Land Management Versus Natural Factors in Land Instability: Some Examples in Northern Spain

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Abstract The objective of this work is to test a hypothesis formulated on the basis of former results which considers that there might be a "global geomorphic change," due to activities related to land management and not determined by climate change, which could be causing an acceleration of geomorphic processes. Possible relationships between some geomorphic processes related to land instability (landslides or sediment generation) and potential triggering factors are analyzed in study areas in northern Spain. The analysis is based on landslide inventories covering different periods, as well as the determination of sedimentation rates. Temporal landslide and sedimentation rate trends are compared with different indicators of human activities (land-use change, logging, forest fires) and with potential natural triggers (rainfall, seismicity). The possible influence of the road network in the distribution of landslides is also analyzed. Results obtained show that there is a general increase of both landslide and sedimentation rates with time that cannot be explained satisfactorily by observed rainfall trends and even less by seismicity. Land-use change appears to be by far the main factor leading to land instability, with some changes producing up to a 12-fold increase of landslide rate. A relationship between road network and the spatial distribution of landslides has also been observed. These results do confirm the existence of an acceleration of geomorphic processes in the region, and also suggest that climate-related factors play a limited role in the changes observed.

Keywords Landslides · Land instability · Sedimentation rates · Land management · Global geomorphic change · Northern Spain

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Introduction

The present contribution deals with the role of some natural and human drivers in processes linked to land instability, denudation, sediment generation, and related sedimentation.

Concern about the role of humans in the transformation of the Earth's surface and its consequences is certainly not new. In 1873, Antonio Stoppani referred to the "Anthropozoic era" and in the early twentieth century Teilhard de Chardin and Vernadsky used the term "Noösphere" (Crutzen 2002). The latter author proposed the establishment of a new geologic epoch, the "Anthropocene," something similar to the proposal by Ter-Stepanian (1988), who used the term "Technogene." In particular, the effect of human action on processes related to denudation, relief evolution, or geomorphic hazards has also been the subject of interest (Marsh 1877; Brown 1956; Wolman and Schick 1967; Costa 1975; Judson 1983; WCED 1987; Douglas 1990; Turner and others 1990; Hooke 1994; Goudie 1995; Slaymaker 2000; Syvitski and others 2005; Bakker and others 2008; Slaymaker and others 2009). However, the

consideration of the modifications described as a process of possible global extent and significance is more recent. The existence of a "geomorphic dimension of global change" was pointed out by Cendrero and Douglas (1996) and later works refer to "global geomorphic change" as a process that should be taken into consideration (Cendrero and others 2006, 2007; Rivas and others 2006; Bonachea and others 2010; Bruschi and others 2012).

The role of human activities in slope instability and denudation has been analyzed in several studies that show an increase of shallow landslides as a consequence of land-use change, mainly due to deforestation or the substitution of forests by grasslands (Haigh and others 1995; Chang and Slaymaker 2002; Glade 2003; Vanacker and others 2003; Meusburger and Alewell 2008). A decrease of landslide occurrence as a consequence of the abandonment of agricultural areas in a study area in the Pyrenees has been described by Beguería (2006). The role of landslides as contributors to sediment generation and related sedimentation rates has also been analyzed (Peart and others 2005; Korup and others 2007; Acharya and others 2009).

The relative role of rainfall and land-use change as landslide triggers in several areas has been studied by different authors (Wasowski 1998; Glade 1998; van Beek and van Asch 2004; Crozier 2005; Piccarreta and others 2006; Wasowski and others 2007). All these studies found that rainfall or rainstorm frequency/intensity changes do not satisfactorily account for the increasing landslide frequency observed. They conclude that land-use changes related to human activity is probably an important factor. On the other hand, Clarke and Rendell (2006) found that in the study area in Southern Italy landslides (and floods as well) show a decreasing trend during the period 1950–1990, roughly parallel to the reduction of the rainfall.

Former work by some of the present authors has shown that different hydrogeomorphic processes seem to have significantly intensified in recent times as a consequence of human activities. Increases of landslide frequency during the twentieth century have been described in areas of northern Spain (González-Díez and others 1996, 1999; Remondo 2001; Remondo and others 2005, 2008; Cendrero and others 2005, 2007; Bonachea and others 2009). Increasing sedimentation rates have been determined in areas with very different morphoclimatic and socioeconomic characteristics, in northern Spain and South America (Remondo and others 2005; Cendrero 2003; Cendrero and others 2005, 2006, 2009; Bruschi and others 2008, 2012; Bonachea and others 2008, 2010). Greater frequency of sinkhole collapse in evaporite terrains has been found in the Ebro valley (Gutiérrez and others 2007; Galve and others 2009). According to the results obtained in those studies, the magnitudes and trends of changes observed in the processes analyzed can hardly be attributed to climate

(i.e., rainfall), seismicity, or other natural triggers. Human influence related to different types of activities appears to be the most likely explanation in all cases.

A conceptual model, considered by the authors as a working hypothesis to express the possible relationship between human activity and geomorphic processes (Cendrero and others 2006), has been tested through the analysis of several study areas within the Rio de la Plata Basin (Bonachea and others 2010) and northern Spain (Bruschi and others 2012). Results obtained by these authors were consistent with the model, and show that the increasing *trend* in the intensity of geomorphic processes does not seem to be due to climate factors. However, this should not be interpreted as meaning that intense rainfall is not a significant triggering factor for geomorphic processes, as shown by several authors (Corominas and Moya 1999; Dai and Lee 2002; Crosta and Frattini 2003; Szabó 2003; Wang and Sassa 2003; Zézere and others 2005). Moreover, common empirical knowledge clearly indicates that processes such as landslides or intense erosion do occur during episodes of intense rainfall. What the results referred to in the former paragraph indicate is that the intensity of those processes is increasing with time, whereas rainfall is not (be it annual precipitation or frequency of intense rainfall episodes). What seems to happen is that the resilience of land surface is decreasing due to changes caused by human activities, thus lowering rainfall thresholds that trigger landslides or produce denudation (Brierly and Stankoviansky 2003).

The above-mentioned hypothesis has important implications for landslide hazard assessments. These imply estimating future frequency of the process, normally on the basis of past frequency (Wieczorek and Glade 2005; Remondo and others 2005, 2008; Bonachea 2006). However, if the model is correct, we should expect future frequency to be considerably greater than the past one. If this is so, most landslide hazard assessments—and probably those for other hydrogeomorphic processes too—might be underestimating future occurrences.

The studies described identify what could be a relationship between indicators of the intensity of human activities in general and the frequency/intensity of landslides and sediment generation, but they did not analyze which activities might be causing the increase of the latter. In this study, data obtained in several study areas during work carried out for former analyses with other aims, together with some new data, are presented and discussed to determine if they confirm the existence of the above-mentioned relationship.

The aim of the work presented here is to analyze to what extent land disturbance caused by certain human activities (land-use change, forestry-related activities, and road network) is having an influence on the intensity of land-

instability processes such as landsliding and sediment generation. To this end, indicators such as landslide frequency and density or sedimentation rates are compared with different indicators of the intensity of human activities, as well as with natural triggers (rainfall and seismicity). As indicated above, there is little doubt about the fact that intense rainfall is the main immediate cause of landslides and sediment generation. What we are trying to see is if the human disturbance is reducing land resilience and producing an acceleration of those processes.

Study Areas

The study areas (Fig. 1) are located on the northern side of the Cantabrian Cordillera, Spain; a mountain range with altitudes over 2,000 m, some 40–60 km from the coast. Slope gradients are therefore high over most of the region often >25°. The climate is oceanic, mild, and humid. Average annual temperature and rainfall vary from 14 °C and 1,200 mm by the coast to 8–9 °C and >2,000 mm in the upper parts of the basins. Rainfall is fairly uniformly distributed through the year. Episodes with intensities >50 mm/24 h occur practically every year. Weathering processes are fairly intense and the regolith layer is well

developed and quite continuous over most of the area (Remondo and others 2005). The conditions described favor the occurrence of landslides, mainly shallow landslides/flows affecting the regolith, an important denudation mechanism in this region.

