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Abstract: The Tyrrhenian side of Central Apennine is located in a lively geological context, in which uplift/denudation dynamics played a key role in landscape evolution. Intense runoff 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 water erosion and gravitational landforms developed on Pliocene clays. On the other hand, these rapidly evolving landforms endanger the artistic heritage of the area, as for the Monte Oliveto Maggiore Abbey that was constructed on the top of a badland hillslope and confers to the landscape an additional value .

In the perspective of monitoring and reconstructing some significant phases of the hillslope evolution of this area an integrated approach has been used, which is based on dendrogeomorphology and geomorphological monitoring techniques. In particular, it was tested the correspondence between the data from dendrogeomorphological indicators and the measured denudation rates on badland hillslopes. The sampling for dendrogeomorphological analysis has been performed in two stages on 45 trees of the Pinus Pinea L. species, on hillslopes affected by gravitational movements and water erosion, in order to identify annual ring growth anomalies, compression wood and exposition of roots. 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 badlands denudation "hot spots" have been equipped with erosion pins and 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 calibrating both the tools in order to extend the analysis in the period preceding the field measurements. This kind of approach, implementable in many contexts, could be particularly helpful in order to forecast the hillslope evolutionary trend.

Research Highlights

- Tree growth anomalies allow to reconstruct spatio-temporal pattern of *calanchi*
- Long term erosion rates are comparable using dendro- and quantitative geomorphology
- Erosion increases in rainy years following dry ones identifiable in tree rings

Effects of water erosion and slope instability on tree rings growth and estimation of erosion rates in the Tyrrhenian side of Central Apennine (Italy) through dendrochronological and geomorphological investigations

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1. Introduction

The intensity of accelerated erosion processes represents one of the most studied topics in the geological and geomorphological field of research since these processes may cause significant landscape modifications at the time scale of a human life (Ananda and Herath, 2003). Damaging effects of erosion processes may be particularly serious when affecting geomorphosites (Pelfini et al., submitted), as well as hazards and risks may be associated to these processes, even influencing the tourist attendance, when they involve human settlements (Piccazzo et al., 2007). Therefore, the monitoring of areas, which are most sensitive to erosion processes, as well as the reconstruction of the past speed up/slow down phases of these processes are of crucial importance, in order to identify the hillslope evolutionary trend and schedule management strategies (e.g. Garavaglia et al., 2010).

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

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

Plio-Pleistocene clayey landscapes of Central Apennine (Piacente, 2004), represent typical environments, where diffused and concentrated runoff processes have been shaping spectacular badlands scenarios (sharp-edged *calanchi* and rounded-edged *biancane*; Alexander, 1980; Torri and Bryan, 1997; Ciccacci et al., 2003; Della Seta et al., 2009), often associated to impressive artistic treasures. Nevertheless, the same lively processes responsible for amazing landscapes often endanger these regions with severe consequences on slope stability and on preservation of cultural heritage (Bollati et al., 2009; Pelfini et al., submitted).

Finally, the strong morphodynamics on badlands often causes damages 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 and sedimentological monitoring techniques with the ones based on biological systems like the tree rings (Schweingruber, 1996) can be particularly useful, as already tested in different contexts (Guida et al., 2008; 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 hillslope evolution of a sample badland area of Central Apennines, which is characterized by fast morphodynamics, as already reported in previous works on the same region (Alexander,1980; Ciccacci et al., 2003, 2008; Moretti and Rodolfi, 2000; Del Monte et al., 2002; Del Monte, 2003; Della Seta et al., 2007, 2009). The integration between geomorphological and dendrogeomorphological techniques focused on the reconstruction of the past hillslope modifications since the ‘90s, with annual (to seasonal) resolution, through the analysis of the effects of hillslope processes on the trees life. The major phases of hillslope evolution since the early ‘90s will be outlined through: 1) dendrochronological and geomorphological erosion rate estimations; 2) spatio-temporal distribution of tree growth anomalies as indicators of tree suffering; 3) correlation among measured denudation, tree ring growth and pluviometric data, in order to discriminate between meteorological and geomorphic causes for trees suffering.

2. Study area

2.1 Geological and geomorphological setting

The study area is located on the Tyrrhenian side of Central Apennine 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 Abbey of the Benedectine Congregation, which confers to the landscape an additional value (Reynard et al., 2009). The study area lies within the Ombrone Basin, which is strongly affected by runoff processes acting on widely outcropping Pliocene clay (examples in Fig. 1).

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 clay, sands and conglomerates within the major depressions (Radicofani Graben, Val di Chiana Graben and Tevere Graben; see Funiciello et al., 1981; Bigi et al., 1992; Barberi et al., 1994). Since the Late Pleistocene, the marine sequence have been uplifted up to several hundreds of meters above present sea level, with the highest rates along an NW–SE elongated zone, in relation with pluton emplacement and widespread 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 a.s.l., is the result of both fluvial erosion and slope denudation on the widespread outcrops of soft sediments, and pervasive erosion by surface running water, favored as well by present day climate conditions and rapid uplift that lead 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 footslope. Where the hillslope is even slightly steeper, rill and gully erosion lead to badland development (*calanchi* and *biancane*) and soil degradation (ephemeral gullies; Foster, 1986), often associated with locally developed piping phenomena (Torri and Bryan, 1997; Faulkner et al., 2004).

Rock falls, slumps and slides occur on relatively steeper slopes while, on gentler slopes, mudflows, soil creep and solifluction are widespread (Fig. 1). The anthropic activities have been strongly concurring 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 to be noticed that some proposals for the adoption of hydraulic and reforestation techniques to slow down denudation on *calanchi* hillslopes had been already illustrated several years ago just for the area of the Monte Oliveto Maggiore Abbey (Gabbrielli, 1960).

2.2. Climatic setting

The Fiume Ombrone Basin climate, from the 1951-1996 Hydrological Year Books data is characterized by mean annual rainfalls of 696 mm a^{-1} (below the national average of 970 mm a^{-1}), although single total annual rainfalls during this time-span have been discontinuous. Rainfall regime shows maximum in November and minimum in July and the greatest number of consecutive rainy days is recorded in 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). Rainfall data from 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 to be noticed that an increase of the frequency and intensity of the extreme rainfall events as well as of the number of consecutive dry days were recorded (Vento et al., 2004).

In general, and in particular during the last years, marked semiarid conditions during the summer period followed by heavy rainfall in 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 since several decades through indirect estimations of suspended sediment yield from catchments (Ciccacci et al., 1986) and field monitoring implemented techniques. Both direct and indirect quantitative geomorphic investigations, widely applied in the Central Italy (Alexander, 1980; Ciccacci et al., 2003; Farabollini et al., 1992; Lupia Palmieri et al., 1995; Moretti and Rodolfi, 2000; Del Monte et al., 2002; Del Monte, 2003; Della Seta et al., 2007; 2009), led to 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 at the catchment and hillslope scales. Despite the time- and spatial-scale effects they observed that water erosion at 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, outlined that over the past 50 years *calanchi* badlands have progressively changed from type A (Rodolfi and Frascati, 1979), with sharp edges and narrow and deep gullies, to type B and then to type C (Rodolfi and Frascati, 1979), due to increased gravitational processes over time in many cases favored by the human activities.

Salvini (2008), as results 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 significant land use changes, particularly to the increase of agricultural levelling practices.

As mentioned above, some important stations for the monitoring of denudation processes in the Crete Senesi area underwent damaging due to strong water erosion and gravitational processes on hillslopes, such as the ones at Calanchi of Monte Oliveto Maggiore, which are added of additional cultural value besides the geomorphological one (Reynard et al., 2009). Due to this additional value, to the partial loss of denudation data and to the presence of reforested hillslopes affected by strong instability (Fig. 1), the contribution of dendrogeomorphological data may be particularly useful to reconstruct the recent hillslope evolution, especially if cross-checked with denudation and rainfall data already available for the studied region.

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 signals recorded in the tree rings are different depending on whether they are due to meteorological or mechanical factors. Thus the discrimination of the stress factor is one the main purposes of dendrogeomorphologists.

