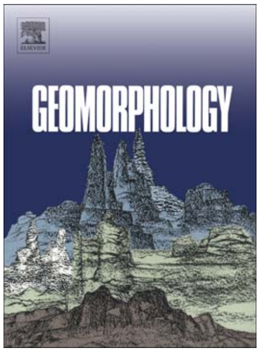

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Dendrogeomorphic analysis of Flash Floods in a small ungauged mountain catchment (Central Spain)

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Abstract

Flash floods represent one of the most significant natural hazards with serious death tolls and economic damage at a worldwide level in general and in Mediterranean mountain catchments in particular. In these environments, systematic data is often lacking and analyses have to be based on alternative approaches such as dendrogeomorphology. In this study, we focus on the identification of flash floods based on growth disturbances (GD) observed in 98 heavily affected Mediterranean pine trees (*Pinus pinaster* Ait.) located in or next to the torrential channel of the Pelayo River in the Spanish Central System. Flash floods are quite common in this catchment and are triggered by heavy storms, with high discharge and debris transport rates favoured by high stream gradients. Comparison of the anomalies in tree morphology and the position of the trees in the channel showed that the intensity of the disturbance clearly depends on geomorphology. The dating of past flash flood events was based on the number and intensity of GD observed in the tree-ring series and on the spatial distribution of affected trees along the torrent, thus allowing seven flash flood events during the last 50 years to be dated, namely in 1963, 1966, 1973, 1976, 1996, 2000, and 2005.

Keywords: dendrogeomorphology; flash flood frequency analysis; tree-ring; mountain catchment; Spain.

1. Introduction

Flash floods are localized hydrological phenomena occurring in small catchments of a few to a few hundred square kilometres, with response times typically being a few hours or less (Borga et al., 2007). As a result, they represent one of the most significant natural hazards with serious death tolls and economic damage at a worldwide level in general (Scheuren et al., 2008) and in Mediterranean mountain catchments in particular (Gaume et al., in press).

Flash flood analysis in Mediterranean mountains poses specific scientific challenges. On one hand, lack of information on precipitation and discharge is significant because of a lack of spatially well-distributed rain or flow data with series that are sufficiently long (i.e. > 30 years). On the other hand, flow gauge stations may not record correctly during extreme events because they are often damaged by the event or because discharge exceeds the recordable level. As a result, systematic data is not available; and prevents enhancement of our understanding of the spatial and temporal occurrence of the process. The analysis of growth-ring series of trees affected by past flash floods (i.e., dendrogeomorphology) can provide an alternative and complementary approach (Yanosky and Jarrett, 2002). Dendrogeomorphology represents one of the most precise and accurate methods for the dating of various geomorphic processes (Alestalo, 1971; Shroder, 1978; Stoffel and Bollschweiler, 2008) and enables the determination of incidences with at least yearly precision. Dendrogeomorphology has also been used to date past flood events in North America (Yanosky, 1999; Bégin, 2001; St. George and Nielsen, 2003) and eastern Europe (Zielonka et al., 2008), but the method has neither been applied so far in the Mediterranean region nor to reconstruct undocumented flash flood events.

Therefore, the aim of this paper is to date past flash flood events in order to improve frequency analysis and hazard estimation. We focus on the identification of flash floods based on growth disturbances in heavily affected trees located in or next to the torrential channel of the Pelayo River in the Spanish Central System and present (i) a detailed geomorphic map (1:1 000) of the torrent; (ii) an analysis of the relation between geomorphology and external tree disturbances; and (iii) a tree-ring-based dating of past flash flood events.

2. Study Site

The study presented in this paper was conducted within the channel and on the lateral banks of the Pelayo River, a torrent with a length of 10 km and a catchment area of 20.6 km^2 that is located on the southern slopes of the Gredos Mountain Range (Spanish Central System; Fig. 1). The torrent originates at 2300 m asl and crosses the village of Guisando (765 inhabitants, 40º13'49" N., 5º9'38" W.; 764 m asl) and two recreational areas (Luis Manuel López Camp and Los Galayos Camping). At 500 m asl, the torrent merges with the Arenal River, a tributary of the Tagus River. The main morphometric characteristics of the study site are summarized in Table 1.

The climate at the study site is continental Mediterranean and vegetation consists of the Mediterranean forest. It is characterized by Mediterranean pine (*Pinus pinaster* Ait.), oak (*Quercus*), chestnut (*Castanea),* walnut (*Juglans*), and hazel (*Corylus*). The altitude in this zone ranges from 800 to 1600 m asl; the annual average temperature varies from 8 to 12ºC; and the zone is characterized by abundant rainfall. In fact, the average annual rainfall amounts to 2000 mm. Geology consists of Upper Palaeozoic plutonic and metamorphic bedrock and surficial Quaternary formations (colluvium and weathering mantles) made up of conglomerates, gravels, and sands.

Flash floods are common in the Pelayo River catchment and are favoured by heavy storms and the high stream gradient, which make extremely high discharge and debris transport rates possible. Meteorological data are available from the “El Risquillo” station located in the lower part of the catchment (05º09´ W., 40º13´ N.; 766 m asl.). In contrast, for this torrential system, flow data is not available.

3. Material and methods

The methods applied in this study are outlined in Fig. 2 and can be divided into three main sections, namely: (i) field procedures; (ii) tree-ring and field data analyses; and (iii) flash flood reconstruction.

3.1. Geomorphic mapping

The geomorphic analysis of the torrential system was carried out applying physiographic and morphometric mapping methods, interpretation of aerial photographs taken in 2007 (Plan Nacional de Ortofotografía Aérea, PNOA), and field verification.

Physiographic units (i.e., high steep slopes, low steep slopes, and piedmont) of the Pelayo River catchment have been defined based on several thematic factors, such as altitude, geology, vegetation, and land use.

Morphometric elements have been classified as slope or torrential elements, but the focus was clearly on torrential landforms. Based on the classification suggested by Cenderelli and Cluer (1998), we distinguish five types of gravel bars: (i) medial-longitudinal gravel bars with equal size channels on both sides of the bar; (ii) longitudinal-lateral gravel bars with a main or external channel on one side and an internal or secondary channel on the other side; (iii) lateral-point gravel bars, where the bar is close to the river banks and a secondary channel; (iv) transverse-diagonal gravel bars with one main channel and a secondary channel active during flash floods; and (v) levees (i.e., natural deposits on the river banks). The type and number of bars were noted in the field, their area calculated, and the spatial distribution of bars along the channel analyzed.