Analyses were carried out in two basins within this region. The first area is the Lower Deva valley (Fig. 1), which has an extent of about 130 km². This basin is made up of moderately folded and faulted Cretaceous and Paleogene sedimentary rocks, mainly limestone, marl, claystone, sandstone, flysch, and volcanics (Remondo and others 2003). Maximum altitude is 900 m and gradients are normally above 25°. The regolith is well developed and fairly continuous, normally 0.5–3 m thick. Land cover has been very much transformed by human activity, with cultivated grasslands and areas afforested with pine-trees as the dominant types (about 85 %). Small shallow landslides affecting the regolith are frequent. Population density is 325 inhabitants/km² (Bonachea 2006), concentrated mainly in the narrow alluvial plains and adjacent areas.

The other basin, Rioturbio (Fig. 1), with an extent of 26 km² and gradients normally in the range 10°–45°, is also made up of moderately folded and faulted Mesozoic sedimentary rocks, with clays, siltstones and sandstones of the Weald facies and limestones and calcarenites of the

Fig. 1 Location of study areas. **a** Lower Deva area (Deva and Elgoibar subareas are indicated). **b** Rioturbio area. *Shaded area* Deva municipality. *Dots* meteorological stations whose records were used for the analysis (*1* Santander; *2* Bilbao; *3* Aixola; *4* Eibar; *5* Altzola)
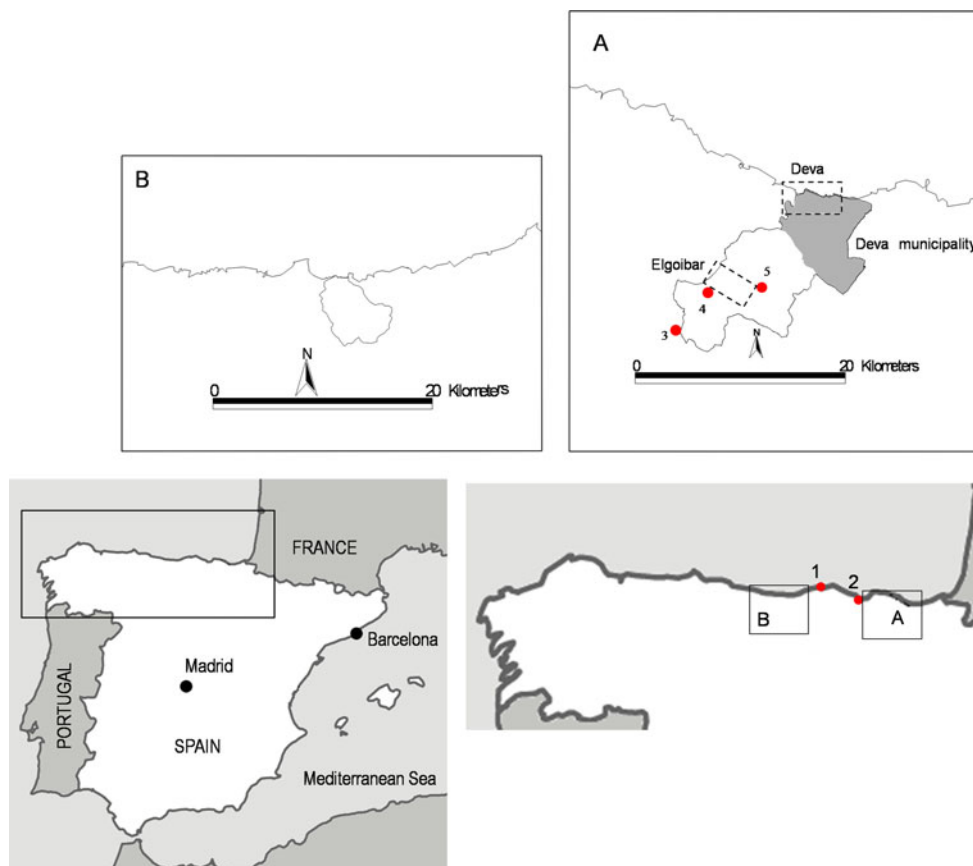
Urgonian group (IGME 1999). Vegetation cover is greatly transformed, although natural forests and scrublands cover 22.6 % of the basin. The regolith is 0.5–3 m thick. Population is scattered, with a density of 186 inhabitants/km^2 (ICANE 2010).

Methodological Approach

The general methodological approach used is very simple. Data were obtained on indicators of the intensity of geomorphic processes (landslide frequency, sedimentation rates), potential human (land-use change, road network, logging, and forest fires) and natural (rainfall, seismicity) triggering factors. Comparisons were made to identify possible relationships. Landslides in this region are an important denudation mechanism (Remondo 2001; Remondo and others 2005; Cendrero and others 2009), something also pointed out in other areas (Peart and others 2005; Korup and others 2007; Acharya and others 2009). Therefore, both landslides frequency/density and sedimentation rates can be used as indicators of land instability.

More than one thousand landslides were inventoried, the vast majority of which correspond to shallow, regolith landslides. Remondo and others (2005) found that over 80 % of landslides in this area, prior to 2001, were of this type. After that date, all landslides identified in the study areas are shallow, regolith ones.

The inventories were carried out using air photos or orthophotographs of different dates (Diputación Foral de Guipúzcoa). The total period covered by the different air photos is 1954–2008.

Landslide inventories elaborated in previous studies in the municipality of Deva (51 km^2; Fig. 1), which were the basis for the formulation of the hypothesis (Remondo 2001; Cendrero 2003; Remondo and others 2005; Cendrero and others 2006; Bonachea 2006), were complemented with others, designed to extend them and increase their time resolution. These inventories were complemented with others designed to analyze possible relationships between landslides and different types of land surface modification by human actions.

Land-use changes and landslides were analyzed in the Lower Deva basin (Fig. 1) on the basis of land-cover/use maps elaborated in 1996 and 2005 by the Department of Agriculture and Fisheries of Guipúzcoa (Departamento de Agricultura y Pesca, Diputación Foral de Guipúzcoa, unpublished report), using air photographs corresponding to 1991 and 2001. Landslide inventories were carried out using orthophotographs and stereo pairs of the same dates (1991, 1:18,000; 2001, 1:15,000; Diputación Foral de Guipúzcoa).

Another analysis was performed in two small subareas within the Lower Deva basin (Fig. 1), Deva (7.90 km^2) and

Elgoibar (3.57 km^2), for which landslide inventories and land-use/cover maps were elaborated using air photographs (years 1954, 1:12,000; 1969, 1:15,000; 1985, 1:15,000; 2001 1:15,000; 2006, 25 × 25 cm pixel; Diputación Foral de Guipúzcoa), to compare landslide occurrence and land use. In these two areas, the possible effect of repeated land-use changes was also analyzed. To that end landslide density and frequency in areas affected by one, two, or three land-use changes during the period covered were determined.

Road cuts and accumulations of unconsolidated materials are often unstable and experience landslides. Moreover, diversion and concentration of runoff produced by roads can trigger landslides. Both effects are more likely to take place near roads. Numerous cases of landslides triggered by roads have been described (Rice 1977; Howes and Sondheim 1988; Rollerson and others 1998; Guthrie 2002, 2005; Borga and others 2005; Sidle and others 2006; Petley and others 2007). The road network in this area is dense and practically all of it has experienced improvement works during the last 30 years. Relationship between landslide occurrence and roads was analyzed comparing the distribution of landslides observed in the 1991 (air photos, 1:18,000) and 2001 (air photos, 1:15,000) inventories mentioned above, with the road network in the Lower Deva basin (Fig. 1). The first ones obviously correspond to slope movements occurred prior to 1991, most of them after 1954 (air photos, 1:15,000), date of the oldest air photos used. The second include landslides occurred in the period 1991–2001.

In all cases, air photo inventories were checked by means of field surveys. Landslides which were visible in the field but could not be observed on air photos were not included in the analyses, to avoid bias toward the more recent periods. Attempts were unsuccessfully made to extract and date sediment cores in the Deva estuary, to obtain complementary information on geomorphic processes. Unfortunately, all points in which fine-grained sediment (one of the conditions needed for the application of the Pb-210 and Cs-137 methods) was found also had evidences of human disturbance and cores could therefore not be used for dating.