The sampling of trees stressed or not by the effects of runoff or slope retreat processes can help to distinguish the cause of the anomalies. Significant stress indicators are compression wood (Timell, 1986), trunk eccentricity (Braam et al., 1987; Baylot and Vautherin, 1992; Garavaglia and Pelfini, submitted) and exposition of roots (Hupp and Carey, 1990; Vandekerckhove et al., 2001; Pelfini et al., 2004; Pelfini & Santilli, 2006; Gartner, 2007; Malik, 2008). The presence of scars on the trunk is more strictly related to mass movements involving large debris affecting tree trunks and, in the study area, no evidences of this kind of effects on trees were detected, even if, as outlined by recent works, mass movements contribute significantly to hillslope denudation (Della Seta et al., 2007; Ciccacci et al., 2008) (Fig. 1d).

Dendrogeomorphological and geomorphological monitoring data are both strictly correlated to the rainfall data. For example the extreme rainfall events speeding up the erosion processes on clayey slopes (Della Seta et al. 2007; 2009) can produce local stresses to trees for slope instability. On the other hand, an extremely dry period may induce suffering to some tree species, in the specific case of the Crete d'Arbia, to the *Pinus Pinea* L. (Cherubini, 1993).

Hence direct and indirect meteorological induced stresses may influence tree ring growth (Fig. 2): the increase of runoff and/or gravitational processes intensity 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 meteorological conditions. Thus, the final tree ring record is the result of the combination of both meteorological and mechanical inputs. Cross dating procedures (Alestalo 1971; Heikkinen, 1994) allow establishing the date of each individual annual ring through matching patterns of rings among different cores and consequently to identify and interpret growth disturbance signals. In this sense it is important to separate the meteorological 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. 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 imply periodical surveys (ideally monthly and several years long records), the dendrogeomorphological investigations work on samples collected simultaneously and, in addition, allows 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 rainfall analysis

Since the 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 (Marini, 1995; Del Monte et al., 2002; Del Monte, 2003). 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, downdale 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 changes on the topographic surface. They show the erosion/accumulation trend and allow estimating 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. The analysis of meteorological data provided total annual and monthly rainfall, maximum and minimum monthly rainfall, as well as seasonal rainy days over the field monitoring period.

4.2 Dendrogeomorphological investigations

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

A detailed survey has been carried out in order to collect samples from trees mostly stressed by erosion processes. Some samples have been taken from exposed roots. During the sampling activities specimens from 45 trees of *Pinus Pinea* L. have been collected and the results obtained will be illustrated.

Samplings of both trunk and roots have been taken using an increment borer. The cores extracted from the trunk were collected at the standard height of the trunk of 1.30 m (breast height). Moreover some few disks have been cut from exposed roots. Where scars were present samples have been taken in correspondence of the damaged portion of the trunk/root (Schweingruber, 1996) with the aim of dating the damaging events, particularly meaningful for the analysis of the root exposition . Moreover some cores from undisturbed trees have been collected for a correct cross dating (Alestalo, 1971; Heikkinen, 1994), since no published reference chronologies are available. The only chronologies available for this species 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 *Pinus Pinea* L. colonization derives mainly from reforestation activities in order to stabilize the calanchi hillslopes. Nevertheless, even if the undisturbed trees are few individuals, their analysis was performed to distinguish growth anomalies affecting both disturbed and undisturbed trees (probably related to meteorological stress) from growth anomalies due to local processes (slope instability) (for the method see Pelfini et al., 2007).

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 Instrument Inc., 2001). The cross dating of the dendrochronological series have been mainly performed visually with TSAP because short chronologies cannot allow an affordable degree of statistic correlation using COFECHA (Holmes et al., 1986).

In detail we analyzed the *Anomaly Index* (Schweingruber et al., 1991; Rolland et al., 2001; Pelfini et al., 2007), useful for analyzing abrupt growth changes (growth release and suppression). The index is based on the percentage growth variation with respect to the mean of the four previous years, for each year, with threshold values (positive and negative) at 40%, 55% and 70%. (Schweingruber et al., 1991; Rolland et al., 2001; Pelfini et al., 2007). The shared presence of comparable Anomaly Index in both disturbed and undisturbed trees have not been considered as an indicator of geomorphological processes interacting with trees because present in both the different geomorphological context.

The *Eccentricity Index* as defined by Casteller et al. (2007) (see also Garavaglia and Pelfini, submitted) is used to quantify the changes in trunk eccentricity before and after a precise event. In this work the calculation was based on Braam et al. (1987) and Baylot and Vautherin (1992) method, consisting of a morphometric comparison between respectively the measurements of both the maximum and minimum dimension of the trunk (external feature) and the annual ring width along a parallel and orthogonal direction with respect to the slope (internal feature).

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

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

In the literature erosion rate has been examined through dendrogeomorphological techniques and in particular through exposition of roots in different contexts, using different species, and different are the result in term of mm of sediments eroded per year (La Marche, 1966; Hupp and Carey, 1990; Gartner et al., 2001; Pelfini and Santilli, 2006; Gartner 2007; Malik, 2008; Malik and Matyja, 2008; Chartier e t al., 2009) and a review of the methodology has been recently proposed by Gartner (2007). Different authors examined exposure of roots, in some cases focusing on gully erosion contexts (Vandekerckhove et al., 2001; Malik, 2008).

Roots have been sampled to perform morphometric analysis (Hupp and Carey, 1990; Gartner et al., 2001; Pelfini and Santilli, 2006; Gartner, 2007) and estimate the erosion rate. In fact, the change in roots micromorphology from the production of root type wood to a trunk type wood, with the distinction from early wood, is a consequence of the exposure. Thus, applying the equation by Hupp and Carey (1990) 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 ($E = D/A$; Hupp and Carey, 1990). The roots chronology has been compared to the corresponding tree chronology in order to obtain an age of exposure, and eventually of scars, as much correct as possible.

3. Results

3.1 Denudation field monitoring and rainfall analysis

As outlined in previous works (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, 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}. 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 up to 7.4 cm a^{-1}.

The most significant denudation graph, with a continuous record from 1995 and new data up to 2009, comes from a *calanchi* monitoring station close to the Radicofani town (Fig. 4a). The graph shows critical denudation events occurred in 1996, 2002, 2005 and2008: in 1996 and 2002 a steepening of the curve indicate critical erosion, while in 2005 and 2008 accumulation was also recorded due to mass movements. The curve shows as well a decrease in steepness, with occasional accumulation events, during the period 1998-2000. By comparing these data with the monthly rainfall distribution (Fig. 4b) it can be noticed that critical denudation was recorded in years showing high seasonal variability of rainfall, especially with considerably high monthly rainfalls occurred in the fall season. As possible factor for stronger erosion with respect to accumulation, it is to be outlined that these critical years in most cases (i.e. 1996, 2002, 2008) alternate with years with particularly low seasonal variability of rainfalls (i.e. 1995, 2001, 2007) and low total annual rainfall (respectively 495.0, 260.5 and 366.6 mm a^{-1}). The erosion rate obtained for this 14 years period is 1.65-1.96 cm a^{-1}, which testify for the accumulation events occurred.

New data from stations more recently set up (2005-2009), recorded at *biancane* stations close to Pienza, confirmed the above results (Fig. 5), 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 Monte Oliveto Maggiore site are represented by sharp-edged badlands, developed in rapidly evolving small catchments. Mass wasting contributes to hillslope denudation together 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.

3.2 Dendrogeomorphological investigations

3.2.1 Trees response to water runoff processes

Dendrogeomorphological analyses carried out on *Pinus Pinea* L. cover the time period 1995-2008 and some interesting data have been obtained.

The *compression wood* is not homogeneously distributed neither in space nor in time. The highest and prolonged concentration has been observed in the central part of the sampled hillslope, close to an area characterized by the fall of several trees in the time interval between the two surveys.

The Anomaly Index calculated as described above, highlights some periods of common suffering for the trees (2000 - 2002, 2007) even if the values obtained are not so regularly distributed. In the maps of figure 6 the comparison between the distribution and intensity of Anomaly Index with respect to compression wood is illustrated over the period 1995-2008. The trees with the longest permanence (3-6 years) of negative anomalies over the 70% threshold are concentrated in a central band of the hillslope. Along the same direction the compression wood is present, especially in the central section (black dotted line) and in the lower section (grey dotted line). In the central section both compression wood and anomaly index reach the relatively maximum values and duration, while in the lower section the compression wood is pervasive, covering the 75-100% of the analyzed period, but it is not as intense as in the central upper part. Some additional observations can be done. The central section has been recently characterized by rapid changes as the presence of fallen trees have been recorded in the time period between the two surveys, while the lower section anyway is located in an area surrounding a wide piping emergence.