3.2. Analysis of external disturbances and sampling strategy

Flash floods may affect the morphology of a tree in different ways, leading to different growth responses in the tree-ring series (Stoffel and Bollschweiler, 2009). The most frequent disturbances and associated reactions in trees growing inside or adjacent to flash flood torrents are shown in Figs. 3 and 4: flash floods may (i) tilt the stems of trees growing in the river, on gravel bars, or river banks through the unilateral pressure of the flow or through the impact of individual boulders (Braam et al., 1987; Fantucci and Sorriso-Valvo, 1999; Stoffel et al., 2005); (ii) expose roots as a result of river bank or gravel bar erosion (Lamarche, 1968; Carrara and Carroll, 1979; McAuliffe et al., 2006); (iii) remove the bark from the stem and injure the cambium from the impact or the abrasion of boulders and wood transported in the flow (Sachs, 1991; Larson, 1994; Bollschweiler et al., 2008); or (iv) sheared off trees and cause the formation of candelabra growth following severe impact by boulders (Butler et al., 1987; Shroder and Butler, 1987).

The sampling strategy was based on these external evidence of flash flood activity in trees. We selected a total of 98 *P. pinaster* that were influenced by flash floods and were located within the channel, on the gravel bars, or on the banks of the Pelayo River. In addition, 16 undisturbed trees were selected in the medium and upper reaches of the valley slopes in order to obtain a reference chronology representing local growth conditions.

For each tree sampled, additional information was noted, such as (i) determination of its coordinates using a GPS; (ii) its geomorphic position; (iii) its position with respect to neighbouring trees; (iv) description of the growth disturbances (GD); (v) tree diameter; (vi) tree height; and (vii) the position of cores sampled. We extracted increment cores using increment borers (Grissino-Mayer, 2003) with a length of 40 and 60 cm (internal diameter in both cases: 5.5 mm).

Two cores were usually sampled per tree, one in the flow direction of flash floods and one from the opposite side. In trees with exposed roots or buried stem bases, samples were taken as close to the ground as possible in order to obtain the largest number of tree rings. In the case of tilted trees, two cores were extracted at the height of the maximum bend, where compression wood was most likely to be present. Finally, at least three cores were selected in trees with visible injuries: two samples from the lateral edges of the injury where signs of the impact were visible in the tree-ring series but where no rings were missing because of abrasion. In addition, one more sample was taken from the opposite side of the stem. In the case of the undisturbed trees, two cores were extracted perpendicular to the slope direction and as close to ground level as possible.

A total of 269 increment cores were collected in the field: 241 samples from the 98 disturbed *P. pinaster* trees growing within the active channel or in its vicinity as well as 28 cores from the 16 undisturbed reference trees.

3.3. Tree-ring analysis

Samples collected from the disturbed and undisturbed trees were analyzed in the laboratory using the standard methods described by Stoffel and Bollschweiler (2008): After air-drying the samples and preparing the core surfaces (polishing), we counted tree rings and measured ring widths using a digital LINTAB positioning table coupled to a Leica stereomicroscope and TSAPWin 4.6 software (Time Series Analysis and Presentation; Rinntech, 2010). This program also allows the representation of measured tree-ring series, as well as cross-dating and quality checks of the growth curves. Ring widths were measured with an accuracy of 1/100 mm. Increment curves of the disturbed trees were then cross-dated with the reference chronology (Rinntech, 2008) in order to correct faulty tree-ring series derived from disturbed samples (e.g., false or missing rings) and to determine initiation of abrupt growth suppression or release. Furthermore, samples were analyzed visually, and tree rings showing compression wood or callus tissue were noted in a dedicated file.

3.4. Dating of flash flood events

The dating of past flash flood events was based on (i) the GD observed in the tree-ring series (i.e., abrupt growth suppression or release, compression wood, eccentric growth, callus tissue, and injuries); (ii) the intensity of the GD signal in the tree-ring record; (iii) the overall number of trees affected by an event; as well as (iv) on the spatial distribution of affected trees along the torrent.

The different parameters were then quantified and specific weights (wGD from 0.1 to 1) were assigned to the different GD (Table 2). The number of trees affected in a particular year and the trees being present for analysis in the same year were then used to derive the percentage of damaged trees (%DT). The spatial distribution of affected trees in the torrent (SD) was attributed a value of 1 in the case of heterogeneous distribution (i.e., several trees that were concentrated in the same area), and a value of 2 was chosen for homogeneous distribution (i.e., trees evenly spaced along the torrent).

The product of these parameters (wGD × %DT × SD) was then used to date past flash flood events; and event years were, in addition, tested for significance using the non parametric Wilcoxon-Mann-Whitney test.

4. Results

4.1. Geomorphic characteristics

Geomorphic mapping on a scale of 1:1000 enabled identification of 67 gravel bars in the torrent, 32 secondary and flooding channels, 99 mass movements and slope deposits, and 4 physiographic units (Fig. 5).

From the 67 gravel bars identified in the study reach, we note a predominance of medial-longitudinal, lateral-longitudinal, or lateral-point gravel bars and a scarcity of transverse-diagonal gravel bars or levees (Table 3).

The spatial distribution of gravel bars changes along the torrent (Table 4). In the upper part, medial bars are more abundant (60% of medial bars are located in this part of the reach); whereas lateral point gravel bars are most significant in the central part of the study site (52% of observed point bars are located in this part).

4.2 Relation between geomorphology and tree disturbance

Thereafter, external disturbances in trees were related with tree positions in the channel. A total of 208 macro disturbances in tree morphology were identified in the 98 *P. pinaster* trees (Table 5). Several signs were normally observed per tree sampled, with tilted trunks (96%), exposed roots (62%), and bark erosion (23%) being the most common features observed. In contrast, apex decapitation (5%) or stem burial (7%) were only occasionally found.

A comparison of the macro disturbances in tree morphology with geomorphic positions of the trees sampled (Table 5) clearly shows that the intensity of disturbance depends on geomorphology. Trees are most heavily affected at the external margins of lateral bars (lateral-longitudinal and lateral-point bar) and become gradually less perturbed as soon as they stand on banks, margins of medial-longitudinal bars, internal curves of meanders, head bars, and internal margins of lateral bars.

Table 5 also shows that a majority of trees with the most energetic disturbances (i.e., stem tilting or exposed roots) are located in the zones with greatest stream power and most significant geomorphic work (i.e., banks and external margin of lateral bars). For instance, trees with tilted stems are located in different geomorphic settings, but their relative number clearly increases with the increasing process energy involved. The relation between the energy of the external evidence and the geomorphic sides is shown in Figure 6.

Figure 6 shows a good relation between the most significant disturbances in tree morphology and the most energetic geomorphic tree positions within the channel. As a general rule, the relative number of tilted trees (floating or exposed roots) increases with increasing process energy. In the case of apex decapitation (bark erosion or stem burial) different peaks can be observed; and the relative number of disturbances in tree morphology does not seem to increase linearly with increasing process energy.