In the Rioturbio basin (Fig. 1), there are numerous shallow landslides visible in the field, but many of them are too small to be visible on air photographs. Therefore, the indicator of land instability used was, instead of landslide frequency, sedimentation rates. A parallelism between landslide frequency and sedimentation rates has been observed in the region for the last few decades (Cendrero and others 2006), but it is quite obvious that although an important contributor, landslides are not the only sediment-generation mechanism. To determine sedimentation rates two sediment cores (61 and 57 cm long) were extracted in

Table 1 Areas affected by land-use changes (km^2) and landslides (No.) in the Lower Deva basin, 1991–2001

Land cover in 1991	Changes and landslides, 2001				
	Afforested	F + CG	Natural woods	Scrublands	Pasturelands
Afforested (61.54)	*48.56 (219)*	3.49 (101)	6.56 (11)	2.78 (8)	0.15
F + CG (32.35)	6.06 (37)	*21.59 (422)*	2.41 (8)	1.44 (12)	0.85 (3)
Natural woods (24.10)	4.75 (32)	0.71 (25)	*17.59 (23)*	0.99 (1)	0.06
Scrublands (8.71)	1.56 (26)	1.30 (34)	1.50 (4)	*3.64 (11)*	0.71
Pasturelands (1.93)	0.35	0.26 (21)	0.24 (1)	0.8 (9)	*0.28 (2)*

Italicized values: no changes

F + CG Farmlands + cultivated grasslands

Fig. 2 Land-use changes and landslides in the Lower Deva basin, 1991–2001. *1* Land-use change during the period. *2* No change. *3* Landslides
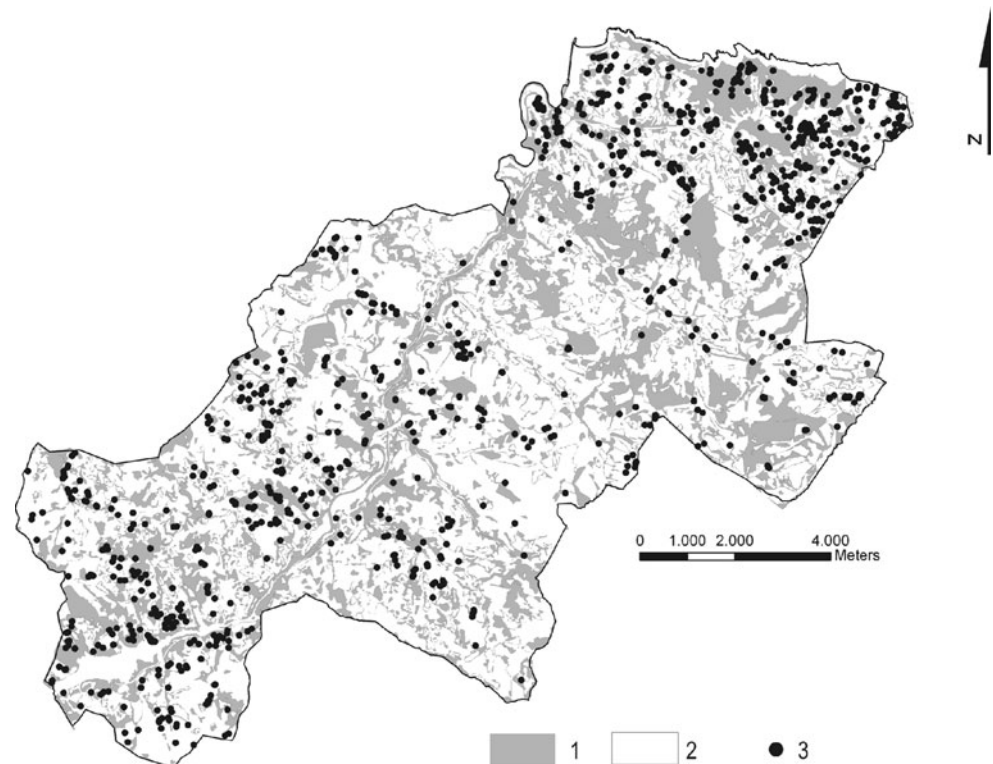
Table 2 Landslide density (No. landslides km^{-2}) in areas subject to land-use changes and areas without change (italicized values) in the Lower Deva basin, 1991–2001

Land cover in 1991	Changes and landslides, 2001				
	Afforested	F + CG	Natural woods	Scrublands	Pasturelands
Afforested	*4.50*	28.93	1.67	2.87	0
F + CG	6.10	*19.54*	3.32	8.33	3.53
Natural woods	6.73	35.21	*1.31*	1.01	0
Scrublands	16.66	26.15	2.66	*3.03*	0
Pasturelands	0	80.77	4.16	11.25	*7.14*

Average for the study area is 7.7 landslides km^{-2} (annual average: 0.77 km^{-2} y^{-1})

F + CG Farmlands + cultivated grasslands

La Rabia estuary in two points not subject to direct influence of tidal or stream currents and undisturbed by human action (Bruschi and others 2012). Cores were cut into 1-cm-thick slices and samples thus obtained dated by means of Pb-210 and Cs-137 methods (described in previous works; Soto and others 2006; Cearreta and others 2008; Bonachea and others 2010; Bruschi and others 2012). Land-use/cover changes were also analyzed using air photographs (1953, 1:20,000, Gobierno de Cantabria; 1975, 1:30,000, IGN; 1997, 1:40,000, IGN; 2005, 1:30,000, IGN). Other human-induced processes that could have an influence on land cover and instability include forestry operations and forest fires. Data on wood produced in the Rioturbio basin were obtained from the Department of Agriculture of the provincial government (Consejería de Desarrollo Rural, Ganadería, Pesca y Biodiversidad, Gobieno de Cantabria), and data on area affected by fire from Carracedo and others (2007, 2008). Both were compared with sedimentation rates.

Comparisons were made between indicators of geomorphic processes and total rainfall or frequency of intense rainfall episodes using rainfall data from AEMET (2010).

It is well known (Canuti and others 1985; Crozier 1986; Wieczorek 1996; Wieczorek and Glade 2005) that what is particularly significant for triggering landslides or causing erosion are intense rainfall episodes. The effect of these episodes is grater if preceded by antecedent rains that contribute to soil saturation. Also, preceding dry periods during which cracks are formed in the soil may favor instability during rainstorm episodes, but that is not the case in this region.

The time resolution of data on indicators of geomorphic processes (sedimentation rates and even more landslide frequency) is much lower that of rainfall data. Therefore, comparisons between specific years with a certain rainfall and the instability processes analyzed cannot be attempted. But comparisons between trends in the frequency of potential triggering events and those processes can be made for the 50 year period covered. This has been carried out on the basis of total rainfall and two expressions of the frequency of intense rainstorms, P95 and No. days/year with precipitation above 25, 50, and 75 mm. The possible relationship with earthquake frequency (IGN 2010) was also analyzed.
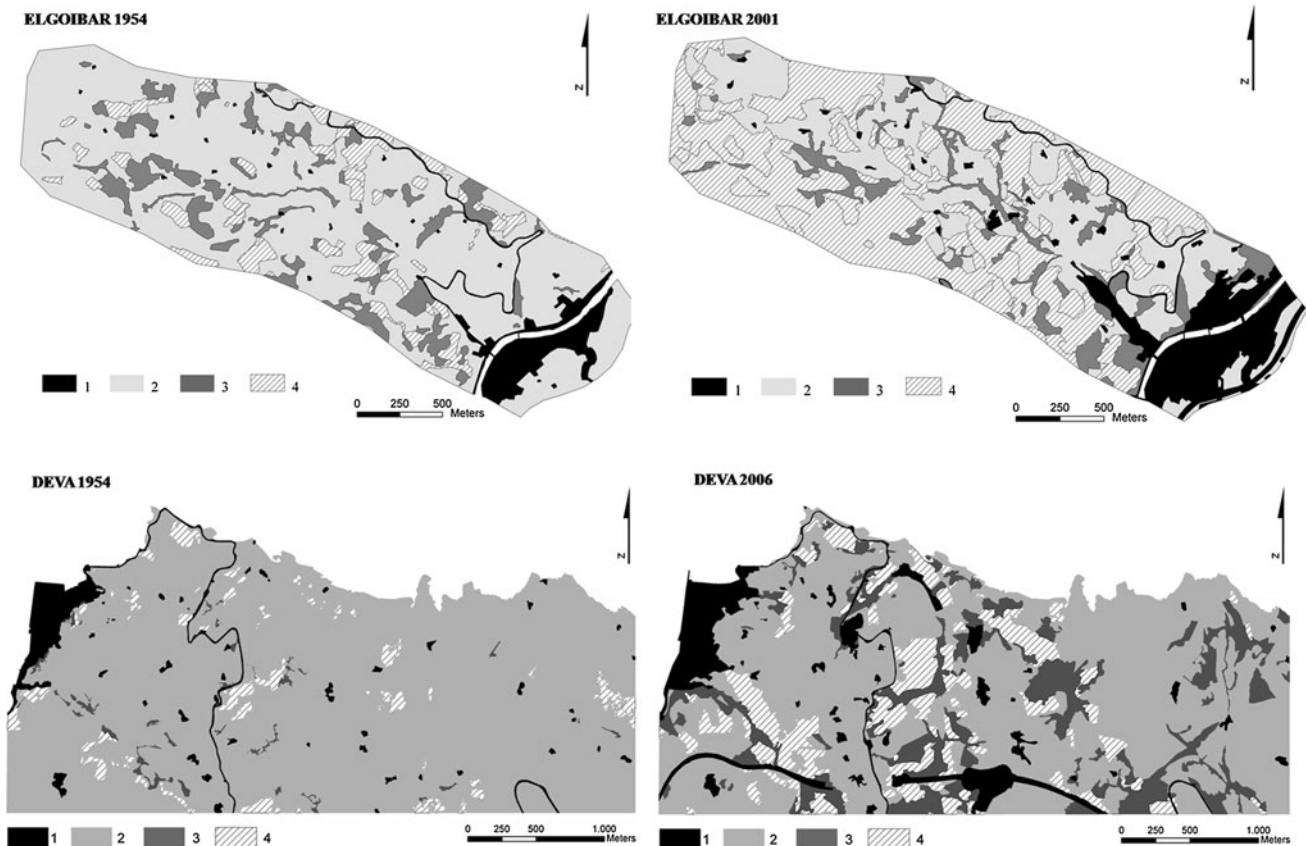