The years with at least 40% of trees with negative anomalies over the 70% threshold have been 2000, 2002, 2007, as illustrated in spatio-temporal maps in figure 7. The trees growing in the central portion of the hillslope are affected by a widespread stress starting in the time interval 2000-2002 (Fig. 7a,b), which involved especially the trees around the upper middle area. Anyway, while in the other portion of the hillslope there is a recover of the positive values, as demonstrated in the 2005 map (Fig 7, c), the trees placed in the central part of the hillslope maintain the strong negative trend. The cross-dated chronologies of the trees in the central portion (55, 56, 52, 14, 15, black dotted line in Fig. 6) are reported in figure 8. It is evident the persistence of the negative trend in 2005 except for the trees 52 and 55, located slightly upslope. In addition, the constant trend of low values after 2002 of the trees 14, 15 and 56 causes for them the absence of a clear negative anomaly in 2007 with respect to the other trees (Fig. 7, d).

The negative anomaly of 2007 recorded in many trees along the hillslope (Fig. 7, d) corresponds in the meteorological record to a relatively dry year (Fig. 9) that is likely to have produced a physiological and diffused stress to the *Pinus Pinea* L. species (Cherubini, 1993) likely not caused by slope instability. Moreover the dendrochronological information, in agreement with meteorological ones, can assist the individuation of the alternation of critical years for erosion, characterized by high seasonal variability of rainfall and high monthly rainfalls especially in the fall season, and years of negligible erosion, with particularly low seasonal variability of rainfalls and low total annual rainfall. This pluviometric pattern, as underline above, has been individuated to be the main responsible for the triggering of erosion processes.

Trunk eccentricity data do not show any meaningful variations neither in the external features nor in the internal ones. The *Eccentircity Index* of 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 per year following Baylot & Vautherin (1992) rarely overcomes 40%.

The spatio-temporal distribution of the dendrogeomorphological indicators may be correlated not only with runoff processes but the trees behavior may reflect as well a shallow sub-surface water flow component. There is evidence of piping processes along the hillslope, as often observed in similar geomorphological contexts. Despite the trees directly in contact with piping caves do not show any abrupt growth change, a persistence of compression wood has been described in the area immediately downslope respect to a wide pipe emergence. Thus, this kind of phenomena may determine the sub-surface flow direction interfering with the trees behavior.

3.2.2 Root exposure

The *Pinus Pinea* L. trees do not show many exposed roots in the study area and the observed ones differ to each other from site to site. The investigations have been focused on the presence of scars, eccentric shape, abrupt growth changes in rings width and micromorphology transformation from root to stem wood. All these features allowed establishing a minimum date of exposure. Hence, the exposed roots provided different erosion rates (ER) based on different age of those features and on the eroded sediment thickness (for detailed values see figure 10).

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

The literature results (Vandekerckhove et al., 2001; Bodoque et al., 2005; Pelfini and Santilli, 2006; Perez Rodriguez et al., 2007 ; Malik, 2008; Chartier et al., 2009) demonstrate 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 Vanderkerchove et al. (2001), considerable as moderate.

Discussion

The results obtained with the integrated approach and their comparison with the meteorological data has provided interesting information regarding the evolution of the hillslopes surrounding the Monte Oliveto Maggiore Abbey.

A limiting factor in analyzing dynamic hillslopes such as the *calanchi* and *biancane* ones is the low probability of finding long tree rings record for a complete reconstruction of past events. Despite the fact that *Pinus 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 the Intra Annual Density Fluctuations (IADF; De Micco et al., 2007). This behavior is quite common among the species in the Mediterranean climate (Lipschitz et al., 1981; 1984; Lipschitz and Lev-Yadun, 1986; Cherubini et al., 2003), 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 *Pinus*

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 by high temperatures (Cherubini, 1993). Finally, the clay terrains are not the ideal bedrock for the settlement of this species (Gellini, 1973), and this fact can probably influence negatively the behaviour of trees.

Nonetheless, the space and time distribution of the Anomaly Index and compression wood indicate a central area of the analyzed hillslope that is constantly affected by tree suffering that resulted in the fall of several trees in the time interval between the two performed surveys. The compression wood in addition is persistent in the lower part of the hillslope, downslope to a wide pipe emergence.

During the analyzed time interval (1995-2008), critical years of denudation have been recognized and the comparison between monitoring station and trees behaviour can be done.

The 2000 is characterized by a high and widespread negative anomaly index (> 70%), that in 2002 corresponds to the peak of distribution. In 2002 an intensification of erosion to critical level has been recorded also at the Radicofani geomorphological monitoring station. In 2005 the recovering of the situation with respect to stress is not reported in the central band of the hillslope, where the persistence of a negative trend is evident, that probably preceded the fall of trees in 2009-2010. The correlation with climatic data is strong in correspondence with the negative anomaly of 2007, when a period of extremely low rainfalls, a critical condition for the *Pinus pinea* L. (Cherubini, 1993), has been recorded in the meteorological dataset. The results here obtained allow to extrapolate some meaningful considerations: there is a good correspondence with dry year (i.e. 2007) and narrow rings (i.e. 2007); moreover in 2008 geomorphological monitoring shows an acceleration of erosion indicating that the alternation between dry years and years with high precipitation may represent the triggering factor for this kind of erosion processes. So the identification of narrow rings in areas not yet monitored might suggest the presence of this alternating pattern of dry years with years characterized by high seasonal variability of rainfall and high monthly rainfalls in the fall season.

Concerning erosion rate estimation through exposed roots, the values obtained can be compared with the ones in literature. For example Perez Rodriguez et al. (2007) found out in a forest, set on a steep slope affected by 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 in different point of the root, obtaining a volumetric gully head retreat of 6 m^3 a^{-1} and gully side retreat of 0.1 m a^{-1}. Malik (2008) distinguished, in terms of erosion rates, among old gullies (0.63 m a^{-1}), hillslope (0.21-0.52 m a^{-1}) and valley bottom (0.18-1.98 m $^{a-1}$).

The values obtained through *Pinus 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}) in correspondence of strong denudated areas and a minimum value (0.27 cm a^{-1}) at the middle portion of the hillslope, that is on the other hand characterized by a continuous negative trend after 2000-2002. Thus, the shallow denudation processes seem not to be responsible for the negative anomaly values obtained in that area. It is conceivable that the tree suffering is linked more strictly to deeper hillslope modification, maybe subsurface flow that gives origin to piping niches more downslope.

Thus, it is not evident the correspondence between negative anomalies on tree rings growth and denudation processes.

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 have the resolution of the entire period of exposure and as a consequence they provide an average value over the investigated period (relatively longer term erosion rates), not recording the single peak events. As a consequence, the maximum erosion rate that was obtained through the roots analysis is lower than the maximum one deriving from the iron pins measurements. In this sense the investigation of erosion rate through exposure of roots allow the extension of the investigations in the past where the geomorphological analysis had not been yet started. In addition, on the base of an accurate morphological survey it is possible to locate the best site where applying the root exposure analysis in order to obtain first results on the modifications due to erosion processes acting on hillslopes, information. Subsequently on the base of the spatial pattern individuated in dendrogeomorphological indicators, it is possible to locate measurements tools for setting a geomorphological constant monitoring.

Finally, comparing the erosion rate values with the climatic data, critical denudation was recorded in years showing high seasonal variability of rainfall, especially with considerably high monthly rainfalls occurred in the fall season.

Conclusions

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

The dendrochronological data, even if limited to a narrow area, are in agreement with the erosion rates estimated through detailed direct geomorphological monitoring performed over the last decades. The performed analyses demonstrated first that the choice of strategic sampling sites allow to extrapolate data enough detailed both to provide information on average erosion rates, and to detect critical periods through compression wood. These data are well correlated with exceptional rainfall or dryness events (i.e. as for the formation of particular micromorphology rings or negative anomalies in tree ring records in 2007) obtaining a good correspondence of the tree response with the meteorological variability and geomorphological monitoring data.

