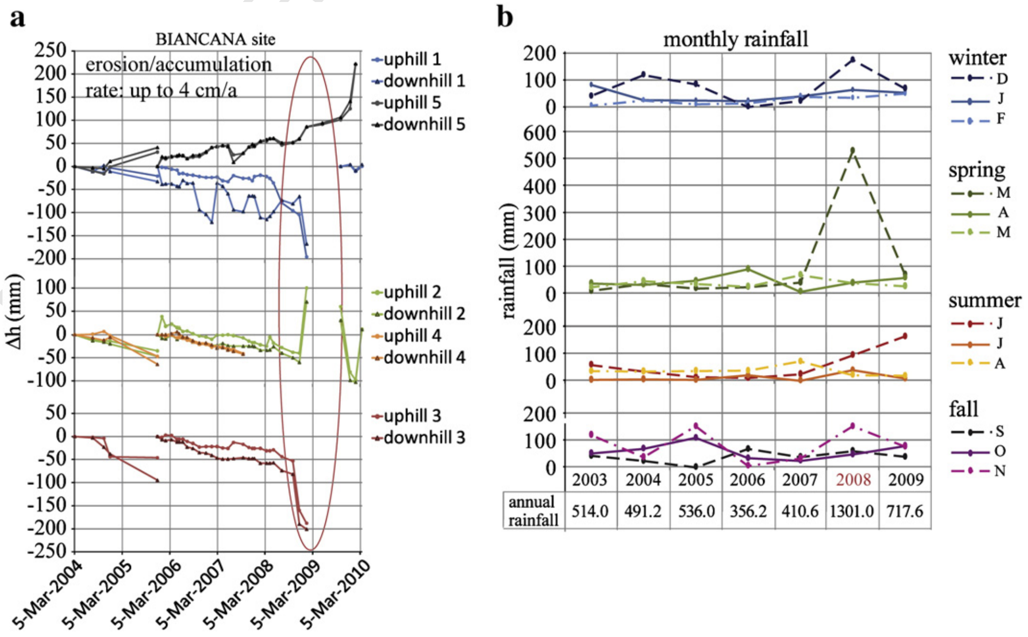
Trees growing in the upper middle portion of the hillslope are affected by widespread stress in 2002 (Fig. 8b). On the basis of the alternating pattern individuated as the triggering factor of water erosion processes, the strong negative anomaly recorded in 2002 may be the result of the intensification of erosion processes along the slope.

Subsequently, while generally on the hillslope there is a recovery of the positive values, as illustrated in the 2005 map (Fig. 8c), the trees placed in the central part of the hillslope still maintain the strong negative trend.

The cross-dated growth curve of the trees in the central portion (area delimited by the black dotted line in Fig. 10) is reported in Fig. 9 (trees 14, 15, 56 in Fig. 9a and 52, 55 in Fig. 9b). It is evident that the negative trend persists in 2005 more precisely for trees 14, 15 and 56 (Fig. 9a) that are aligned. In Fig. 9b the larger width of rings of trees 52 and 55 can be ascribed to a corresponding increment in the intensity of *compression wood*.

Another critical year is represented by 2007 (Fig. 8d) when almost 50% of the trees showed a negative anomaly value greater than 70% and almost 70% have a negative anomaly greater than 40%.

It is noteworthy that the constant trend of low values after 2002 for the aligned trees 14, 15 and 56 in the central portion of the slope could be related to the lack of deep negative anomaly in 2007 (Fig. 8d): it is due to the method for calculating the *anomaly index* itself that uses, as comparison, the previous four-year time interval. In fact, by varying the time interval of comparison the *anomaly index* results become greater than the 70% threshold.



Q3

Fig. 6. Denudation graphs from new monitoring stations (a, c) and monthly rainfall distribution over the same period (b, d).

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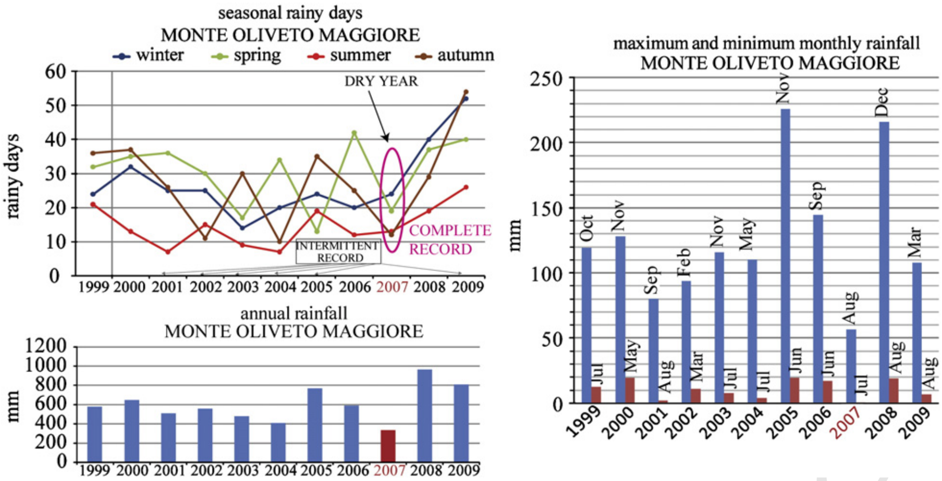

Fig. 7. Rainfall distribution from thermo-pluviometric series recorded by the closest meteorological station. Despite the discontinuous record for several years, 2007 data are complete indicating a significantly drier year, with the absolute minimum of summer rainfall.