4.2. Growth disturbances

Tree-ring counting of the flash flood affected trees enabled an assessment of tree age and their distribution along the torrent (Fig. 7). The trees used in this study are on average 38 years old (STDEV: 22 years). The oldest tree sampled attained sampling height in A.D. 1869 and the youngest tree sampled in 1998. The upper sector of the torrent contains the youngest trees.

A total of 280 GD could be detected in the tree-ring series of the disturbed trees (Table 6), most frequently in the form of growth decreases (present in more than 70% of the samples). Injuries and callus tissue were, in contrast, scarce and only observed in 7% of the samples.

4.3. Dating of flash flood events

The dating of past flash flood events was based on specific weights and the product of GD. The percentage of trees affected and the distribution of affected trees is shown in Table 7. In total, GD are observed in 22 different years since A.D. 1943. Based on the Wilcoxon test (95% confidence interval) and *p* 0.04, we consider seven of the years with GD as flash flood years namely: 1963, 1966, 1973, 1976, 1996, 2000, and 2005.

Based on the tree morphology and the GD in the tree-ring series, the evidence is good for the existence of events in the other years as well, but the small number of trees available for analysis did not allow them to be considered events with equal confidence. One example is the year 1989, where the confidence interval is lower but significant. The spatial distribution of trees affected in particular years is shown in Fig. 8.

5. Discussion

In the present study, 98 *P. pinaster* trees affected by flash floods have been analyzed with 241 increment cores to reconstruct flash flood events at Pelayo River (Spanish Central System) covering the past 50 years. While the time covered by this reconstruction is much shorter compared to other, non-Mediterranean environments (e.g., Stoffel et al., 2008; Mayer et al., in review.), our study clearly shows the potential of flash flood analyses based on information contained in growth-ring series of affected trees. Tree-ring analysis was complemented with detailed geomorphic mapping focusing on gravel bar formation according to the classification of Church and Jones (1982) and Cenderelli and Cluer (1998). The spatial distribution of the gravel bars changes along the torrent. The proximal-distal ocurrence of channel bars follows the schematic diagram proposed by Church and Jones (1982). In very high flows, like in the present case, sediment is mobilized from the channel and flow resistance is accordingly modified when the greatest water and sediment loads are transported through the channel.

In an attempt to foster our understanding of flash flood impact on trees, we compared the intensity of dendrogeomorphic evidence on the stem surface with the tree position relative to the channel. Results are qualitative and indicate that damage intensity would clearly depend on the position of the tree within or next to the flash flood channel. Specific weights were determined for different dendrogeomorphic GD following the procedures of Fantucci (2007) or Fantucci and Sorriso-Valvo (1999). However, and because of the climate sensitivity of *P. pinaster* (Alia et al., 1996; Blanco et al., 1997), we had to adapt the weights suggested by the aforementioned authors and define intensities of reactions specific for *P. pinaster*. The use of weights, the quantification of these parameters, and the coefficient of confidence are new in dendrogeomorphic research and represent a valuable tool for the definition of flash flood events in Mediterranean catchments.

Although it represents a widespread species of the Mediterranean landscapes, notably *P. pinaster* has rarely been used for dendrochronologic studies. This is mainly because stands older than 100 years are very difficult to find. In addition, most trees from the lower mountain level have been wounded artificially for resin extraction in the past (Bogino and Bravo, 2008), which makes them of limited use for any kind of dendrogeomorphic research. Provided that we manage to distinguish the disturbances caused by resin extractors from those caused by flash floods at a wood-anatomical level (Ballesteros et al., 2010), it might possible to use these artificially damaged but generally much older trees in future research as well.

We must also stress that dendrogeomorphic reconstructions always yield minimum frequencies of events. This means that the events dated in this study represent individual flash floods of the Pelayo River of the last 50 years, but that the period between two reconstructed events does not necessarily need to be without flash floods (Zielonka et al., 2008). The dated events presented in this study are well represented, and we are very confident about these flash floods because (i) GD related to specific events were identified in a large number of trees, (ii) trees affected were homogenously distributed along the channel reach studied, and (iii) the intensity of the flash flood “signature” was strong in a large set of trees.

In addition, we also identify years with a more limited number of primarily weak signatures, such as in 2003, 1999, 1997, 1990, 1970, and 1956. Based on the reactions observed in the tree-ring series, we assume that these GD would be the result of flash floods as well. In some cases, the tree-ring signatures appear to be weak because of strong tree responses in the growth-ring series resulting from preceding events.

For other years, as e.g., 1989, neighbouring catchments registered intense flash flood events (Ballesteros et al., 2010) that make the presence of a simultaneous event in the Pelayo River more probable. Another limitation of dendrogeomorphic work based on *P. pinaster* becomes obvious for the possible event of 1999, when late and weak GD were preferably added to an event in 2000 for which several injuries could be used for accurate dating of a high intensity event.

Based on the above considerations, we believe that there are two types of flash flood events at Pelayo River: on one hand, we identify flash floods characterized by high magnitude but low frequency. These events are capable of causing major damage to the vegetation and could be reconstructed in the growth-ring series of a large number of trees. On the other hand, we identify a second type of event of smaller magnitude and higher frequency, but still large enough to occasionally cause less severe damage to the vegetation. Such a separation of higher frequency–lower magnitude from lower frequency–higher magnitude events may improve magnitude-frequency analysis of flash floods and hazard estimation in the future.

6. Conclusions

This paper clearly illustrates the strength of dendrogeomorphology in flash flood analysis and documents how dating of past events can be improved in areas where the lack of historical documents, rainfall, and discharge data prevents the use of traditional methods. In addition, the detailed analysis of geomorphology and GD in trees also revealed that a good correlation exists between the energy of geomorphic processes and forms and the energy necessary to cause the damage observed in the trees. Based on these parameters we were able to date seven well represented, larger magnitude flash flood events and seven weak intensity events over the last 50 years.

The use of weights and coefficients of confidence is new in dendrogeomorphic research and represents a valuable tool for the definition of flash flood events, as they provide the primary data necessary for the determination of flash flood frequency and for the realization of hazard estimations in ungauged Mediterranean mountain catchments.

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List of Figures

Fig. 1. (A) Location of the study area in the Gredos Mountain Range (Spanish Central System); (B) overview of the Pelayo River catchment and the study site of this analysis; (C) the Pelayo River at Guisando village during normal conditions and (D) during the flash flood event in December 2008 (picture of 2008 flash flood event, courtesy of Gloria Suarez García, used with permission).

Fig. 2. Flow diagram illustrating the different analysis methods applied, from the data sources to the results.

Fig. 3. Predominant dendrogeomorphic macro-evidence in trees affected by flash floods and associated responses in tree-ring width and cell structure: (A/D) root exposure; (B) sheared off tree and candelabra growth; (C) stem tilting; (B/C) injuries.