Fig. 3 Land use/cover in the Elgoibar (in 1954 and 2001) and Deva (in 1954 and 2006) subzones. *1* Built-up areas; *2* F + CG (farmlands plus cultivated grasslands); *3* natural woods; *4* afforested areas
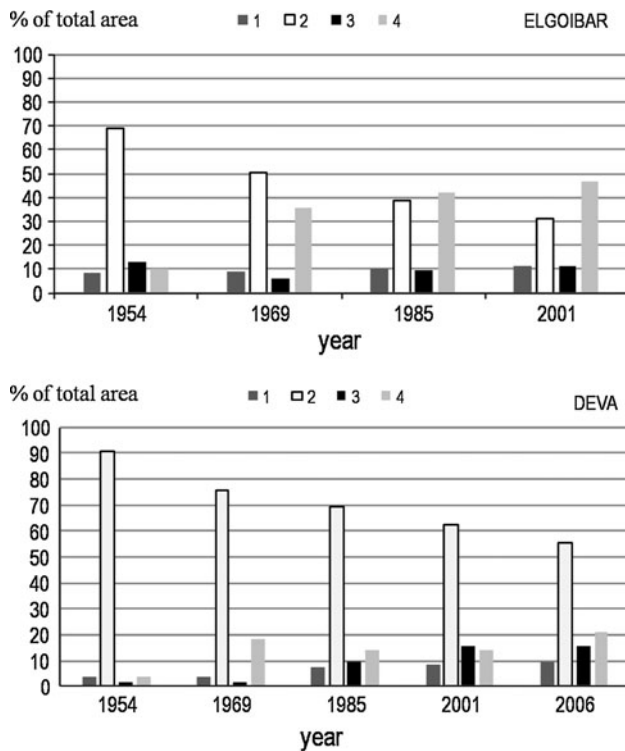
Fig. 4 Evolution of land-use types in the Elgoibar and Deva subzones for the years analyzed (km²). *1* Built-up areas; *2* F + CG (farmlands plus cultivated grasslands); *3* natural woods; *4* afforested areas

Results and Discussion

Lower Deva

Land-Use Changes and Geomorphic Processes

Lower Deva Basin A total of 1,010 landslides were inventoried in the Lower Deva basin for the 1991–2001 period (Table 1; Fig. 2). At a first glance, no clear-cut relationship between land-use change and landslide occurrence can be observed. Nevertheless, when landslide density is considered (Table 2) it is clear that the farmlands plus cultivated grasslands (abbreviated as F + CG) present frequencies considerably higher than the 7.7 average for the whole study area. This is especially so when there have been changes from other types of land cover into farmlands. Farmlands plus cultivated grasslands which remained as such (and obviously were the result of older land-use changes) had a density of 19.54 landslides km⁻² in the 10 years covered by the survey. When landslide occurrence is associated with a land-use change in the period of analysis, density varied between 26 and 80 landslides km⁻². The only other change which shows a density clearly higher than the average but nevertheless lower than the former ones was from scrublands to

Table 3 Areas subject to land-use change (km²) and landslides occurred (No, in bracket) in the Deva subzone during the period 1954–2006

Land cover in 1954	1969				1985				2001				2006			
	Afforested	F + CG	Natural woods	Built-up areas	Afforested	F + CG	Natural woods	Built-up areas	Afforested	F + CG	Natural woods	Built-up areas	Afforested	F + CG	Natural woods	Built-up areas
Afforested (0.31)	0.28 (1)	0.03	–	–	0.68	0.61 (9)	0.16	–	0.60 (1)	0.38 (11)	0.11 (1)	–	1.0644 (1)	–	–	–
F + CG (7.17)	1.17 (5)	5.93 (23)	0.07	–	0.40	4.81 (57)	0.55	0.24	0.40 (1)	4.39 (20)	0.60 (1)	0.09	0.5651 (10)	4.3882 (28)	–	0.0323
Natural Woods (0.11)	0.02	0.03	0.06	–	0.02	0.04	0.06	0.02	0.08	0.15 (3)	0.50	0.03	0.0009	–	1.2120	0.0007
Built-up areas (0.31)	–	–	–	0.31	–	0.05	–	0.26	–	–	–	0.57	–	–	–	0.7192 (1)
Total no. of landslides in the period	29				66				38				40			

No land-use changes in italics numbers

afforested. This is probably the result of forestry operations. It therefore appears that land-use change is a significant factor leading to land instability in the area.

Deva and Elgoibar Subzones Land-use changes that occurred in four different periods, between 1954 and 2006, were analyzed in the Deva subzone and for three periods (1954–2001) in the Elgoibar subzone (Fig. 1). The results (Figs. 3, 4) show that in both cases there was a marked reduction of F + CG and a steady increase of built-up areas, the latter basically on flat areas with no influence on landslides. Afforested areas and natural forests show a less regular variation, with an increase of the former in Elgoibar.

Total number of landslides and landslides density (No. km^{-2}) are presented for each land-use change and period considered (Tables 3, 4, 5, 6), although the latter figure could be a bit misleading in some cases, due to the small area affected by some of the changes. Tables 3 and 4 show that a large proportion of landslides in both study areas occurred on farmlands or areas transformed into farmlands from other uses, 151 in Deva and 47 in Elgoibar. Only 22 landslides in Deva and 12 in Elgoibar took place in other situations. The latter represent about 12.7 % in Deva and 20 % in Elgoibar. Landslide density is shown in Tables 5 and 6. During the initial 1954–1969 period all landslides appeared on farmlands and afforested areas, without significant differences between both. However, in 1969–1985 and 1985–2001 practically all landslides occurred in farmlands or areas that were transformed into farmlands from other uses, with frequencies very much above the average for each period. The significance of 9.09 landslides km^{-2} on natural woods in Deva (Table 5) for the period 1985–2001 is very limited, as this is due to one single landslide. During the last period analyzed (Deva subzone, 2001–2006; Table 5), the greatest density

corresponds to areas transformed from farmlands into afforested, and to a lesser extent to farmlands remaining as such. This probably reflects the effects of initial forestry operations. Irrespective of the influence of land-use changes, landslide frequency shows a general increase after 1969. The increase factor for landslide frequency (No. km^{-1} y^{-1}) between the first and second–third periods was 2.16–1.25 in Deva and 7.42–6.14 in Elgoibar. For the period 2001–2006 (Deva subzone) it was 4.16. Both subzones show a decrease in the period 1985–2001, compared to 1969–1985. In Deva, where the time series is longer, this is followed by a new increase.

Results on the possible effect of repeated land-use changes on landslides are presented in Fig. 5. Data obtained suggest that there is no a relationship between repeated land-use changes and landslide density.