Moreover, the 2007 the anomaly appears to be due to climatic stress as evidenced by the undisturbed trees series.

In terms of the spatial migration of anomalies, the negative anomalies seem to move downslope from 2002 to 2007 (Fig. 8b, d).

In the maps of Fig. 10, the comparison between the distribution and intensity of the *anomaly index* with respect to *compression wood* is illustrated over the period 1995–2008 (for more details see Section 5.2.4). Trees with the longest permanence of negative anomalies (3–6 years) over the 70% threshold are concentrated in the upper portion and a central portion of the hillslope.

5.2.3. Compression wood and eccentricity index analysis in tree ring series from unstable slopes

The *compression wood* is not homogeneously distributed in either space or time. The maximum coupling between duration and intensity has been observed especially in the central section (black dotted line) and in the lower section (grey dotted line) of Fig. 10.

In the central part of the hillslope there is an area that has been characterized by the fall of several trees in the time interval between the two surveys (2009–2010). The same trees demonstrate having suffered for a long period (Fig. 9).

The compression wood is persistent again in the lower part of the hillslope, downslope to a wide pipe emergence.

Trunk eccentricity data do not show any meaningful variations either in the external features (Braam et al., 1987) or in the internal ones (Baylot and Vautherin, 1992). The *eccentricity index*, calculated according to Braam et al. (1987) does not show any significant variation (<40%) between the specimens extracted orthogonal and parallel to hillslope inclination. The index, calculated year by year following Baylot and Vautherin (1992) rarely overcomes 40%.

These data could indicate that even if the trunks are not deformed in their shape (no significant value in the *eccentricity index*), the production of *compression wood* is in any event a signal of reaction to underground movements, for example, that act to undermine the stability of the trees in some limited areas. The presence of mass movements in the surroundings (for example, indicated in 2005 see Section 5.1) is not influential in the sample area and does not cause any general variation in the *eccentricity index* in trees.

5.2.4. Comparison among anomaly index, eccentricity index and compression wood

In the maps of Fig. 10 the comparison between the distribution and intensity of the *anomaly index* with respect to *compression wood* is illustrated over the period 1995–2008.

We compared the percentage values of persistence years of both the indicators for each sampled tree. The correlation is poor ($R^2 = 0.0128$; Fig. 11), suggesting that local factors (slope instability) Q10 and regional factors (climate) may affect differently the *anomaly index* and *compression wood* persistence in trees.

The spatial analysis of the data (Fig. 10) provides clearer information about the persistence of the disturbances due to local factors and about which portion of the slope is the most affected by instability processes.

In the lower sector the *compression wood* is pervasive, covering 75–100% of the analysed period, but it is not as intense as in the central part. In the upper section the *anomaly index* shows the longest persistence of negative values. Finally, in the central sector of the slope both *compression wood* and the *anomaly index* reach relatively maximum values and duration.

Some additional observations can be made. The central section has been recently characterized by rapid changes, such as the presence of fallen trees that have been recorded in the time period between the two surveys. On the other hand, the lower section is located in an area surrounding a wide piping emergence. The spatio-temporal distribution of the dendrogeomorphological indicators may be correlated not only with surface running water, but the trees' behaviour may reflect a shallow subsurface water flow component as well.

There is evidence of piping processes along the hillslope, as often observed in similar geomorphological contexts. Despite the trees just above the piping niches not showing any abrupt growth change, a persistence of *compression wood* has been described in the area immediately downslope of a wide pipe outlet. Generally, phenomena like the last one may generate local slope instability or regressive erosion phenomena that may affect tree stability, and consequently tree growth, both upslope and downslope the pipe outlet.

In the specific case, the outflow from the pipe, that may be particularly powerful and concentrated, may be responsible of an intensification in the water erosion in the area immediately downslope, causing a persistent compression wood in the trees.

Finally, in such a geomorphological context, in which the processes act not uniformly in the area, the spatial analysis has revealed to be a necessary tool for investigating the processes.