The choice of a multidisciplinary approach provided both confirmations of the results of each technique application and supplementary information from each methodology. In fact the different scale of sedimentological and dendrogeomorphological investigations provide respectively short- (seasonal) and relatively longer term (several years) erosion rates that supply a complete view over the possible hillslope evolutionary trend. Dendrochronological investigations allow the extension in the past of the analysis and provide information, that even if punctual, supply a general overview of the erosion trend of hillslopes. In addition the dendrogeomorphological investigations in areas not yet monitored could be a valid tool in order to suggest where to place monitoring stations on the base of the spatial analysis of dendrogeomorphological indicators.

Finally, it is possible to reconstruct a spatio-temporal pattern of *calanchi* landscape evolution investigating tree rings growth anomalies. Moreover the erosion rates are comparable using dendro- and quantitative geomorphology and the critical erosion phases are usually detectable in correspondence of an alternation of dry and rainy years, the former ones identifiable in tree rings. The results underline the importance of combining different methods especially when one is a monitoring system and the other look to the past.

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Figures caption

Fig.1 – 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 hillslope 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 duct 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.

Fig.2 – Sketch of the relationship among meteorological inputs, hillslope processes and tree growth. The separation of twofold signals influencing tree ring growth is one of the main goals of this investigation.

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

Fig. 4: (a) one of the most significant denudation graphs obtained through the geomorphological monitoring. Denudation trend has been interpreted taking into account the monthly rainfall distribution over the same period (b).

Fig. 5: Denudation graphs from new monitoring stations (a,c) and monthly rainfall distribution over the same period (b, d).

Figure 6 – 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 number of years of persistence in each tree in the considered time interval; the intensity classes are intended as the number of years respect to the maximum obtained. (b) Compression wood distribution in terms of number of years of persistence in each tree in the considered time interval; the intensity classes are intended as number of years of deep compression wood with respect to the total number of years of persistence in each tree.

Figure 7 –Distribution of Anomaly Index in years recognized to have more than 40% of negative Anomaly Index values over the 70% threshold (a: 2000; 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 downhillslope side cores chronologies, in which the abrupt growth changes are more evident.

Figure 8 – Cross dated rough chronologies of uphillslope (m) and downhillslope (v) sides of the trees 14, 15, 52, 55, 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 upper portion of the hillslope, while the aligned trees maintain a constant low growth.

Fig. 9: Rainfall distribution from meteorological data recorded by the closest pluviometer. Despite the discontinuous record for several years, 2007 data are complete indicating a strongly drier year, with the absolute minimum of summer rainfall.

Fig. 10 Exposition of roots along the examined hillslope. The respective erosion rates are different: (a) Strong creep area, scar dated at 2005 (ER = 3.25 -3.75 cm a^{-1}); (b) root at the ground level in the area surrounding the fallen trees with scar dated at 2000 (ER = 0.27 cm a^{-1}); (c) root showing a permanent stem like wood anatomy; in 2005 the root show 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}).