Roads and Landslides

Distribution of landslides observed in the air photos of 1991 and 2001 in the Lower Deva basin is shown in Figs. 6 and 7. The graph in Fig. 7a shows that over 50 % of the landslides occurred within 50 m from the roads, and about 85 % within 100 m. More significant than the former is relative density (No. km^{-2}, calculated using 2 m intervals) presented in Fig. 7b, which is independent of the area covered by each distance class. It can be seen that there is great variability of landslide density with distance (presumably reflecting other factors that also play a role) but, nevertheless, landslides in both periods do tend to be less frequent with increasing distance. Also, it is worth pointing out that the frequency of landslides was in all distance classes greater during the second period (10 years) than during the first period (over 37 years), and that the slope of the general trend was also greater for the most recent period. This suggests that human influence has increased in

Table 4 Areas subject to land-use change (km^2) and landslides occurred (No., in bracket) in the Elgoibar subzone during the period 1954–2001

Land cover in 1954	1969				1985				2001			
	Afforested	F + CG	Natural woods	Built-up areas	Afforested	F + CG	Natural woods	Built-up areas	Afforested	F + CG	Natural woods	Built-up areas
Afforested (0.35)	*0.27*	0.08	–	–	*0.95 (4)*	0.25 (6)	0.06	–	*1.25 (4)*	0.15 (5)	0.10	–
F + CG (2.48)	0.81	*1.54 (3)*	0.10	0.03	0.49	*1.08 (20)*	0.17	0.06	0.32 (1)	*0.91 (11)*	0.12 (1)	0.03
Natural woods (0.45)	0.18 (1)	0.18	*0.09*	–	0.06	0.04	*0.10*	–	0.09	0.05 (2)	*0.18 (1)*	0.01
Built-up areas (0.29)	–	–	–	*0.29*	–	0.01	–	*0.30*	–	0.01	0.01	*0.34*
Total no. of landslides in the period	4				30				25			

No land-use changes in italics numbers

Table 5 Landslides density (No. landslides km^{-2}) and frequency (No. landslides km^{-2} y^{-1}) for different land-use changes in the Deva subzone during the period 1954–2006

Land cover in 1954	1969				1985				2001				2006			
	Afforested	F + CG	Natural woods	Built-up areas	Afforested	F + CG	Natural woods	Built-up areas	Afforested	F + CG	Natural woods	Built-up areas	Afforested	F + CG	Natural woods	Built-up areas
Afforested	3.57	–	–	–	–	–	–	–	1.66	28.94	9.09	–	1.06	–	–	–
F + CG	4.27	3.87	–	–	14.75	11.85	–	–	2.50	4.55	1.66	–	17.6	6.38	–	–
Natural woods	–	–	–	–	–	–	–	–	–	20	–	–	–	–	–	–
Built-up areas	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1.39
Average for period (No. km^{-2})	3.6				8.3				4.8				5.1			
Average for period (No. km^{-2} y^{-1})	0.24				0.52				0.3				1.0			
Increase factor					2.16				1.25				4.16			

recent times, especially considering that rainfall in the latter period was considerably lower than in the previous one, as shown further on.

The results indicate that roads do play an increasing role in landslide occurrence in the area. However, the great variability of the density/distance values obtained (Fig. 7b) shows that this variable cannot be incorporated into probabilistic landslide susceptibility or hazard models (Remondo and others 2008; Bonachea and others 2009).

Rioturbio Basin

In the Rioturbio basin, land-use changes (Figs. 8, 9b) were compared with sedimentation rates. The only fairly well-defined trends of change in this area are the decrease of scrublands/pasturelands and the increase of built-up areas. Natural forests and marshes did not change much in extent and farmlands or afforested areas showed different changes according to the periods analyzed. The indicator of land instability used here was, as mentioned above, sedimentation rate. Landslides identified in this area were very small in size and most of them could only be observed in the field, not in air photos. Therefore, it was not possible to make inventories for past periods. From the results shown in Fig. 9a it appears that land instability increased during the period analyzed. This increase, however, does not seem to bear a clear relationship with land-use changes. The reduction of scrublands and afforested areas—the latter after 1975—could be one plausible explanation.

The other human-induced processes considered that could have an influence on land instability are forestry operations and forest fires. Results obtained (Fig. 9c, d) do not show a clear relationship with sedimentation rates (Fig. 9a). There were important forest fires in 1975 and also, but much smaller, in 1979 (Fig. 9d), which could be related to an apparent sedimentation peak.

Natural Triggers

Rainfall

As indicated before, there is no doubt that rainfall is the main direct *trigger* of landslides and sediment generation in this part of northern Spain. For instance, the intense rainfall episodes of August 1983 (128 mm/24 h), in July 1988 (70 mm/24 h), or October–November 1992 (140 and 130 mm/24 h) triggered a high number of shallow movements. However, according to the results presented by Remondo and others (2005), in the Lower Deva valley, the general *trend* of increasing landslide frequency observed during the second half of the last century does not seem to

Table 6 Landslides density (No. landslides km^{-2}) and frequency (No. landslides km^{-2} y^{-1}) for different land-use changes in the Elgoibar subzone during the period 1954–2001

Land cover in 1954	1969				1985				2001			
	Afforested	F + CG	Natural woods	Built-up areas	Afforested	F + CG	Natural woods	Built-up areas	Afforested	F + CG	Natural woods	Built-up areas
Afforested	–	–	–	–	4.21	24	–	–	3.20	33.33	–	–
F + CG	–	1.94	–	–	–	18.51	–	–	3.12	12.08	8.33	–
Natural woods	5.55	–	–	–	–	–	–	–	–	40	5.55	–
Built-up areas	–	–	–	–	–	–	–	–	–	–	–	–
Average for period (No. km^{-2})	1.12				8.4				7			
Average for period (No. km^{-2} y^{-1})	0.07				0.52				0.43			
Increase factor					7.42				6.14			
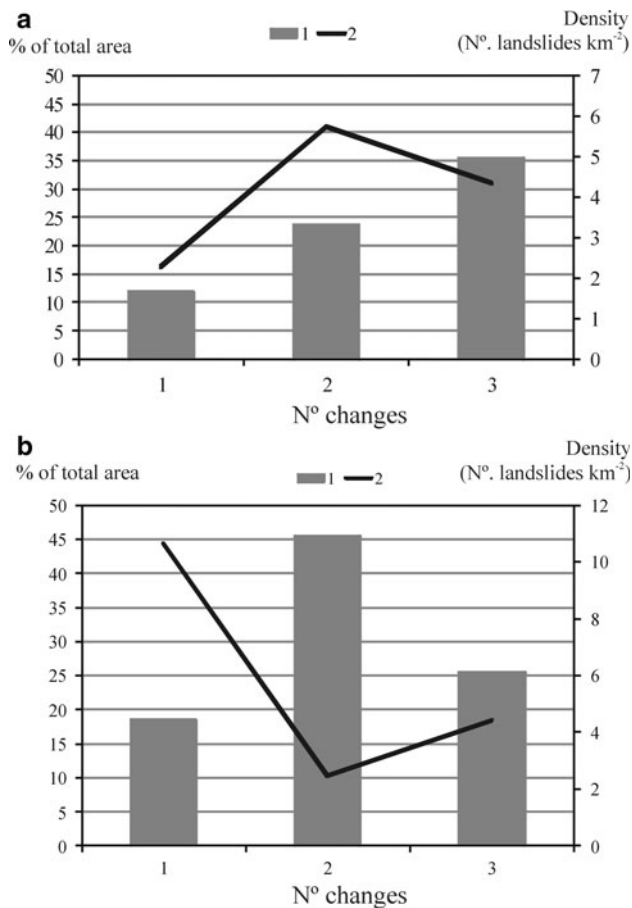
Fig. 5 Areas affected by one or more land-use changes and landslide density in them. **a** Deva subarea. **b** Elgoibar subarea. *1* Area affected. *2* Landslide density

be related to a similar rainfall trend, be it total precipitation or storm frequency (Figs. 4, 11 of Remondo and others 2005; Fig. 6 of Cendrero and others 2006).

The analysis of rainfall data shows that both total annual precipitation (Fig. 10a) and frequency of intense rainfall episodes (the latter expressed as P95—Fig. 10b—and number of days with rainfall greater than 25, 50, and 75 mm/day—Fig. 10c) decreased in the region from the late seventies onwards. Hourly data are available for the Santander airport station since 1983. The number of days/year during which maximum hourly intensity exceeded 30 and 50 mm is shown in Fig. 10d. The trend shown by the latter is very similar to the other two expressions of rainstorm frequency. Data on both frequency of intense rainstorms (P95 and N° days/year with high rainfall) and total precipitation show that the maximum values were reached in the seventies. The general trend afterward shows decrease or, in some cases, stability.