5.2.5. Erosion rate estimation through root exposure

The *P. pinea* L. trees do not show many exposed roots in the study area and the observed ones provide different results from site to site. The investigations focused on the presence of scars, eccentric shapes, sudden growth change in ring width and micromorphology transformation from root to stem wood. All these features allowed the establishment of a minimum date of exposure. Hence, the exposed roots

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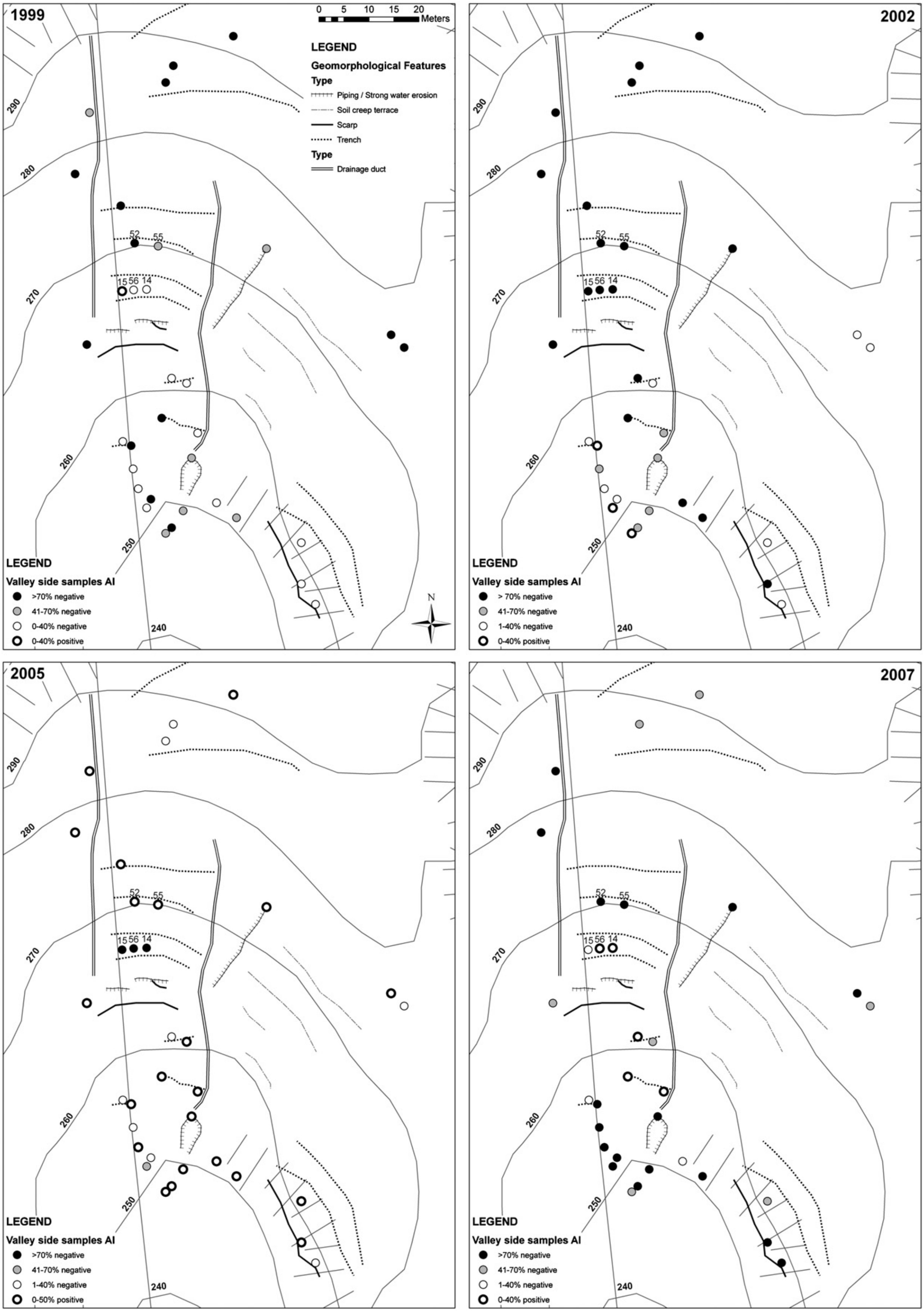

Fig. 8. Distribution of *anomaly index* in years recognized to have more than 40% of negative *anomaly index* values over the 70% threshold (a: 1999; b: 2002; d: 2007) and in 2005 (c) when decreasing stress was recorded for all the trees except for some of them aligned in the central part. The values illustrated derived from the downslope side core chronologies, in which the abrupt growth changes are more evident.