Figure 1

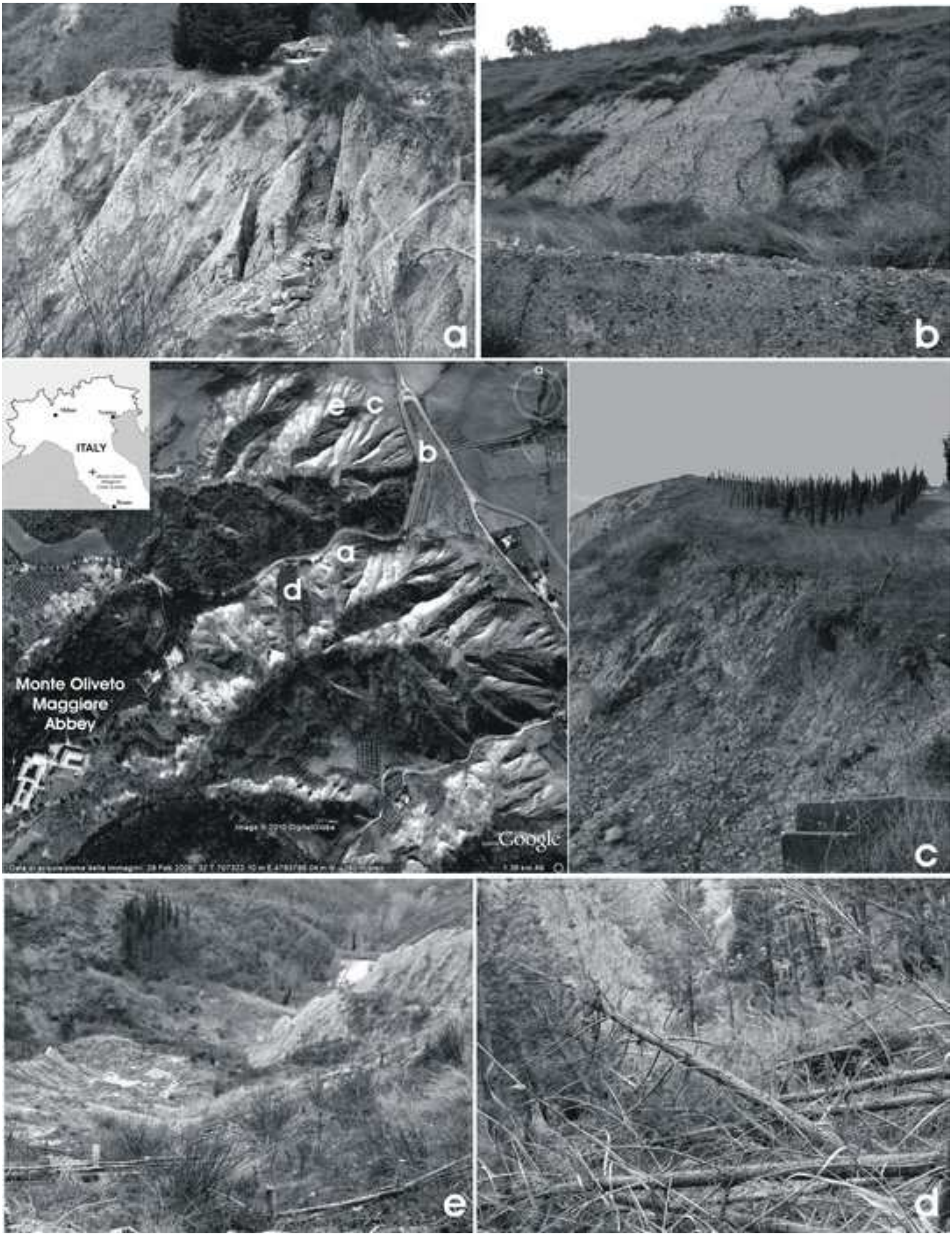

Figure 2

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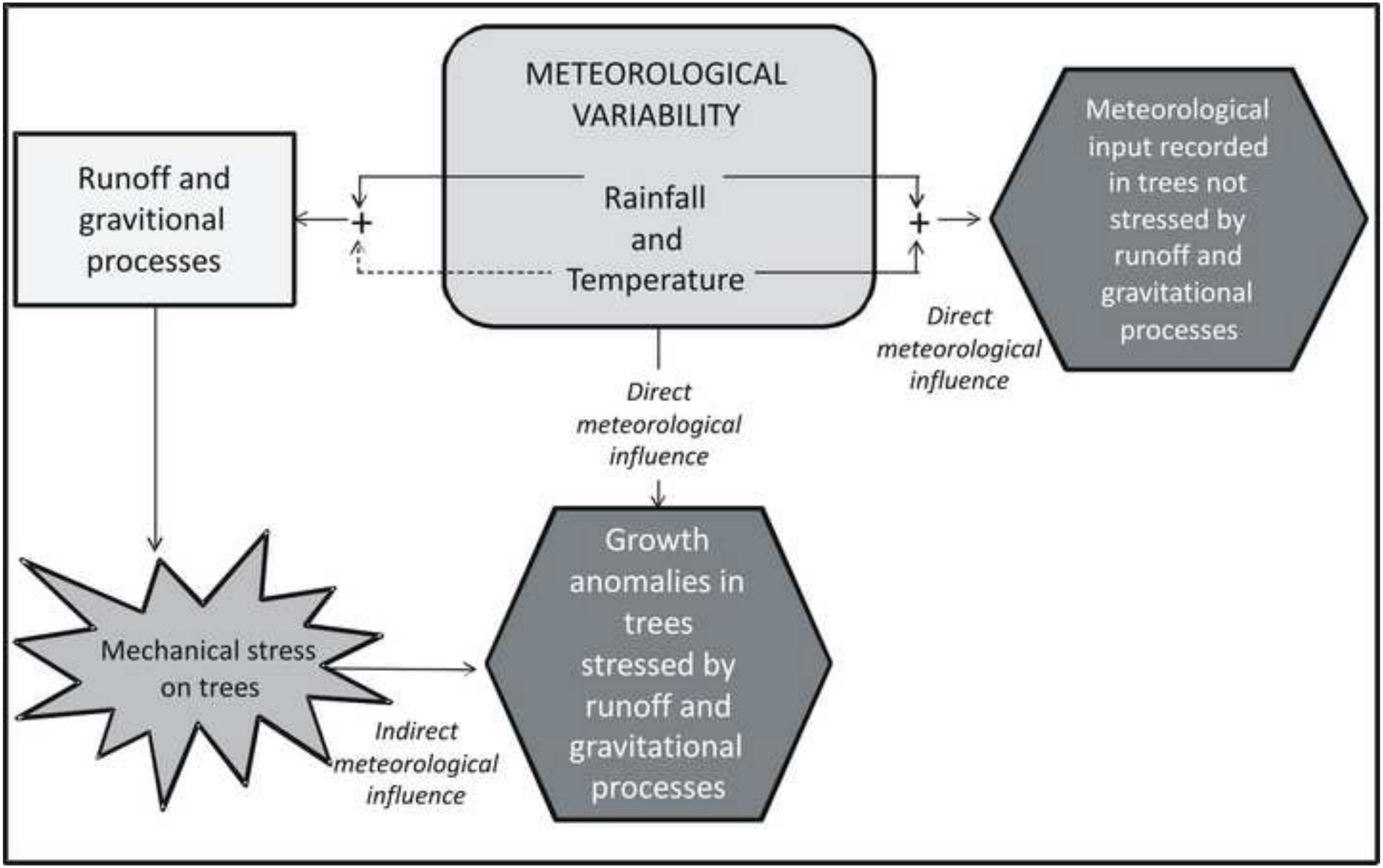

Figure 3

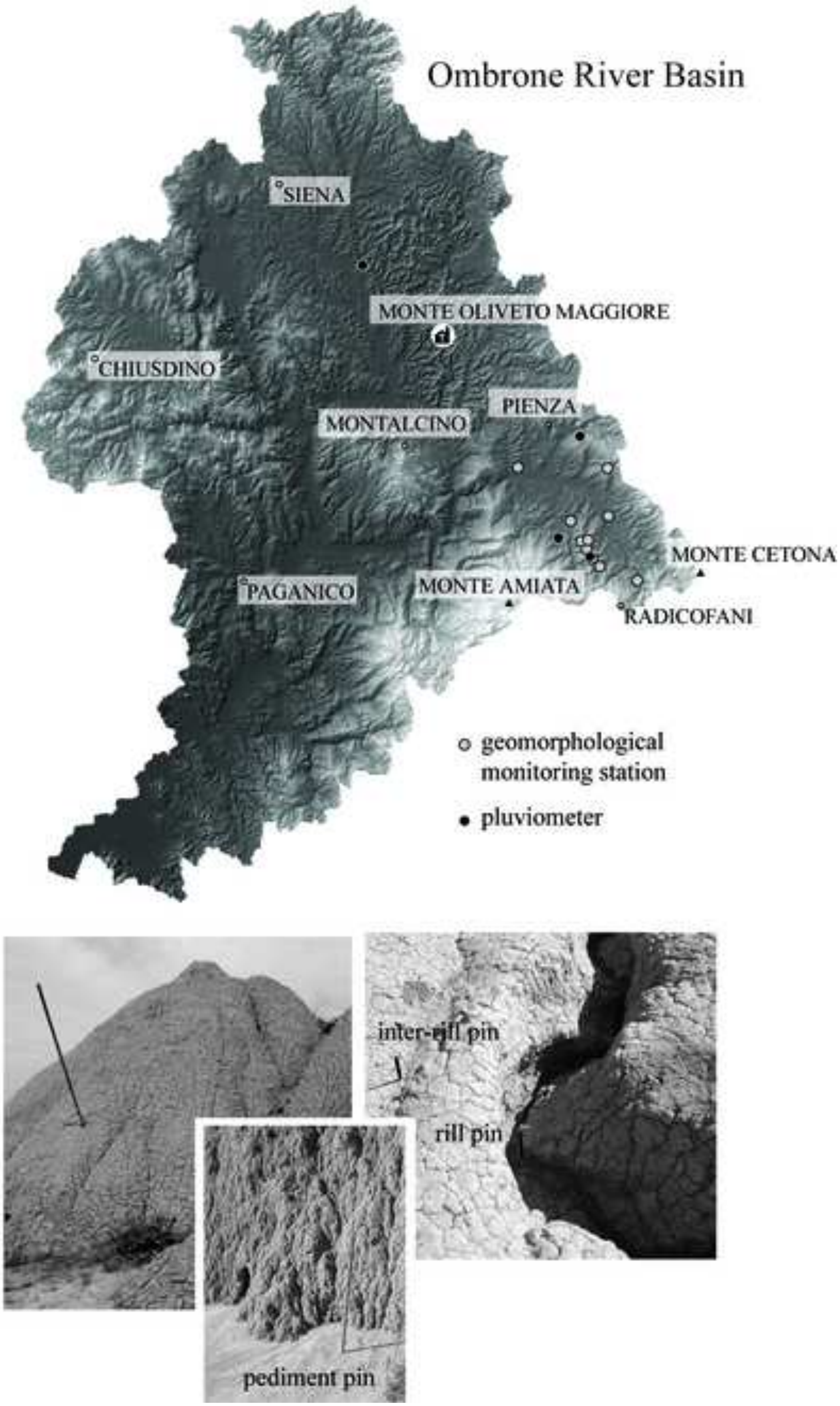
Ombrone River Basin
SIENA
MONTE OLIVETO MAGGIORE
CHIUSDINO
PIENZA
MONTALCINO
MONTE CETONA
PAGANICO
MONTE AMIATA
RADICOFANI
○ geomorphological monitoring station
● pluviometer
inter-rill pin
rill pin
pediment pin