Fig. 4. External evidence of flash flood activity in trees growing along the Pelayo River: (A) abrasion scars; (B) bark erosion; (C) stem tilting; (D) stem burial; (E) floating roots; (F) exposed roots. The blue arrows indicate the flow direction.

Fig. 5. Geomorphological mapping of the upper part of the study reach. The legend shows the classification of units and elements.

Fig. 6. Relation between the energy of the external evidence and the geomorphic sides. Ball size represents the percentage of trees showing a specific disturbance located in a specific geomorphic side related to the total number of trees showing that disturbance. The legend may be checked in Table 5.

Fig. 7. Age structure of the sampled trees in the torrent. Left: upper sector of the study reach. Right: lower sector.

Fig. 8. Spatial distribution of living and damaged trees of four dated events.

List of Tables:

Table 1

Morphometric characteristics of the catchment and the study reach

Morphometric characteristics	
Area	20.6 km^2
Average slope	16°
Elevation range	2300-500 m asl
River longitude	6 km
Study reach longitude	2.5 km
Elevation range of study reach	1300-900 m asl
Main Aspect	SE

Table 2

Weights used for the quantification of different growth disturbances with different intensities[a]

Growth disturbances (GD)	Weights (wGD)
Injury	1
Intense growth decrease	0.75
Intense compression wood	0.5
Intense growth release	0.5
Weak growth decrease	0.5
Intense eccentric growth	0.25
Weak compression wood	0.25
Weak growth release	0.25
Weak eccentric growth	0.1

[a] Intense means that the GD is well recognizable directly in the increment core, and weak means that the GD is hardly recognizable directly, but well recognizable with the help of a magnifying glass and the disturbed growth curves.

Table 3

Types of gravel bars and area (absolute and relative) in the study reach

Bar Type	Number	Area (km^2)	%Area / %Total
Medial-longitudinal	23	1.27	14.94
Longitudinal-lateral	18	0.7	8.24
Point bar	19	0.47	5.53
Levees	5	0.4	4.71
Transverse-diagonal	2	0.07	0.82

Table 4

Spatial distribution of bars along the studied reach (upper, central, and lower part) (values are given per gravel bar type)

Bar Type	Upper	%	Central	%	Lower	%
Medial-longitudinal	14	60.87	5	21.74	4	17.39
Longitudinal.-lateral	10	55.56	5	27.78	3	16.67
Point bar	4	21.05	10	52.63	5	26.32
Levees	4	80.00	0	0.00	1	20.00
Transverse-diagonal	2	100.00	0	0.00	0	0.00

Table 5

Trees showing external disturbances and located in different geomorphic settings[a]

Geomorphology		Medial Bars			Lateral Bars				Main Channel		Sec. Channel		Conf.	Banks	Subtotal	Total	%
Evidence	Side/ Element	M	TB	HB	EM	IM	TB	HB	EC	IC	SR	EC					
Stem burial	C-D	1			1	2		1		2					7	7	7.14
Bark	A-B	1	1		2	1				2				1	8	23	23.47
erosion	C-D				4	2			1	2				6	15		
Exposed	A-B	3			8	1	6	5	1	1		1	1	11	38	61	62.24
roots	C-D	2	1	1	5	2		3		3		1		5	23		
Floating	A-B	2			1	1	1								5	17	17.35
roots	C-D	2		1	4		1	1		1				2	12		
Tilted	A-B	4		1	6	1	1	4		3	1		1	6	28	95	96.94
stem	C-D	4	1	5	15	3	9	6	1	2	2		1	15	64		
Injuries	C	2			2			2					1	2	9	9	9.18
Sheared off	-			1	1		1	1						1	5	5	5.10

Total	-	21	3	9	49	13	19	23	3	16	3	2	4	49	214	-	-

[a]Gravel bars are grouped in medial (medial-longitudinal) and lateral (including lateral-longitudinal. lateral-point and transverse-diagonal bars). Abbreviations: HB: head of bar; TB: tail of bar; M: margin; EM: external margin; IM: internal margin; SR: straight reach; EC: external curve of a meander (i.e. undercut slope); IC: internal curve of a meander (i.e., slip-off slope); C-D. disturbance in the flow direction. and A-B. disturbance perpendicular to the flow direction.

Table 6

Absolute and relative number of growth disturbances observed in the 98 *P. pinaster* trees

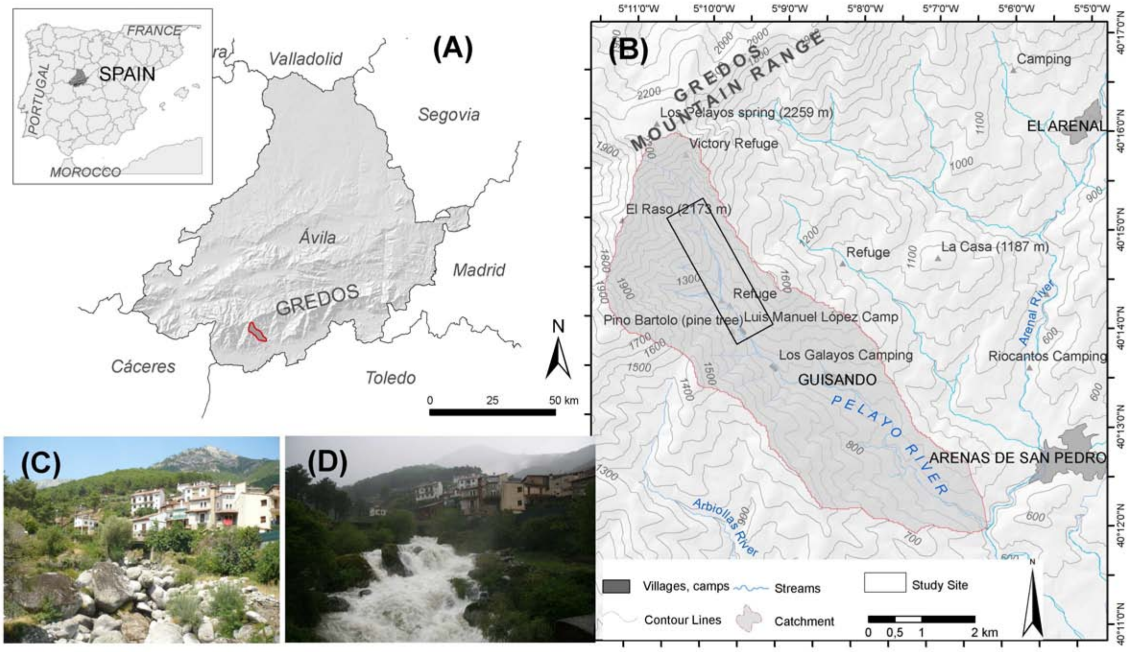
Growth Disturbances (GD)	Samples	%
Growth decrease	165	70.81
Growth increase	42	18.02
Eccentric growth	26	11.16
Reaction wood	30	12.87
Injury/callus tissue	17	7.30