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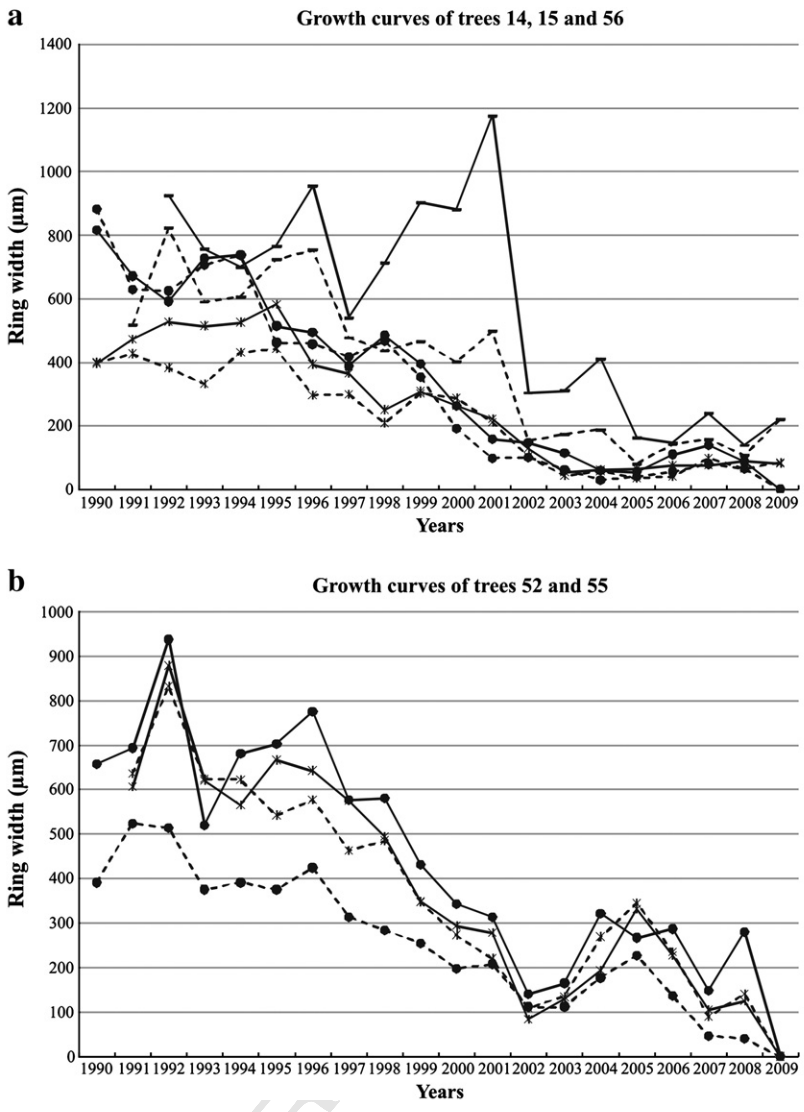

Fig. 9. Cross-dated rough chronologies of upslope (m) and downslope (v) sides of the trees 14, 15, 52, 55 and 56, whose location is indicated in Figs. 4 and 5. The negative anomaly of 2002 is evident and a gradual recovering is visible only for trees 52 and 55 located on the upper portion of the hillslope, while the aligned trees maintain a constant low growth.

provided different erosion rates (ERs) based on the different ages of those features and on the eroded sediment thickness (for detailed values see Fig. 12).

The maximum values have been observed in an area affected by strong water erosion (3.25–3.75 cm a^{-1}) (Fig. 12a), while the minimum rate was measured in the central portion of the slope close to the fallen trees (0.27 cm a^{-1}) (Fig. 12b). In Zachar's classification (Zachar, 1982 adapted by Cremaschi and Rodolfi, 1991) the obtained values indicate a severe (Fig. 10b) to catastrophic (Fig. 10a) denudation, ascribed also to intense soil creep.

The literature (Bodoque et al., 2005; Chartier et al., 2009; Malik, 2008; Pelfini and Santilli, 2006; Perez Rodriguez et al., 2007; Vandekerckhove et al., 2001) demonstrates how the erosion rate values may change depending on the context. In comparison, the values obtained are intermediate between those indicated by Malik (2008) that can be classified as catastrophic, and those by Vandekerckhove et al. (2001), considered as moderate.

It is evident that the erosion rate values obtained through dendrochronology investigations have the resolution of the entire period of root exposure. As a consequence, the values obtained are averaged over the investigated period and they can be considered relatively long term ERs. The single peak events are not recorded and the maximum ER that we obtained through the roots analysis is, in any event, lower than the maximum that can derive from the single erosion pin measurements.

6. Discussions

From the results obtained by the *P. pinea* L. analysis, the possibility emerges of using dendrochronology to reconstruct the evolution of badland relief.