Figure 4

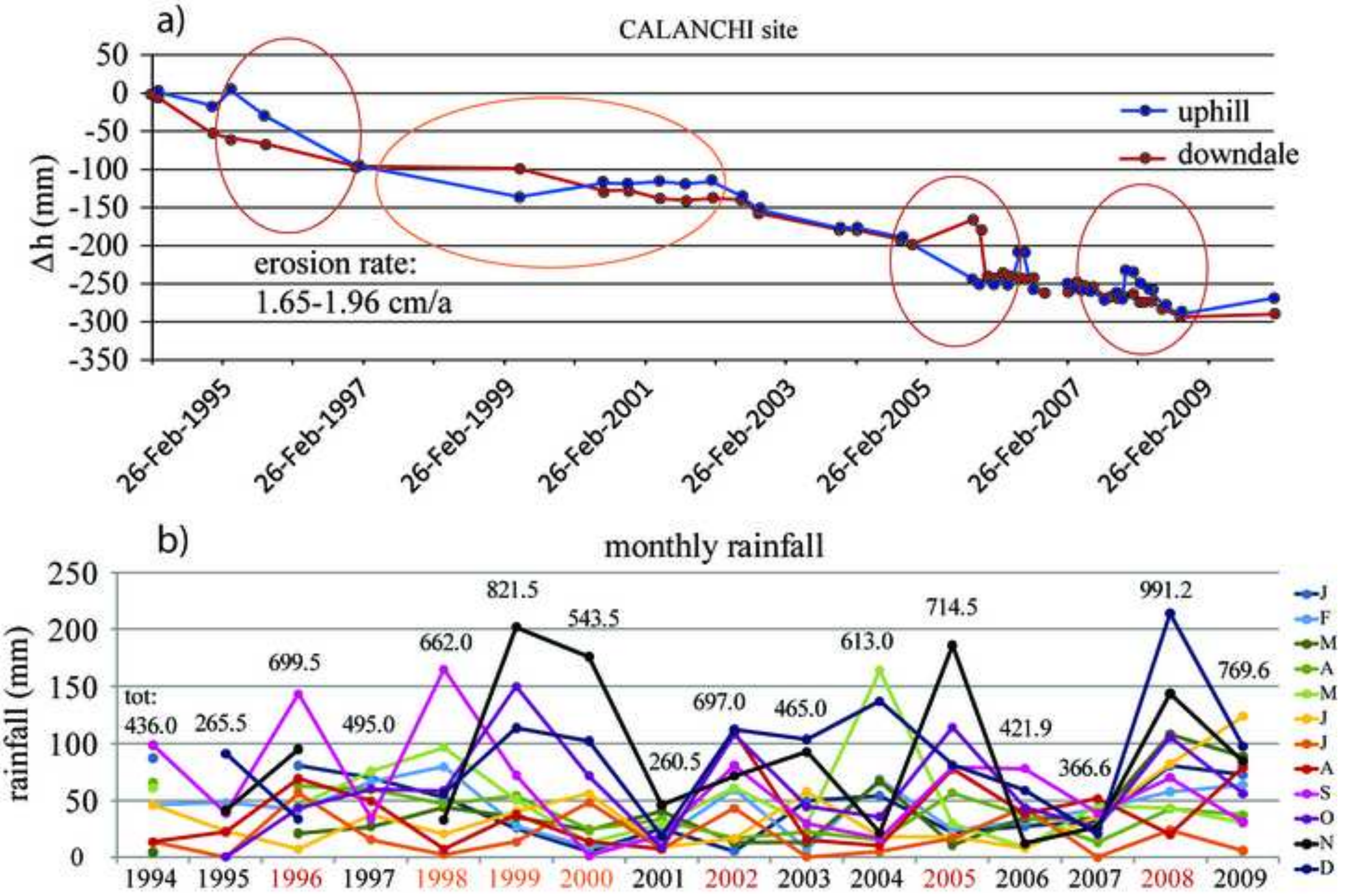
a)
CALANCHI site
Δh (mm)
50
0
-50
-100
-150
-200
-250
-300
-350
uphill
downdale
erosion rate:
1.65-1.96 cm/a
26-Feb-1995
26-Feb-1997
26-Feb-1999
26-Feb-2001
26-Feb-2003
26-Feb-2005
26-Feb-2007
26-Feb-2009
b)
monthly rainfall
rainfall (mm)
250
200
150
100
50
0
tot:
436.0
265.5
699.5
495.0
662.0
821.5
543.5
260.5
697.0
465.0
613.0
714.5
421.9
366.6
991.2
769.6
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
J
F
M
A
M
J
J
A
S
O
N
D

Figure 5

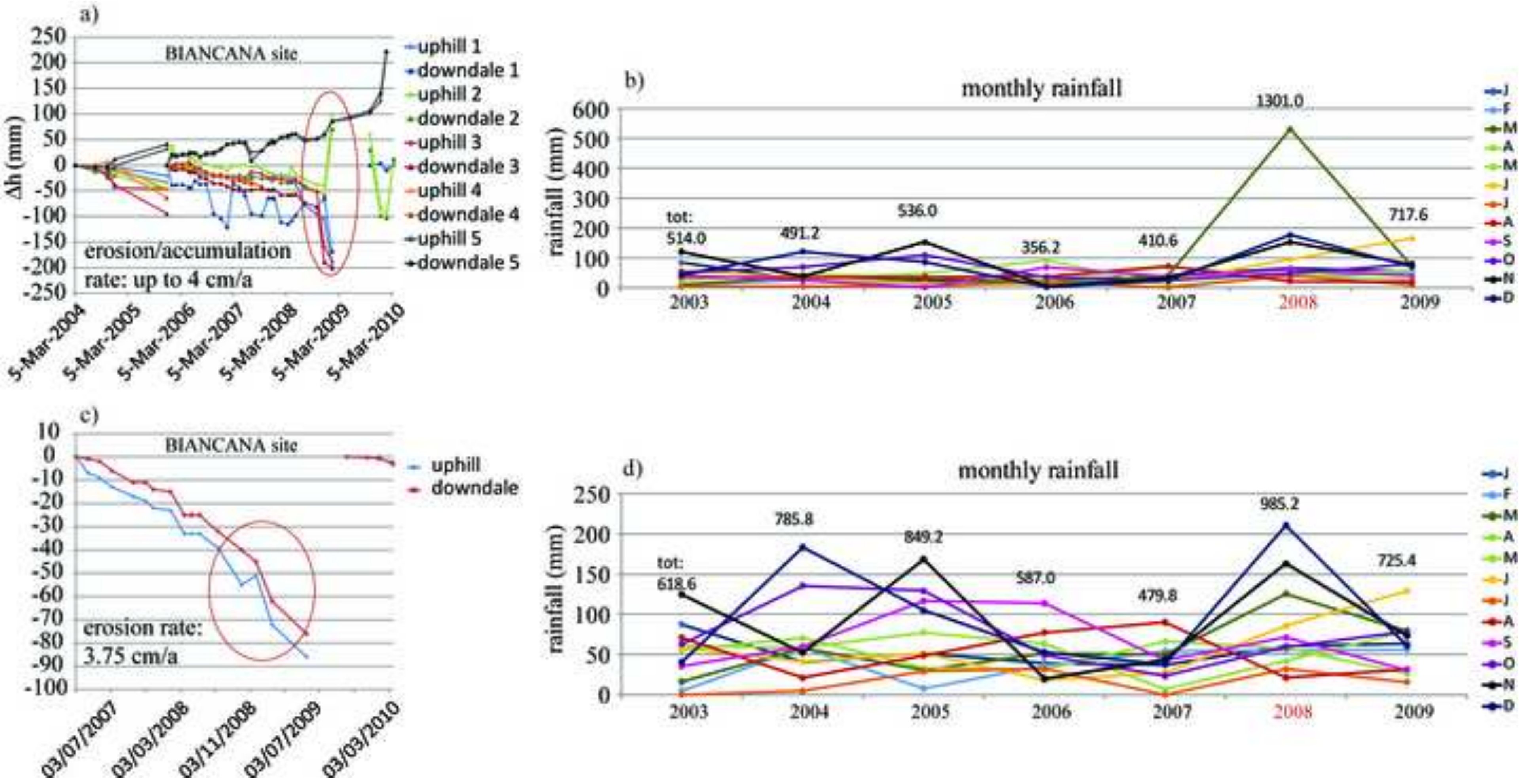
a)
BIANCANA site
Δh (mm)
250
200
150
100
50
0
-50
-100
-150
-200
-250
erosion/accumulation
rate: up to 4 cm/a
5-Mar-2004
5-Mar-2005
5-Mar-2006
5-Mar-2007
5-Mar-2008
5-Mar-2009
5-Mar-2010
uphill 1
downdale 1
uphill 2
downdale 2
uphill 3
downdale 3
uphill 4
downdale 4
uphill 5
downdale 5
b)
monthly rainfall
rainfall (mm)
600
500
400
300
200
100
0
tot:
514.0
491.2
536.0
356.2
410.6
1301.0
717.6
2003
2004
2005
2006
2007
2008
2009
J
F
M
A
M
J
J
A
S
O
N
D
c)
BIANCANA site
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
erosion rate:
3.75 cm/a
03/07/2007
03/03/2008
03/11/2008
03/07/2009
03/03/2010
uphill
downdale
d)
monthly rainfall
rainfall (mm)
250
200
150
100
50
0
tot:
618.6
785.8
849.2
587.0
479.8
985.2
725.4
2003
2004
2005
2006
2007
2008
2009
J
F
M
A
M
J
J
A
S
O
N
D