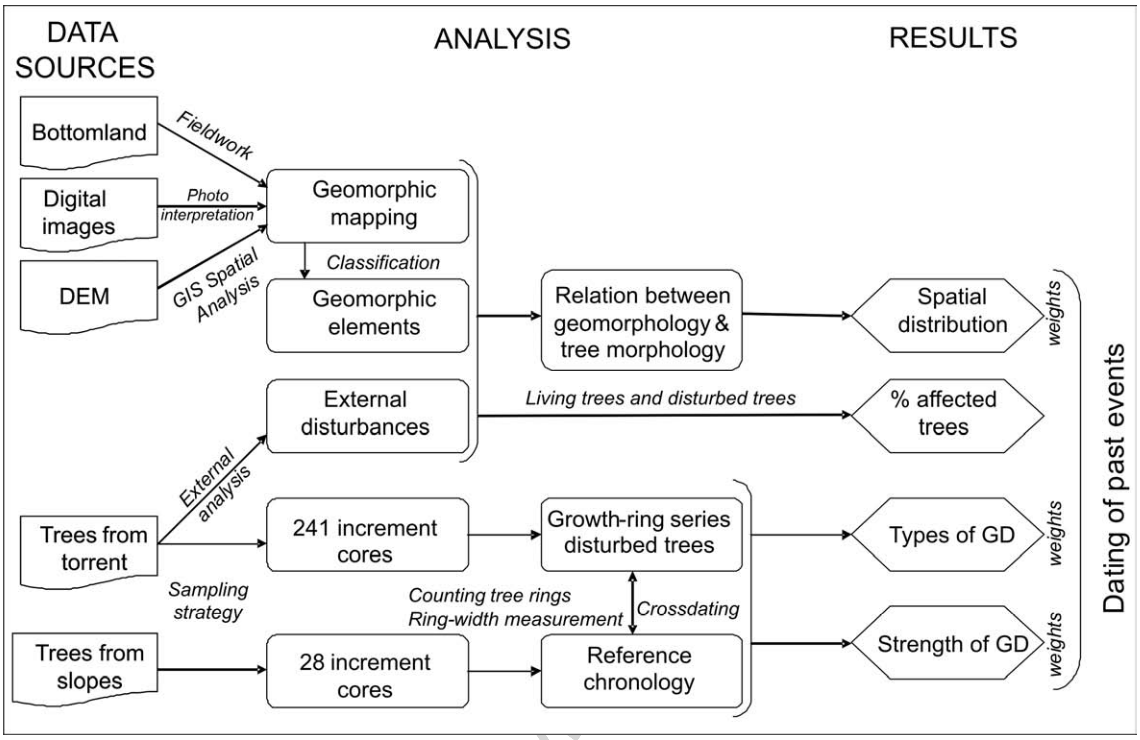
Table 7

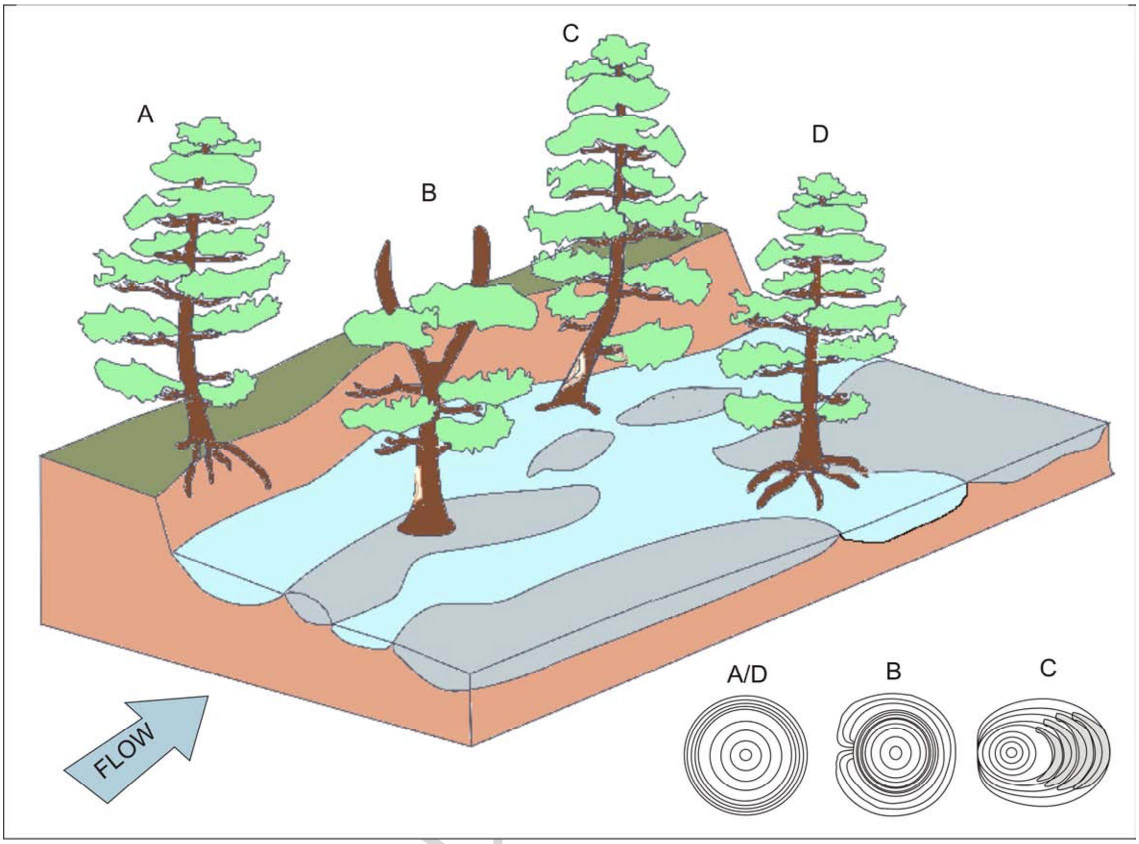
Calendar year, damaged trees, living trees, percentage of damaged trees, weight values for the detected growth disturbances, weight for the spatial distribution along the torrent, and the calculated coefficient of confidence