A limiting factor in analysing dynamic hillslopes, such as the *calanchi* and *biancane*, is the low probability of finding long tree rings records for a complete reconstruction of past events. Despite the fact that *P. pinea* L. enters a single true winter dormancy period leading to the formation of distinct earlywood and latewood, and that this fact favours the reconnaissance of different years (Lipschitz et al., 1984), the main problem concerning this species is the presence of Intra Annual Density Fluctuations (IADF; De Micco et al., 2007). This behaviour is quite common among the species in the Mediterranean climate (Cherubini et al., 2003; Lipschitz and Lev-Yadun, 1986; Lipschitz et al., 1981, 1984), where dry periods may lead to suffering conditions and production of an "early latewood" as described by De Micco et al. (2007) for *Pinus pinaster*. In fact for the *P. pinea* L. species, water represents the major factor influencing tree ring growth and a reduction in the water supply can lead to the production of narrow rings, in particular if accompanied

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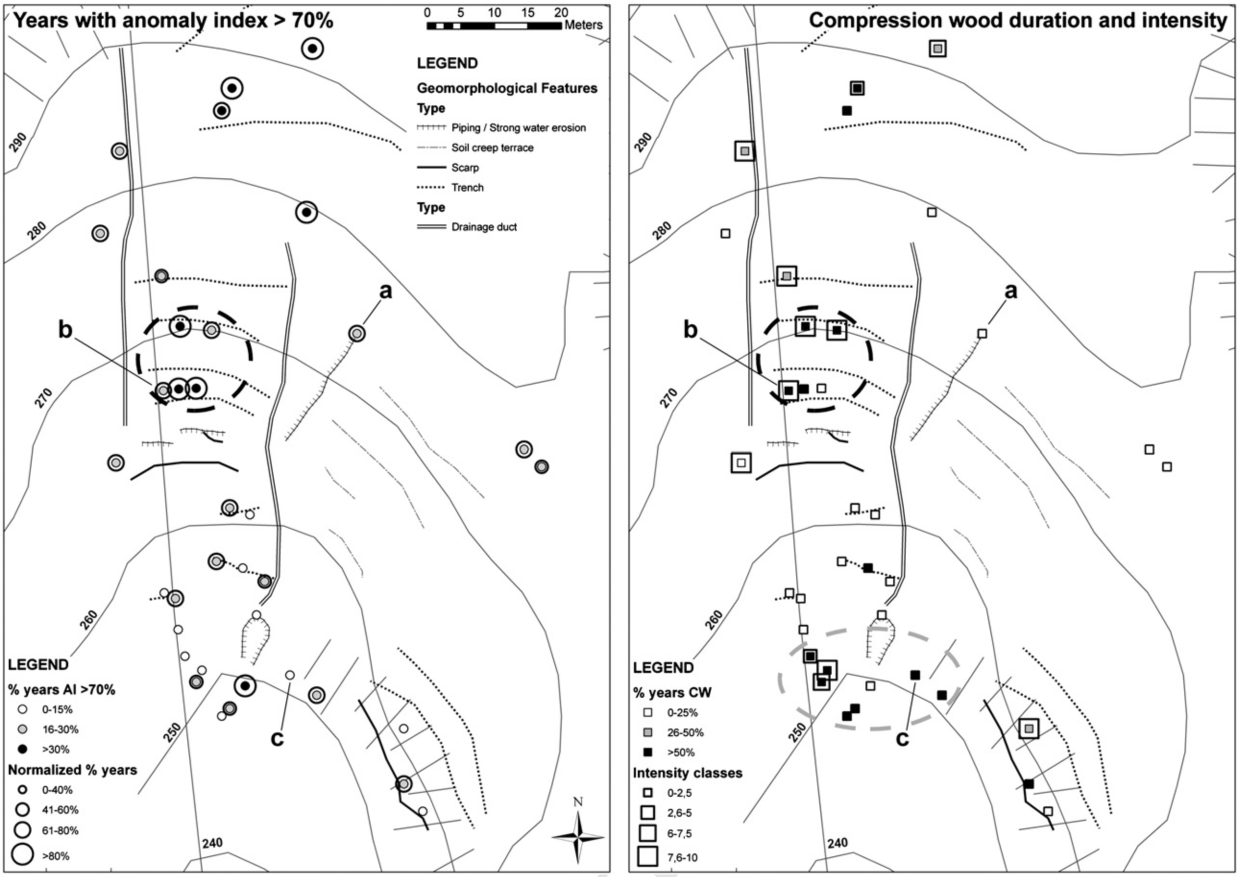

Fig. 10. Distribution of *anomaly index* and *compression wood* during the period 1995–2008; (a) distribution of the thresholds of *anomaly index* (40% and 70% of variation) in terms of the number of years of persistence in each tree in the considered time interval; the intensity classes are intended as the number of years with respect to the maximum obtained; (b) *compression wood* distribution in terms of number of years of persistence in each tree over the considered time interval; the intensity classes are intended as the number of years of deep *compression wood* with respect to the total number of years of persistence in each tree. The location of trees with exposed roots is indicated (a, b, c).

by high temperatures (Cherubini, 1993). As we have observed in this climatic context, the low variability in temperature range especially during the summer season leads us to consider that rainfall plays the most important role as the indicator to be used to support the interpretation of the origin of anomalies.