Figure 6

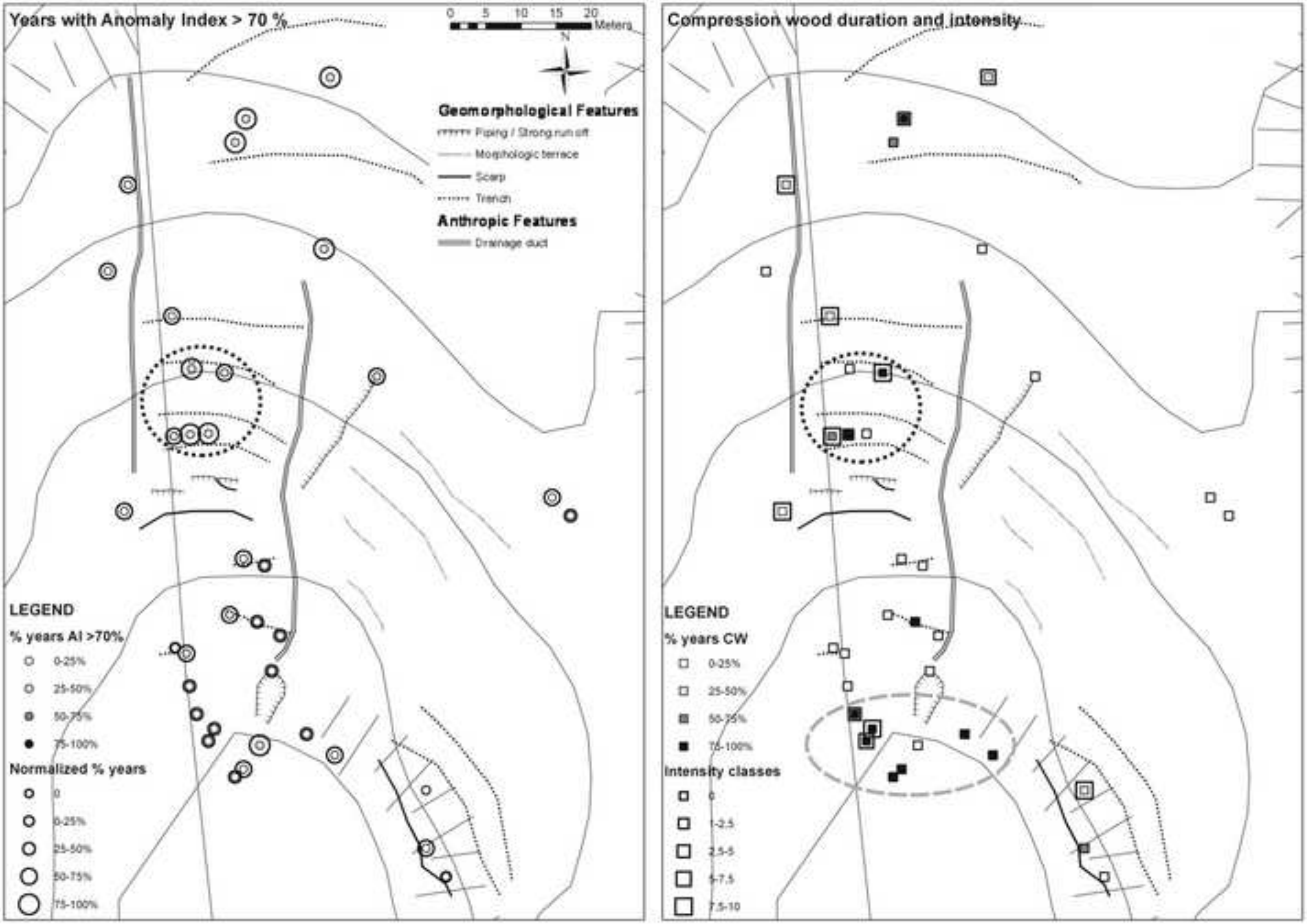
Years with Anomaly Index > 70 %
0
5
10
15
20
Meters
N
Geomorphological Features
Piping / Strong run off
Morphologic terrace
Scarp
Trench
Anthropic Features
Drainage duct
LEGEND
% years AI >70%
0-25%
25-50%
50-75%
75-100%
Normalized % years
0
0-25%
25-50%
50-75%
75-100%
Compression wood duration and intensity
LEGEND
% years CW
0-25%
25-50%
50-75%
75-100%
Intensity classes
0
1-2.5
2.5-5
5-7.5
7.5-10

Figure 7

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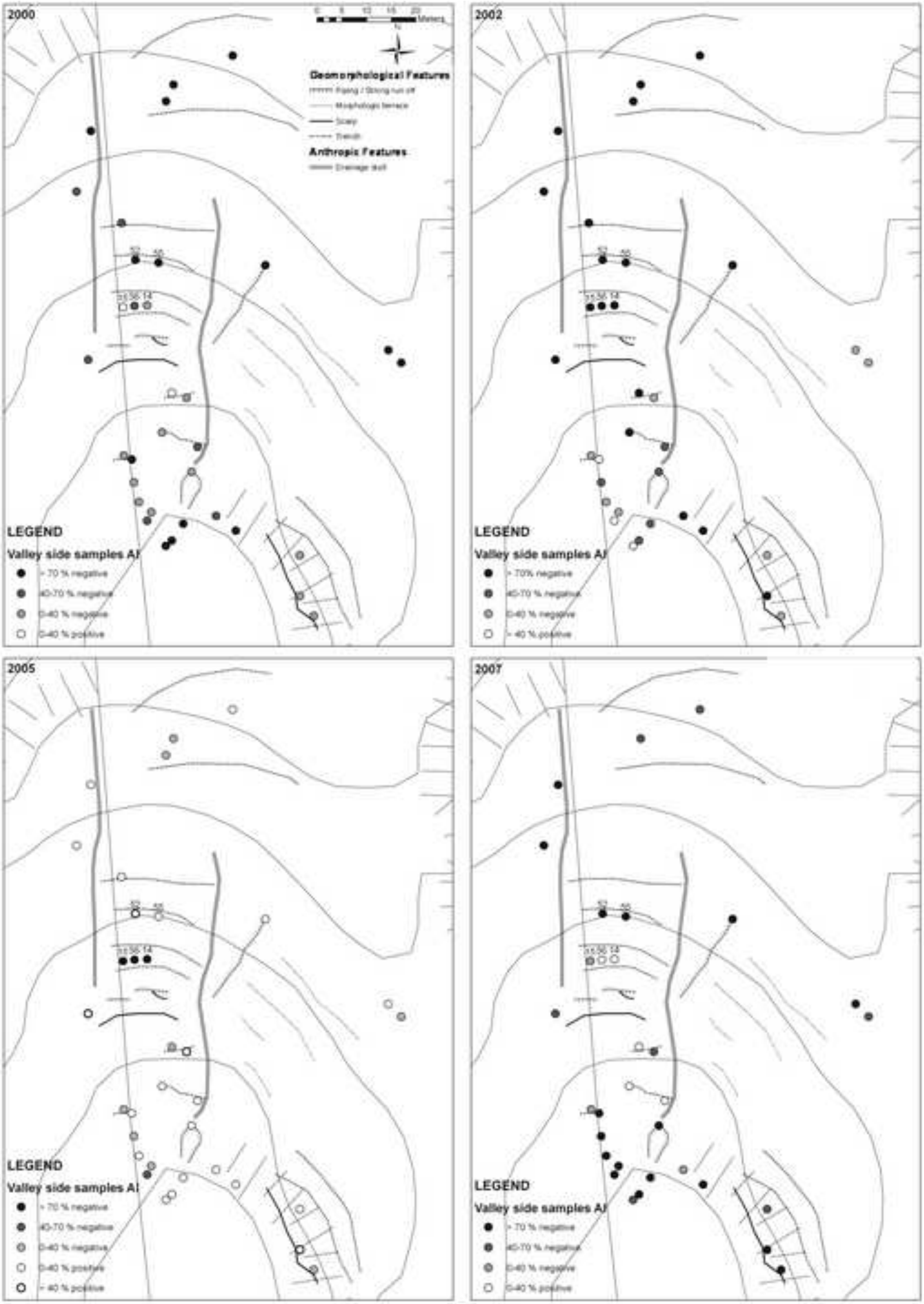