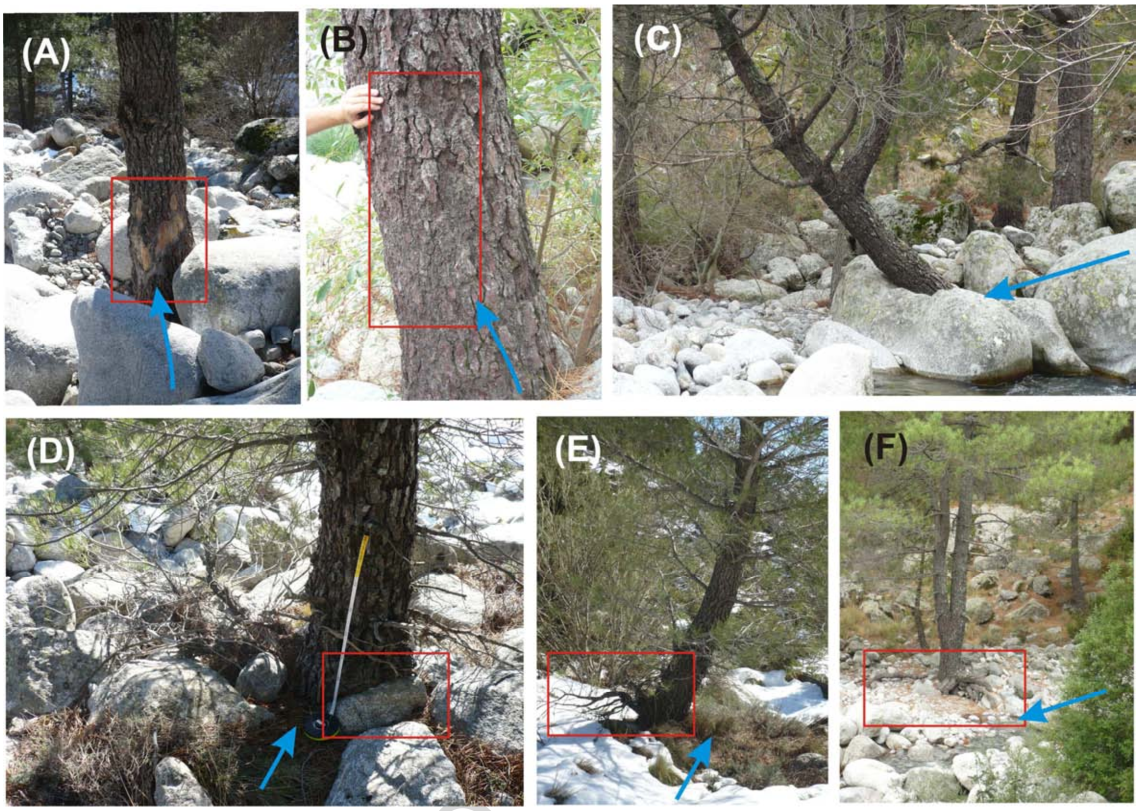
Calendar year	Damaged trees (DT)	Living trees (LT)	% Damaged trees (%DT)	Weight of GD (wGD)	Spatial distribution (SD)	%GDxsGDxHD
1943	1	5	20.00	0.75	1	15.00
1944	1	5	20.00	0.75	1	15.00
1954	2	14	14.29	1	1	14.29
1956	3	16	18.75	1	1	18.75
1963	6	26	23.08	1.5	2	69.23
1964	2	26	7.69	0.75	1	5.77
1966	7	26	26.92	4.35	2	234.23
1970	4	43	9.30	1.35	1	12.56
1971	2	43	4.65	1.25	1	5.81
1973	4	46	8.70	2.35	2	40.87

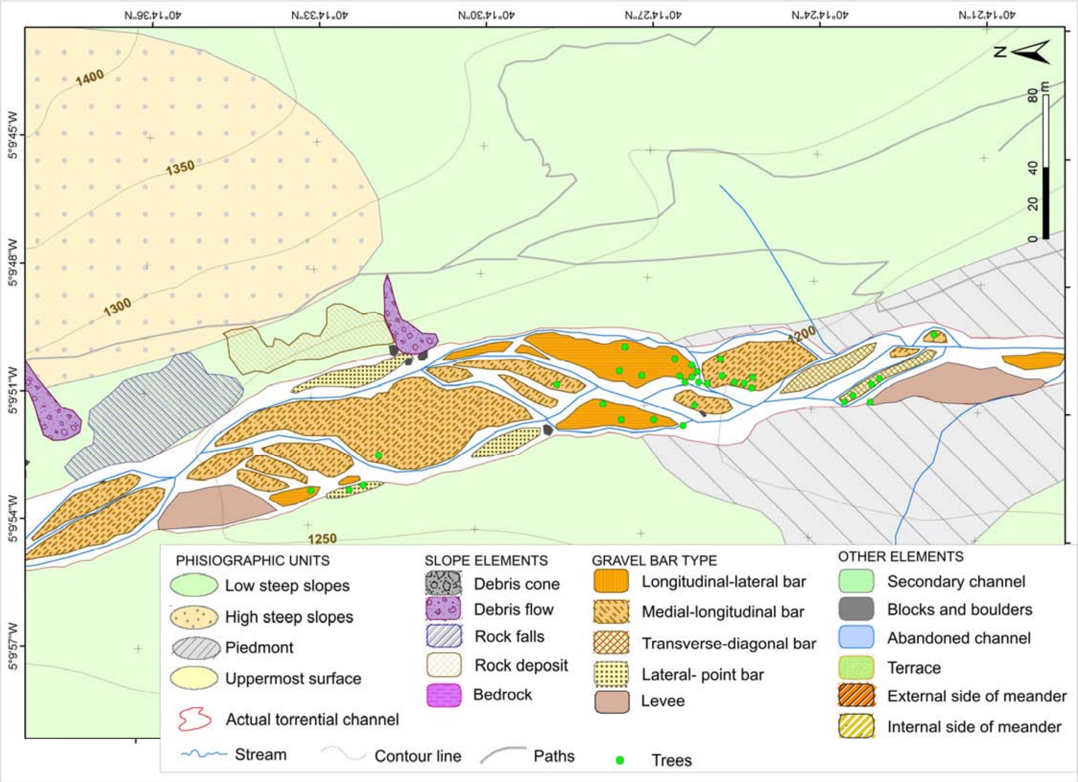
1976	7	50	14.00	3.6	2	100.80
1984	2	63	3.17	1	1	3.17
1989	5	79	6.33	2.1	2	26.58
1990	3	80	3.75	2	1	7.50
1992	5	90	5.56	1	1	5.56
1996	15	93	16.13	4.5	2	145.16
1997	4	94	4.26	1.75	1	7.45
1999	4	94	4.26	2.5	1	10.64
2000	36	94	38.30	21.5	2	1646.81
2003	3	94	3.19	2.25	1	7.18
2005	6	94	6.38	6.5	2	82.98
2007	3	94	3.19	3	1	9.57