Finally, clays are not the ideal bedrock for the settlement of this species (Gellini, 1973), and this fact can probably negatively influence the behaviour of trees.

The non-homogeneity of the slope is evident and some localized trees behaviour reflects the underground flow pattern with no evidence on the surface. This non-homogeneity is reflected in the poor correlation, for all the area, between the values of persistence years of both the indicators (*anomaly index* and *compression wood*; Fig. 11). On the other side, the space and time distributions of the *anomaly index* and *compression wood* (Fig. 10) indicate a central area of the analysed hillslope that is constantly affected by tree

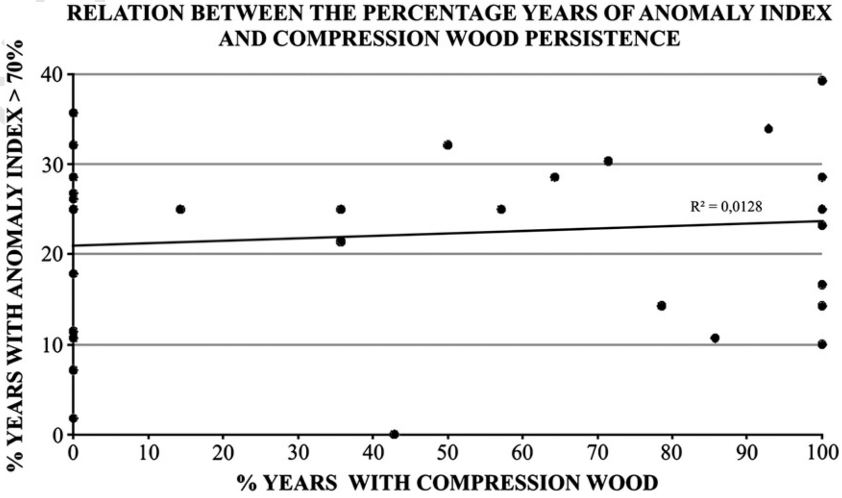

Fig. 11. Relation between percentage years of *anomaly index* greater than 70% and *compression wood* persistence.

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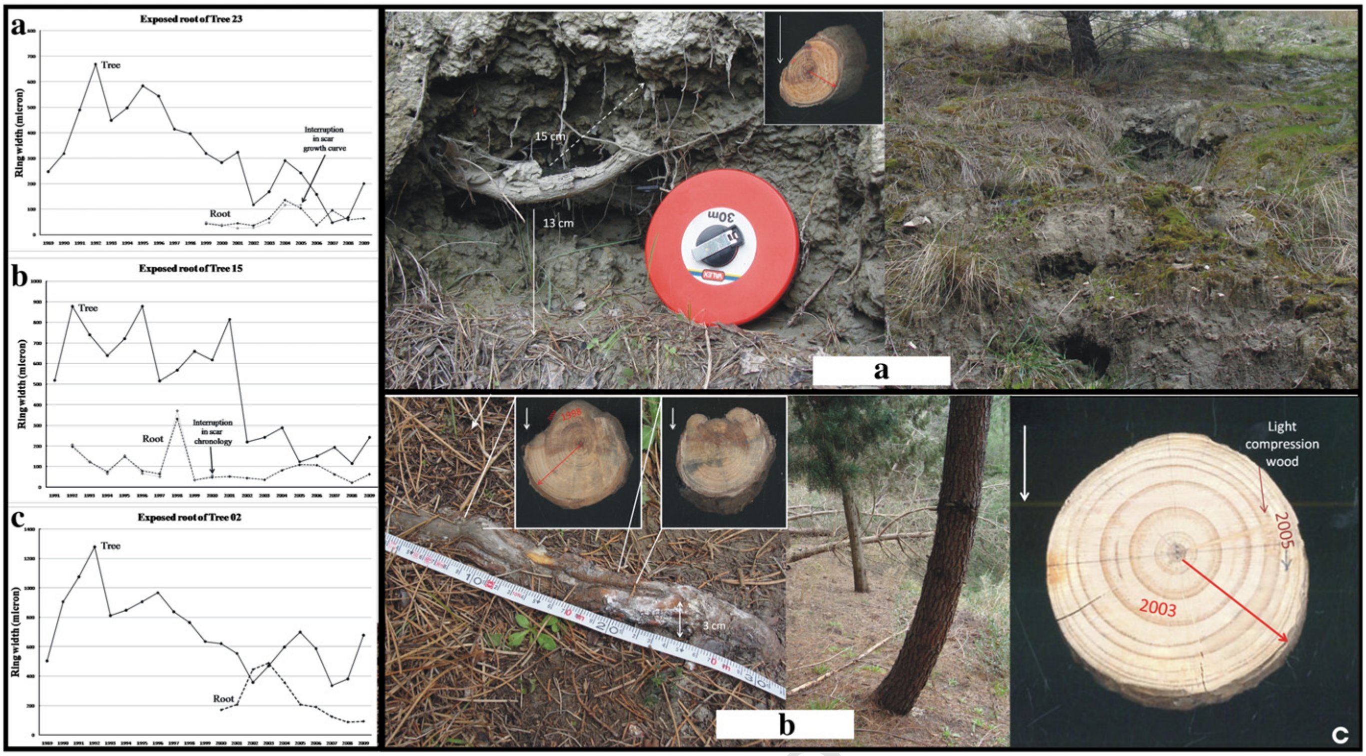