In the case of the Deva and Elgoibar subareas comparisons with rainfall data (Figs. 11, 12) from neighboring stations are not very meaningful, because the overlap is 15 years. Nevertheless, landslide frequency in recent times is also higher than in the earlier period.

In the area where the time resolution of landslide data is better (Deva municipality) a correspondence between rainstorm frequency and peaks (around 1983 and 1996) in landslide frequency seems to exist. This correspondence is logical although it should be interpreted with caution, due to the distance and different settings of rainfall stations with respect to the study area, and the impossibility to make year-to-year comparisons. It is well known that the number or intensity of rainstorms in a given year can differ considerably between neighboring stations. The ensemble of data indicate that total number of rainstorms during the more recent period as well as peak values of annual frequency are lower than in the earlier period, whereas landslide frequency is higher.

Fig. 6 Road network (*1*) and landslides occurred within 100 m from the road axis (*stars*) in the Lower Deva area. *2* Area within more than 100 m from the road axis; *dots* landslides occurred within more than 100 m form the road axis. **a** 1991 landslides. **b** 2001 landslides
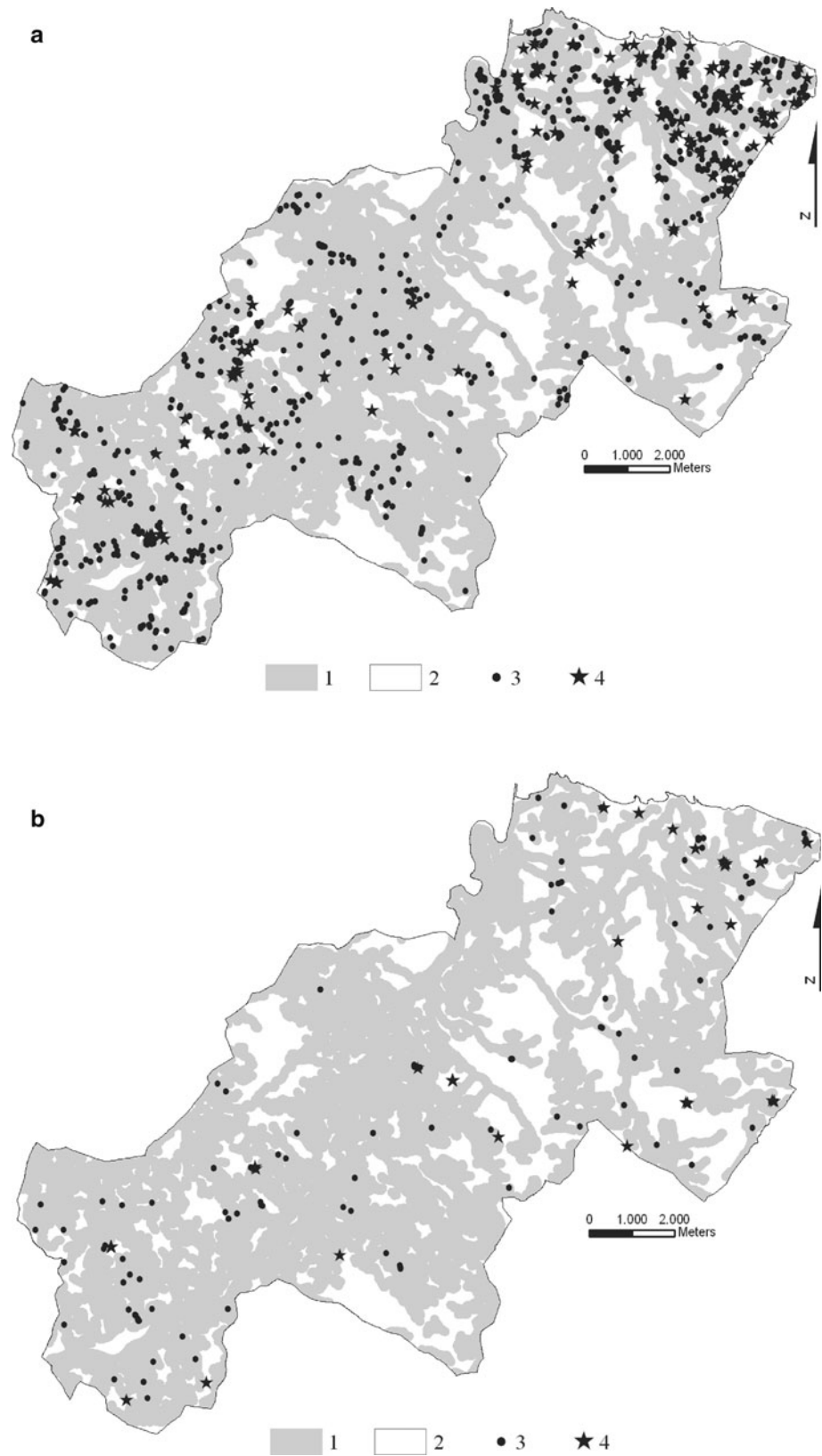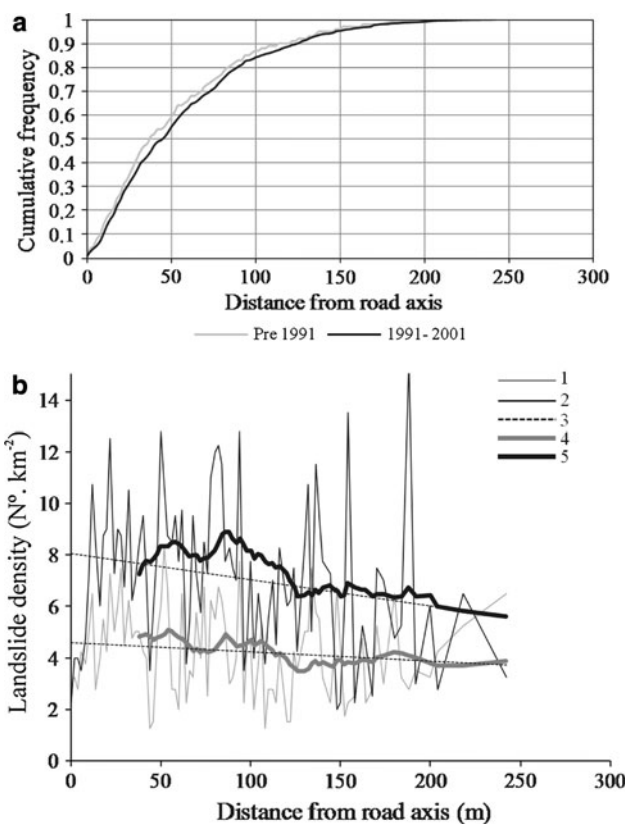
Fig. 7 Cumulative frequency of landslides (a) and landslide density (b) with respect to distance to road axis for 1991 and 2001. *1* 1991 frequency. *2* 2001 frequency. *3* Interpolated linear trends. *4* Moving average (20 m) 1991. *5* Moving average (20 m) 2001

Comparison between rainfall data (Fig. 10a, b) and sedimentation rates in the Rioturbio area (Fig. 9a) does not suggest a relationship between the two variables. As commented above, the regional trend in both total rainfall and storm frequency shows an increase till around the middle 1970s and a decrease afterward, the latter coinciding with the period of greatest increase in sedimentation rates.

Thus, the trend toward the intensification of geomorphic processes (sedimentation rate, landslide frequency) observed during the last three decades does not seem to be explained by a parallel trend in rainfall. This should not be interpreted as meaning that rainfall is not a significant triggering agent. Rather, that the increase observed in the rates of geomorphic processes seems to be related to increasing land sensitivity. That is, the same number of storms or amount of rainfall in recent times produced grater geomorphic effects than a few decades ago, presumably as a consequence of changes in land surface (preparatory factors; Crozier 1986).