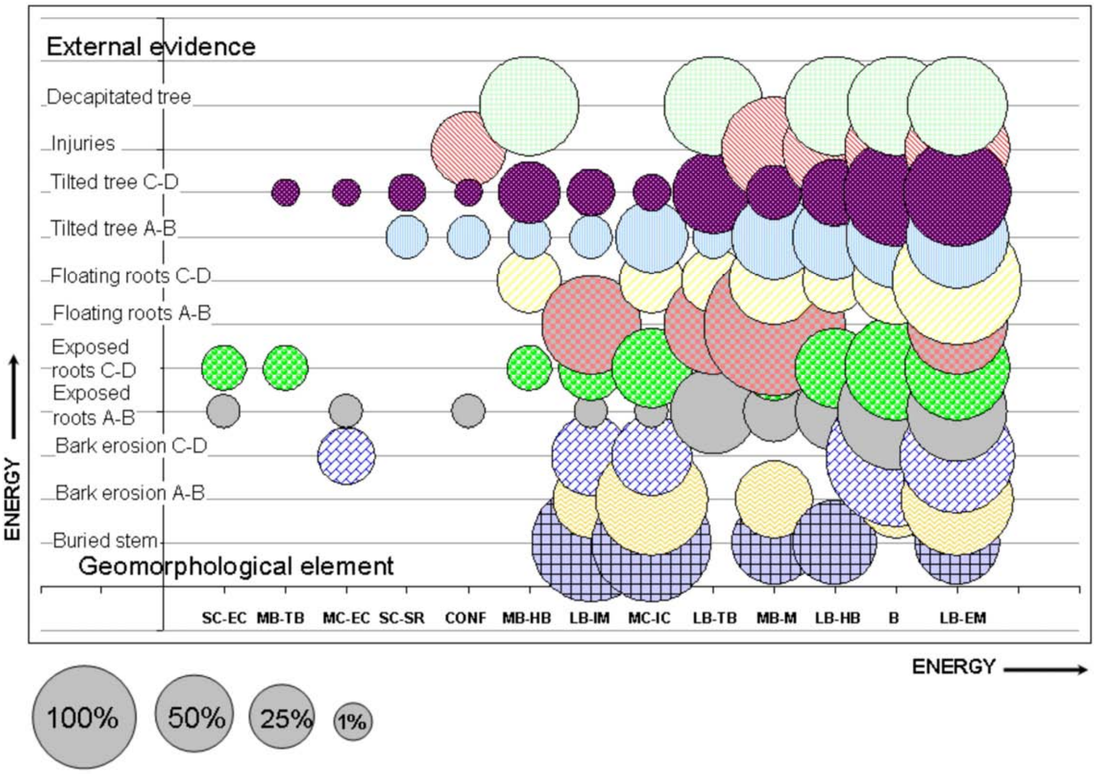

(A)
FRANCE
SPAIN
PORTUGAL
MOROCCO
Valladolid
Segovia
Ávila
Madrid
GREDOS
Cáceres
Toledo
N
0 25 50 km
(B)
5°11'0"W
5°10'0"W
5°9'0"W
5°8'0"W
5°7'0"W
5°6'0"W
5°5'0"W
40°17'0"N
40°16'0"N
40°15'0"N
40°14'0"N
40°13'0"N
40°12'0"N
40°11'0"N
GREDOS MOUNTAIN RANGE
Los Pelayos spring (2259 m)
Victory Refuge
El Raso (2173 m)
Refuge
Pino Bartolo (pine tree)
Luis Manuel Lopez Camp
Los Galayos Camping
GUISANDO
Camping
EL ARENAL
La Casa (1187 m)
Arenal River
Riocantos Camping
PELAYO RIVER
ARENAS DE SAN PEDRO
Arbiollas River
Villages, camps
Streams
Study Site
Contour Lines
Catchment
0 0,5 1 2 km
N
(C)
(D)

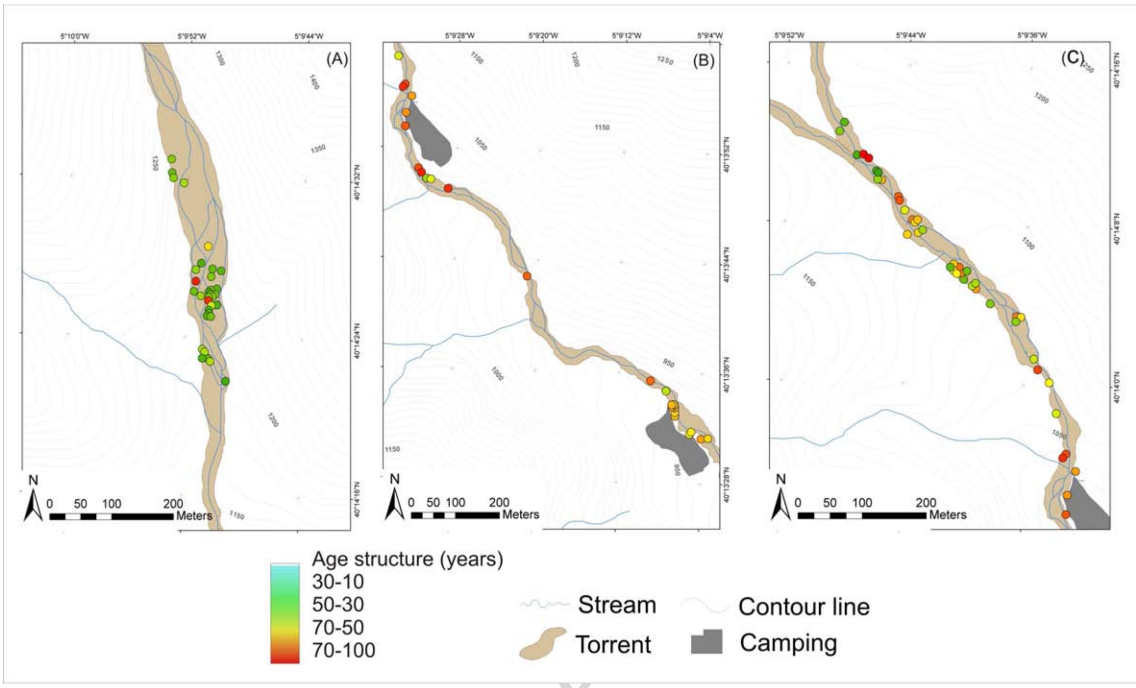

DATA SOURCES
ANALYSIS
RESULTS
Bottomland
Fieldwork
Digital images
Photo interpretation
DEM
GIS Spatial Analysis
Geomorphic mapping
Classification
Geomorphic elements
Relation between geomorphology & tree morphology
Spatial distribution
weights
External disturbances
Living trees and disturbed trees
% affected trees
Dating of past events
External analysis
Trees from torrent
241 increment cores
Growth-ring series disturbed trees
Types of GD
weights
Sampling strategy
Counting tree rings
Ring-width measurement
Crossdating
Trees from slopes
28 increment cores
Reference chronology
Strength of GD
weights