Q2 Q12 **Fig. 12.** Exposure of roots along the examined hillslope. The location of the trees (a, b, c) is indicated in Fig. 6. The respective erosion rates are different: (a) Strong run-off area, scar dated at 2005 (ER = 3.25–3.75 cm a^{-1}, exposure year: 2005); (b) root at ground level in the area surrounding the fallen trees with scar dated at 2000 (ER = 0.27 cm a^{-1}, exposure year: 1998); (c) root showing a permanent stem-like wood anatomy; in 2005 the root shows *compression wood* with a peak in the chronology; based on this exposure date the erosion rate has been calculated (ER = 1.58 cm a^{-1}, exposure year: 2003).

suffering which resulted in the fall of several trees in the time interval between the two performed surveys. The *compression wood* is persistent in the lower part of the hillslope, downslope to a wide pipe outlet, while the negative values of the *anomaly index* are more persistent in the upper slope.

During the analysed time interval (1995–2008), critical years of denudation have been recognized by monitoring and the comparison between monitoring station data and trees behaviour provide meaningful results.

The year 2002 is characterized by a high and widespread (almost 50% of trees affected) negative *anomaly index* (>70%). In 2002, intensification of erosion to a critical level has also been recorded at the Radicofani geomorphological monitoring station.

Regarding the pattern of high monthly rainfall/low monthly rainfall years, the alternation of dry (2001) and wet (2002) years could have caused stress to the trees as a consequence of intensification of water erosion.

In 2005, there is a general recovering with respect to stress even if it is not reported in the central band of the hillslope (see Section 5.2.2), where the persistence of a negative trend is evident, that probably led to the fall of trees in 2009–2010.

The correlation with thermo-pluviometric data is strong in correspondence to the negative anomaly of 2007, when a period of extremely low rainfall, a critical condition for the *P. pinea* L. (Cherubini, 1993), has been recorded in the climatic dataset. The presence of IADF (De Micco et al., 2007) in some trees in correspondence with the year 2007 can be linked to the dry conditions of the year as a validation of the climatic interpretation of this anomaly. In addition, the undisturbed trees just highlight this negative peak in that year.

The results here obtained allow the extrapolation of some meaningful considerations: there is good correspondence with a dry year (i.e. 2007) and narrow rings with the presence of IADF in some cases (i.e. 2007).

In this case it is also evident that for prolonged periods of suffering (longer that 4 years), like the one characterizing the central portion of the slope, the results of the *anomaly index* do not express the real erosion intensity (see observations in Section 5.2.2).

Moreover, in 2008 geomorphological monitoring shows an acceleration of erosion indicating once again that the alternation between dry years and years with higher total annual rainfall may represent a significant influencing factor for acceleration of water erosion processes. The absence of an evidently negative anomaly in 2008 is probably due to the tree suffering that had already seriously started in 2007.

The features that have been considered to individuate a climate originated anomaly in trees are:

- climatic anomalies are more widely and randomly distributed (see for example Fig. 8d) than the geomorphic ones that appear to be guided by the ground setting (see for example Fig. 8b);
- climatic anomalies should be recorded in both disturbed and undisturbed trees;
- climatic anomalies affecting trees located in disturbed areas are accompanied by other indicators besides the rings narrowing: specifically IADF (De Micco et al., 2007).

Finally, the identification of narrow rings in areas not yet monitored might suggest both the presence of extreme meteorological conditions (2007) and the presence of the alternating pattern of dry years with years characterized by high summer rainfalls (2002) that trigger water erosion processes.

Concerning erosion rate estimation through exposed roots, the values obtained can be compared with those in the literature. For example, Perez Rodriguez et al. (2007) found out in a forest, set on a steep slope affected by the Mediterranean climate, a rate of 2.5–8.8 mm a^{-1}. When strictly connected to gully erosion the values become higher. Vandekerckhove et al. (2001) proposed a volumetric method that requires a complex sampling strategy at different points in the root, obtaining a volumetric gully

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head retreat of 6 $m^3\ a^{-1}$ and gully side retreat of 0.1 $m\ a^{-1}$. Malik (2008) distinguished, in terms of ERs old gullies (0.63 $m\ a^{-1}$), hillslope (0.21–0.52 $m\ a^{-1}$) and valley bottoms (0.18–1.98 $m\ a^{-1}$).