Earthquakes

Although they should be considered (Keefer 1984; Keefer and others 2006; Papadopoulos and Plessa 2000; Bommer and Rodríguez 2002; García-Rodríguez and others 2008; Owen and others 2008), earthquakes are not a very likely trigger of landslides in the study areas because seismicity is very low in northern Spain. In the region of study
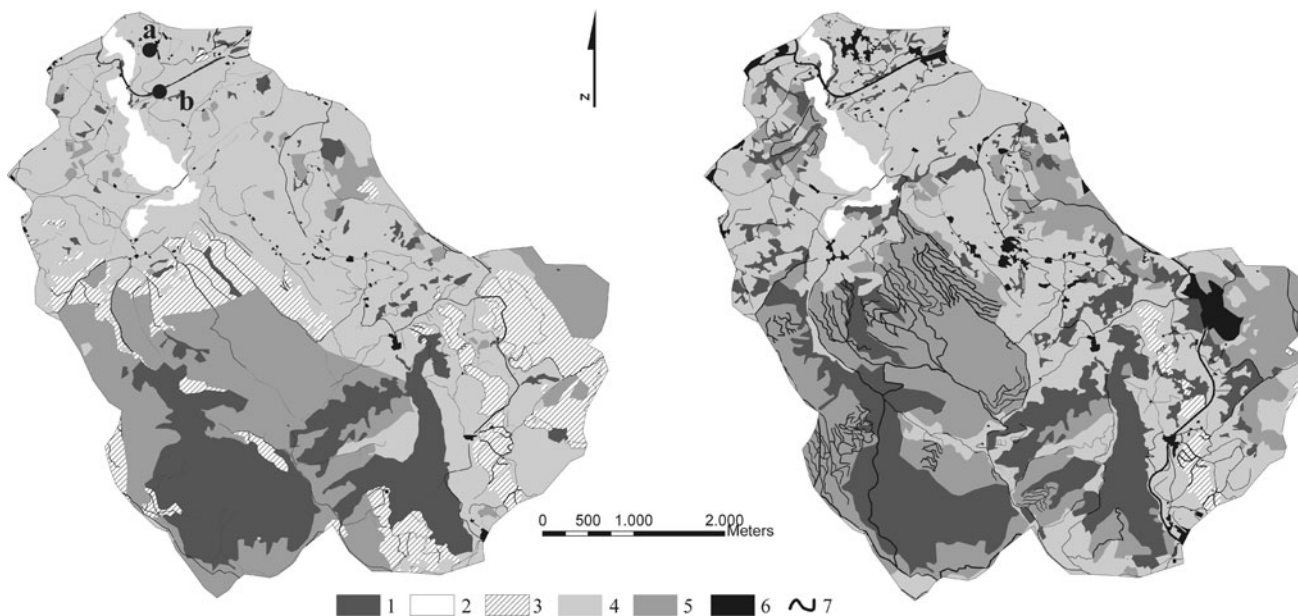

Fig. 8 Land-use changes in the Rioturbio basin between 1953 (*left*) and 2005 (*right*). *1* Natural woods; *2* marshes; *3* scrublands/ pasturelands; *4* F + CG; *5* afforested; *6* built-up areas; *7* roads and

tracks. Points where cores were extracted for determination of sedimentation rates are indicated (*a* and *b*)