Figure 8

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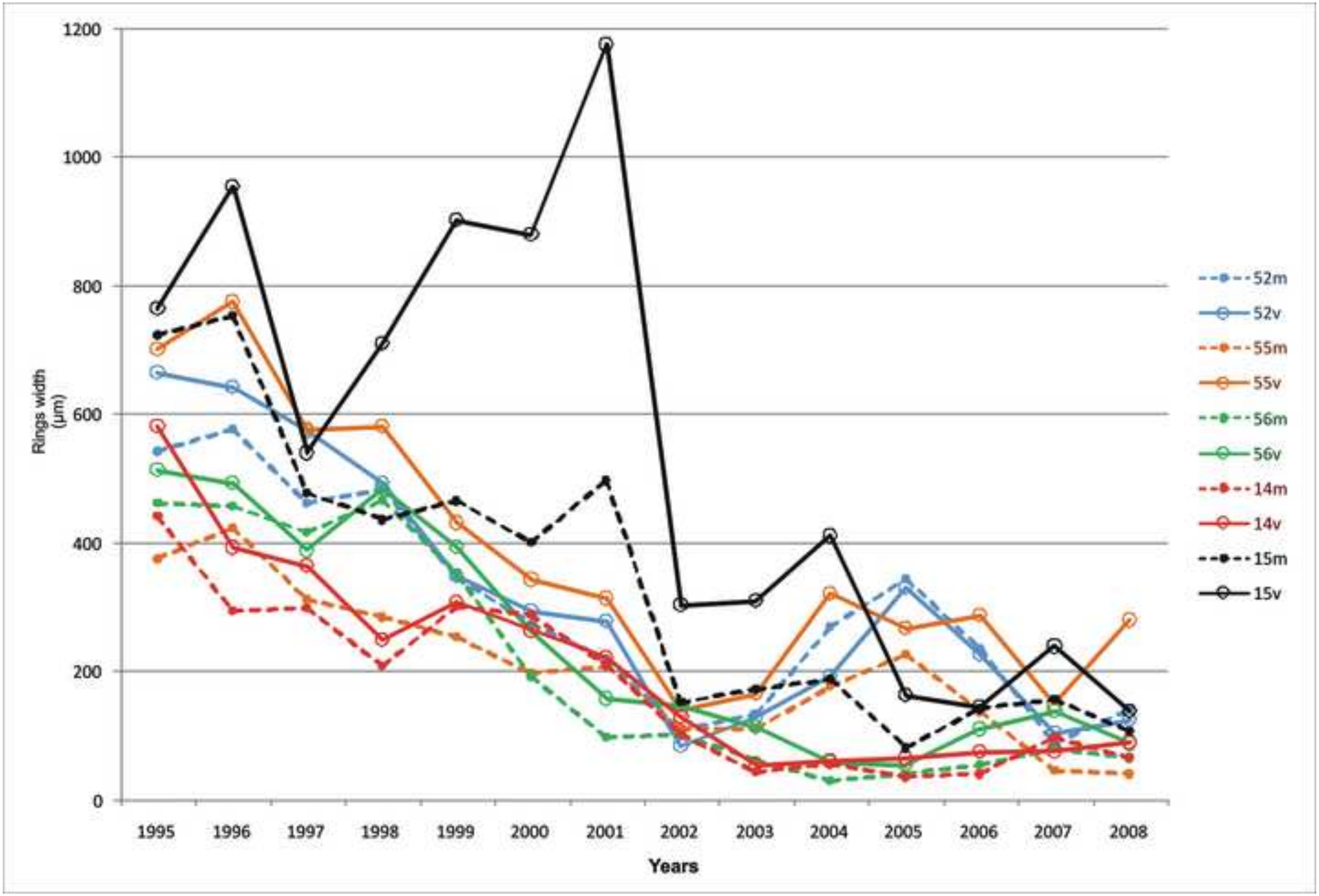

Figure 9

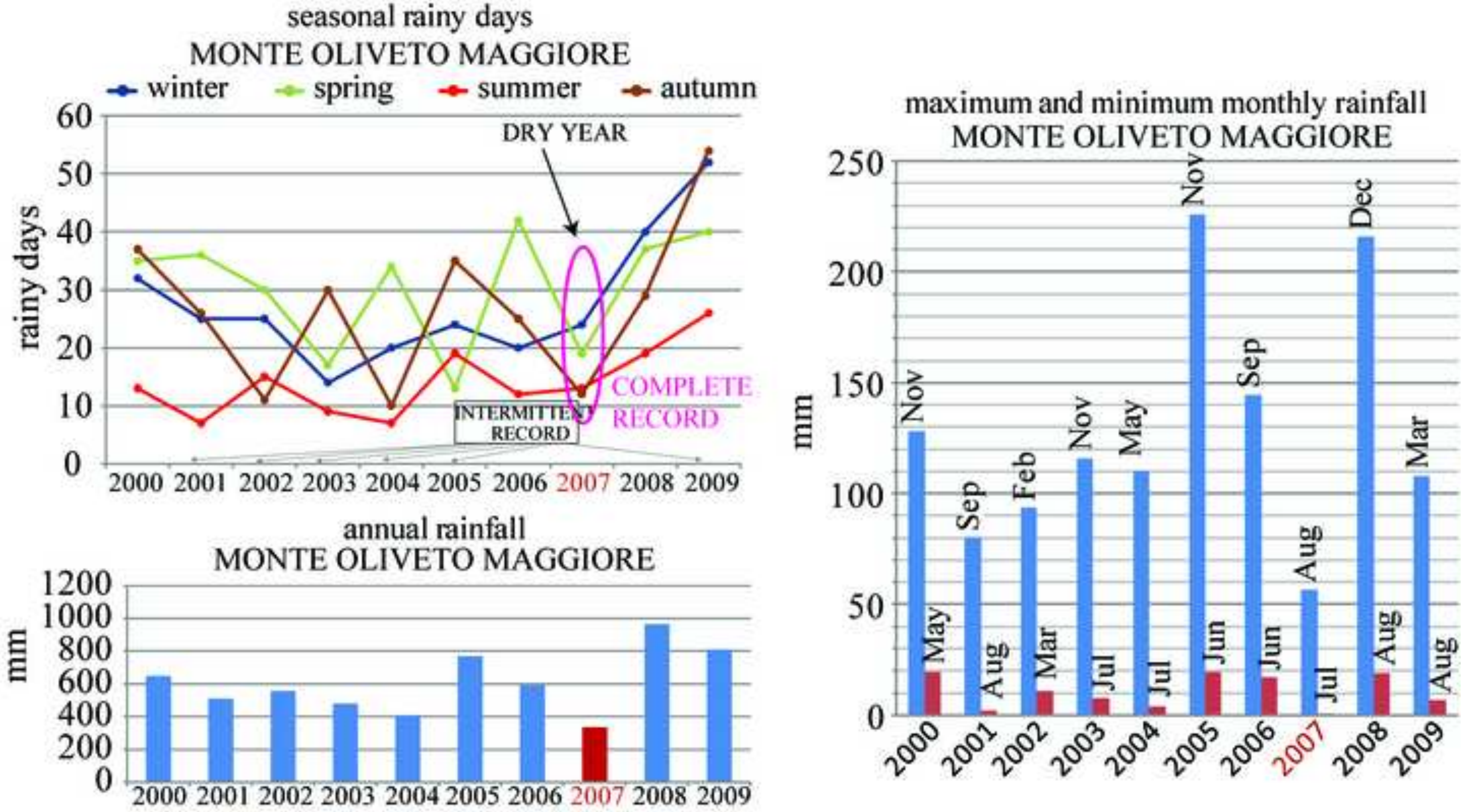
seasonal rainy days
MONTE OLIVETO MAGGIORE
winter
spring
summer
autumn
rainy days
60
50
40
30
20
10
0
DRY YEAR
COMPLETE RECORD
INTERMITTENT RECORD
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009
annual rainfall
MONTE OLIVETO MAGGIORE
mm
1200
1000
800
600
400
200
0
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009
maximum and minimum monthly rainfall
MONTE OLIVETO MAGGIORE
mm
250
200
150
100
50
0
Nov May
Sep Aug
Feb Mar
Nov Jul
May Jul
Nov Jun
Sep Jun
Aug Jul
Dec Aug
Mar Aug
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009

Figure 10

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