The values obtained through *P. pinea* L. roots demonstrate a strong variability in the different portion of the hillslope with a maximum value (3.25–3.75 $cm\ a^{-1}$) compared with strongly denudated areas and a minimum value (0.27 $cm\ a^{-1}$) in the middle portion of the slope, that is, on the other hand, characterized by a continuous negative trend after 2002.

In the central area the lowest ER obtained by root exposure (0.27 $cm\ a^{-1}$, Fig. 12b) could suggest that no surface running waters have evident effects on this portion of the slope. The fall of the trees recorded in 2009–2010 can be related to underground phenomena acting locally and that cause the undermining of trees with the production of *compression wood*, a slight tilt of the stem and a prolonged persistence of narrow rings, without evidence on the surface.

In a geomorphological context like this we can associate this effect with soil creep and piping which both contribute to relief evolution.

In summary:

a. the subsurface flow, favoured by soil creep, and the consequent piping phenomenon withdraw the water flow from the ground's surface and surface running water erosion is limited;
b. the lack of mechanical support allows the trees to produce *compression wood* as a reaction to the tree tilting even if this tilting does not show any significant variation in trunk eccentricity;
c. the prolonged growth suppression (2002–2007) in the recent years for the fallen trees could be related to this stress situation.

The denudation value characteristic of the lower portion of the hillslope (1.58 $cm\ a^{-1}$) is comparable to the average value recorded at the Monte Oliveto Maggiore pins (1–1.5 $cm\ a^{-1}$) and more in general from the more complete record of the Radicofani pins (1.65–1.69 $cm\ a^{-1}$). In fact, the erosion rate values obtained through dendrochronology investigations include the resolution of the entire period of exposure and, as a consequence, they provide an average value over the investigated period (relatively longer term ERs), not recording the single peak events. As a consequence, the maximum ER that was obtained through the roots analysis is lower than the maximum one derived from the erosion pin measurements.

The estimation of the erosion rate through root exposure also allows reconstruction for past periods lacking geomorphological data. In addition, based on accurate geomorphological surveys, it is possible to locate the best site to apply the root exposure analysis. Besides, the spatial pattern of their values, the dendrogeomorphological indicators, permits the location of measurement tools for setting constant geomorphological monitoring.

Finally, comparing the erosion rate values with thermo-pluviometric series, critical denudation was recorded in years showing high seasonal variability of rainfall, especially if considerably high monthly rainfall occurs in the autumn.

7. Conclusions

The *calanchi* and *biancane* landscape is one of the most attractive, especially when associated with cultural heritage such as the Monte Oliveto Maggiore Abbey in the Crete d'Arbia area (Southern Tuscany). The interest in monitoring denudation processes is in the fast modifications they experience and the need to estimate denudation rates at these sites may become fundamental for environmental management.

The detection of the possible climatic or geomorphic origin for growth anomalies in trees, the spatio-temporal distribution of the anomalies and the dendrogeomorphological indicators (*compression wood*, *eccentricity index*), the comparison of ERs obtained by geomorphological monitoring and dendrogeomorphology, provide data that confirm the usefulness of applying this multidisciplinary approach.

The dendrochronological data, even if limited to a narrow area, are in agreement with the ERs estimated through detailed direct geomorphological monitoring performed over recent decades. The performed analyses demonstrated first that the choice of strategic sampling sites allows the extrapolation of data detailed enough to both provide information on average ERs, and detect critical periods through *compression wood* and the *anomaly index*. These data are well correlated with exceptional rainfall or periods of dryness (i.e. as in the formation of particular micromorphology rings or negative anomalies in tree ring records in 2007) obtaining a good correspondence between the tree response and thermo-pluviometric variability and the geomorphological monitoring data.

The choice of a multidisciplinary approach provided both confirmations of the results of each technique and supplementary information from each methodology. In fact, the different scales of geomorphological and dendrogeomorphological investigations provide respectively short- (seasonal) and relatively longer term (several years) ERs that supply a complete overview of the possible relief evolutionary trend. Dendrochronological investigations allow the extension of the analysis to the past and provide information that, even if punctual, supplies a general overview of the erosion trend of hillslopes or of the underground flow development even if not accompanied by surface evidence. In addition the dendrogeomorphological investigations in areas not yet monitored could be a valid tool to suggest the best location for monitoring stations, based on the spatial analysis of dendrogeomorphological indicators.

Finally, investigating tree ring growth anomalies allows the reconstruction of a spatio-temporal pattern of *calanchi* landscape evolution. Moreover, the ERs are comparable using dendro- and quantitative geomorphology and the critical erosion phases are usually detectable in comparing alternating dry and wet years, the former identifiable with tree rings.

The results underline the importance of combining different methods, especially when one is a present-day monitoring system and the other extends to the past.

8. Uncited references

Ciccacci et al., 1981
Garavaglia et al., 2010

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