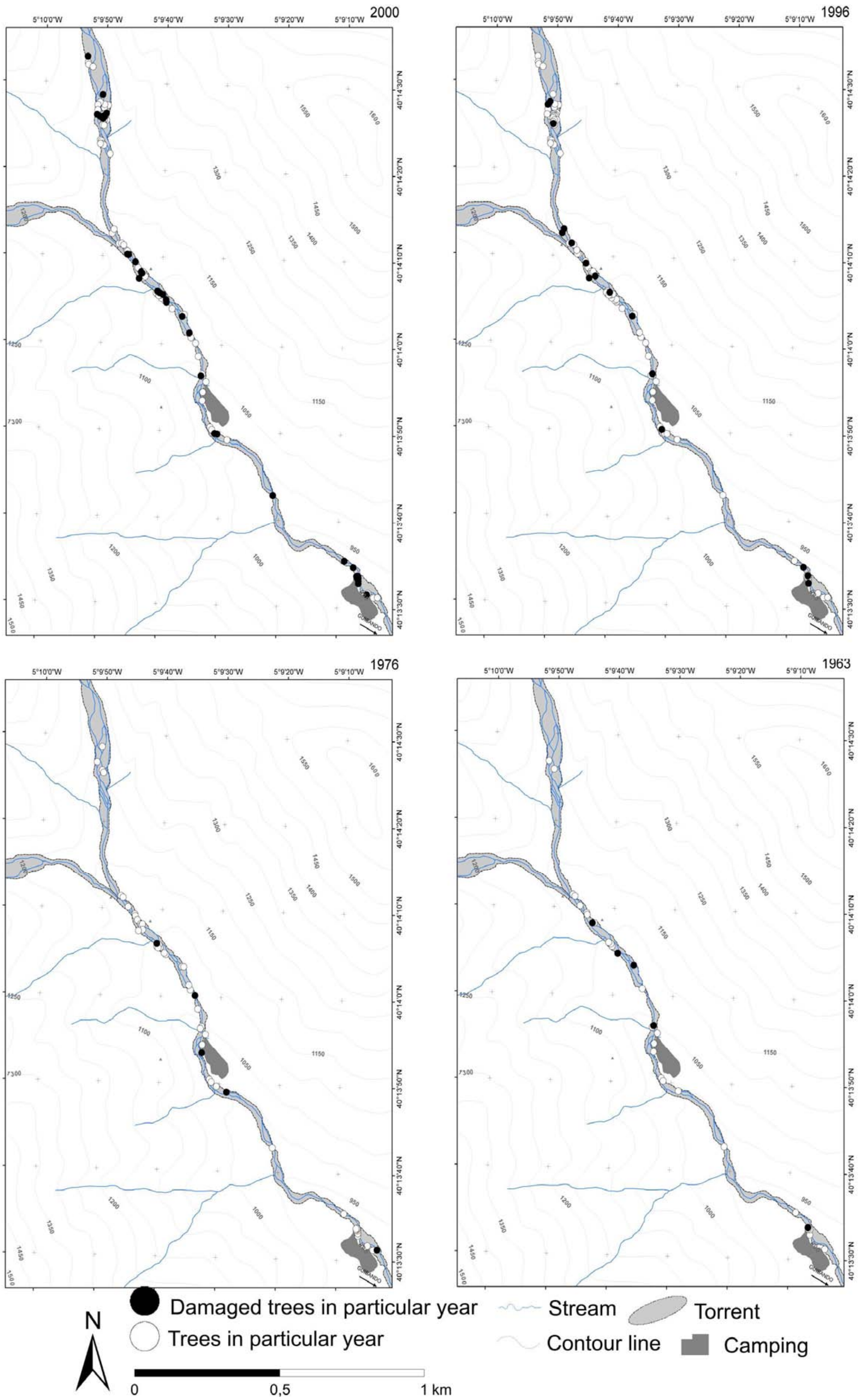

A
B
C
D
FLOW
A/D
B
C


(A)
(B)
(C)
(D)
(E)
(F)


40°14'36"N
40°14'33"N
40°14'30"N
40°14'27"N
40°14'24"N
40°14'21"N
5°9'45"W
5°9'48"W
5°9'51"W
5°9'54"W
5°9'57"W
N
0 20 40 80 m
1400
1350
1300
1250
1200
PHISIOGRAPHIC UNITS
Low steep slopes
High steep slopes
Piedmont
Uppermost surface
Actual torrential channel
SLOPE ELEMENTS
Debris cone
Debris flow
Rock falls
Rock deposit
Bedrock
GRAVEL BAR TYPE
Longitudinal-lateral bar
Medial-longitudinal bar
Transverse-diagonal bar
Lateral- point bar
Levee
OTHER ELEMENTS
Secondary channel
Blocks and boulders
Abandoned channel
Terrace
External side of meander
Internal side of meander
Stream
Contour line
Paths
Trees


External evidence
Decapitated tree
Injuries
Tilted tree C-D
Tilted tree A-B
Floating roots C-D
Floating roots A-B
Exposed roots C-D
Exposed roots A-B
Bark erosion C-D
Bark erosion A-B
Buried stem
Geomorphological element
ENERGY
SC-EC
MB-TB
MC-EC
SC-SR
CONF
MB-HB
LB-IM
MC-IC
LB-TB
MB-M
LB-HB
B
LB-EM
ENERGY
100%
50%
25%
1%


5°10'0"W
5°9'52"W
5°9'44"W
(A)
1300
1400
1350
1250
1200
1150
40°14'32"N
40°14'24"N
40°14'16"N
5°9'28"W
5°9'20"W
5°9'12"W
5°9'4"W
(B)
1100
1200
1250
1150
1050
1000
950
900
40°13'52"N
40°13'44"N
40°13'36"N
40°13'28"N
5°9'52"W
5°9'44"W
5°9'36"W
(C)
1250
1200
1100
1150
1050
40°14'16"N
40°14'8"N
40°14'0"N
N
0
50
100
200
Meters
Age structure (years)
30-10
50-30
70-50
70-100
Stream
Contour line
Torrent
Camping


2000
1996
1976
1963
5°10'0"W
5°9'50"W
5°9'40"W
5°9'30"W
5°9'20"W
5°9'10"W
40°14'30"N
40°14'20"N
40°14'10"N
40°14'0"N
40°13'50"N
40°13'40"N
40°13'30"N
N
● Damaged trees in particular year
○ Trees in particular year
Stream
Torrent
Contour line
Camping
0
0,5
1 km