Fig. 9 Sedimentation rates and land use in the Rioturbio basin. a Sedimentation rates; *a* and *b* cores dated. b Land use (*1* Natural woods; *2* marshes; *3* scrublands/pasturelands; *4* F + CG; *5* afforested; *6* built-up areas); c timber production (m³). d Area affected by forest fires (ha)
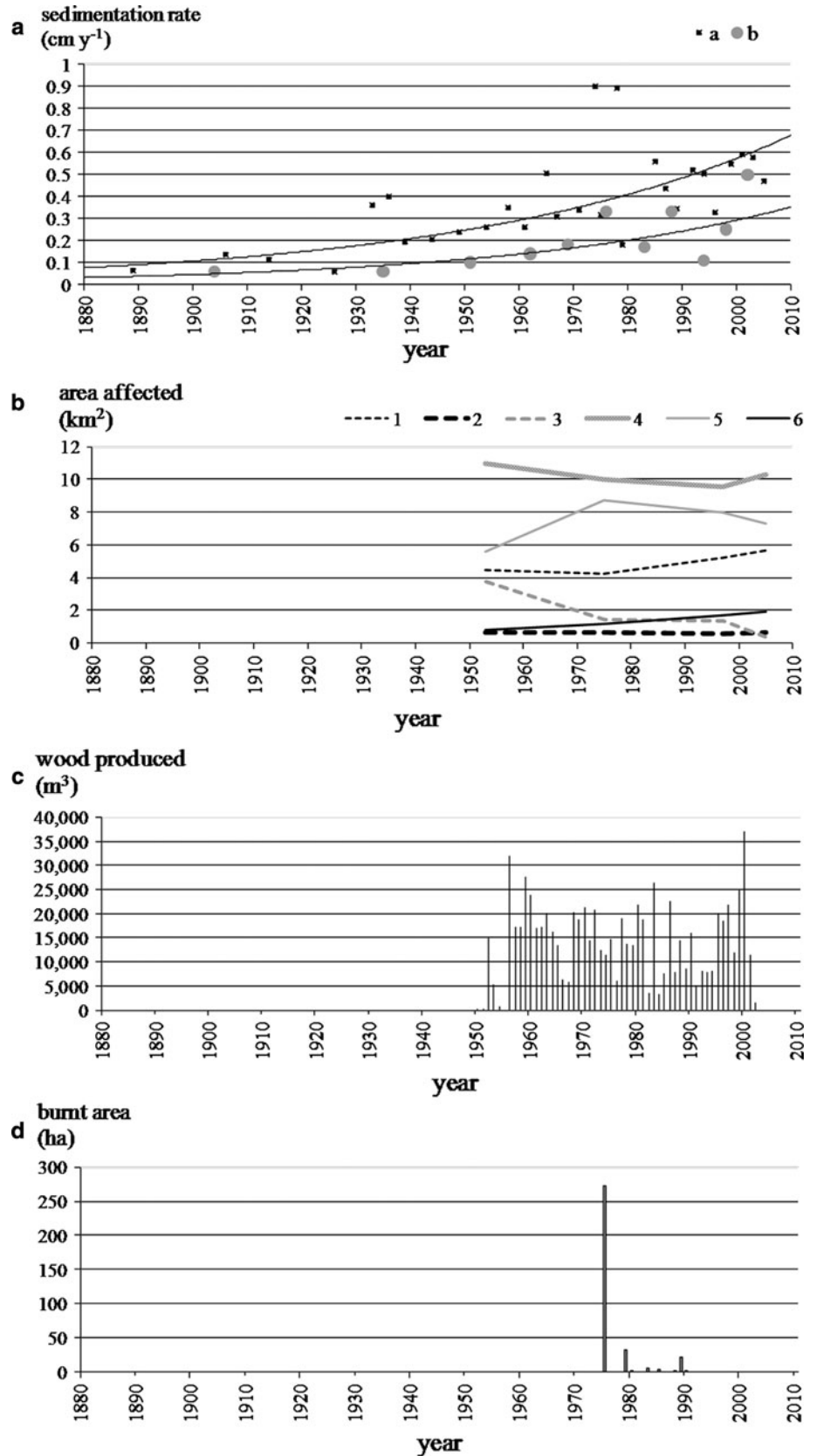
Fig. 10 **a** Annual rainfall (5-year moving average). *1* Bilbao; *2* Eibar; *3* Santander. **b** Rainfall percentile P95 (5-year moving average). *1* Bilbao; *2* Santander. **c** No. days/year with rainfall >25 mm (*1*), 50 mm (*2*), and 75 mm (*3*) and their respective 5-year moving averages (*4–6*) for Santander airport station. **d** The same for Bilbao airport station. **e** No. days/year in which maximum hourly rainfall was >30 (*1*) or 50 mm (*2*), and their respective 5-year moving averages (*3* and *4*), for Santander airport station
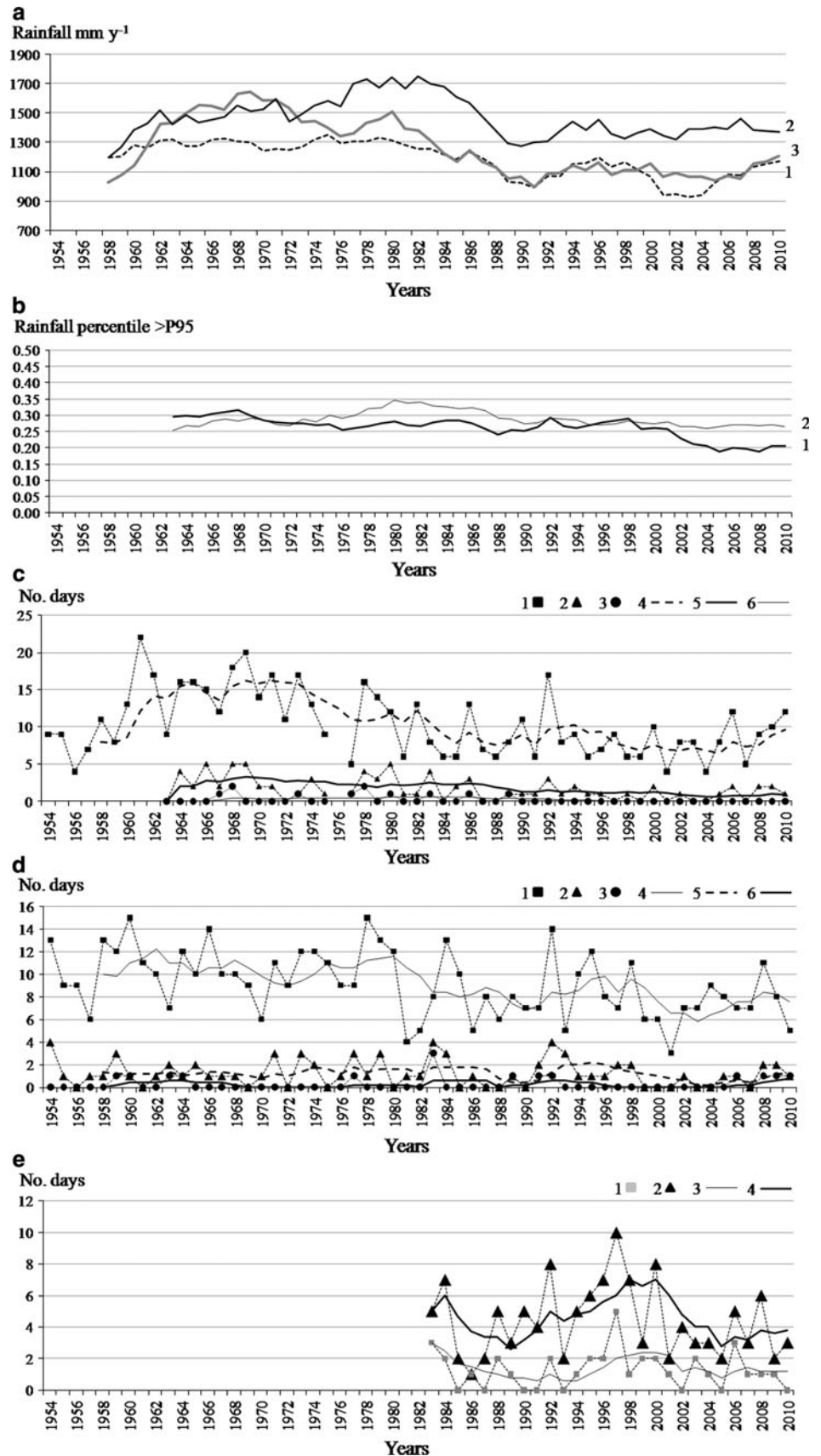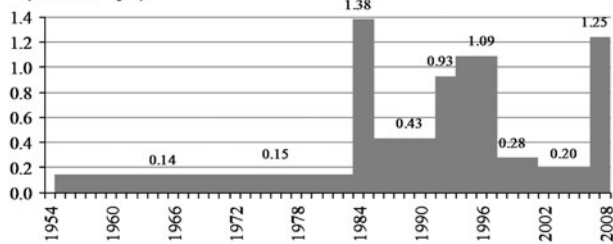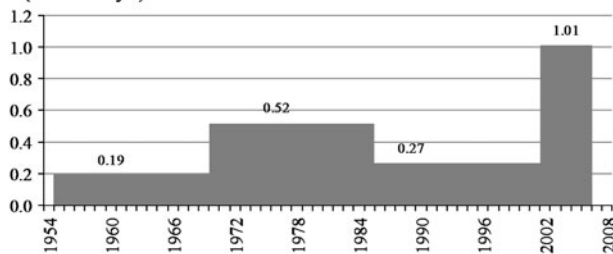
Fig. 11 Annual rainfall (5-year moving average) in Altzola (*thin line*) and in Aixola (*thick line*). Number of storms with precipitation >20 mm/day (*triangles*) and 50 mm/day (*squares*) in Aixola
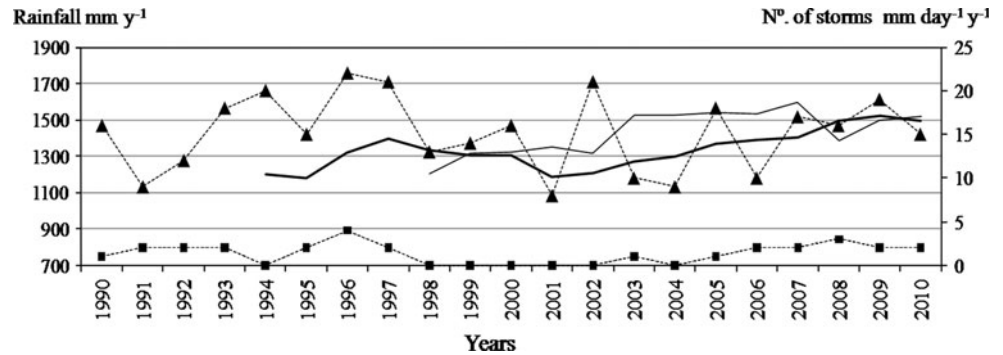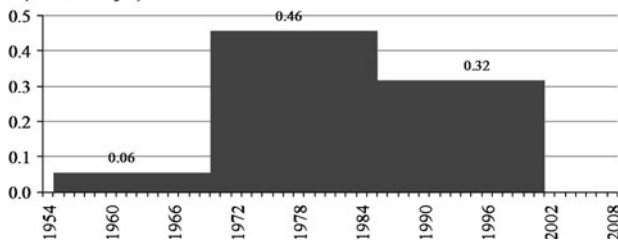

Fig. 12 a Landslide frequency (No. km^{-2} y^{-1}) in the Deva municipality (after Remondo and others 2005) as well as the Deva (**b**) and Elgoibar (**c**) subareas

(provinces of Cantabria, Vizcaya and Guipúzcoa), only one case of landslide triggered by an earthquake, in 1932, has been documented (González-Díez and others 1996, 1999). Additionally, the former authors identified what appears to be an episode of landslides triggered by seismic activity around 5,500 years BP. In both cases, most landslides thus produced were larger and affected bedrock, not only the regolith as in the case of landslides analyzed here. Existing earthquake records in the region do not register significant

activity since the beginning of the instrumental period, in 1907 (Diputación Foral de Guipúzcoa 1986; IGN 2010). The database of the Instituto Geográfico Nacional (IGN 2010) registers in Guipúzcoa 26 earthquakes of magnitude >2.5 between 1972 and 2010, with a maximum of 3.6 in 1978. Only 6 of them had epicenters less than 10 km away from the study areas. No episode of terrain instability which could be attributed to those earthquakes has been registered around any of the study areas in Guipúzcoa. In Cantabria, the activity has been even less.

Recapitulation

A number of authors in different parts of the world have also found significant increases of landslide occurrence related to land-use changes. Haigh and others (1995) found in an area of the Himalayas that reduction of tree cover associated with steeper slopes and higher road cuts, significantly increased landslide and erosional processes. In an area of Southern Italy, Wasowski (1998) described an acceleration in landslide processes determined by the preparatory role played by human activities. Glade (1998, 2003) and Crozier (2005) pointed out that deforestation in New Zealand has contributed significantly to the increase of landslide rate during the last decades. Vanacker and others (2003), using a model approach, confirmed that the overall susceptibility to slope movement in the Andes is highly dependent on recent land-use change. In particular, the conversion from secondary forest to grassland and/or cropland induces increased risk of shallow slope movement. Van Beek and van Asch (2004), also on the basis of a model, found that predicted landslide activity would respond more intensely to land-use changes than to rainfall variations. Since the 1960s, the increased population and land occupation for agriculture have resulted in frequent episodic slope movements. Beguería (2006) found that land-use changes and degradation in the Pyrenees had a significant effect on landslides, even decades after human activities had ceased. His results also confirmed the inertia of geomorphic processes as a consequence of slow changes in soil characteristics. In the same region, García-Ruiz and

others (2010) have shown that deforestation and associated changes in soil hydrology and strength played a significant role in landslide occurrence, increasing terrain sensitivity to snowmelt and large storms. Clarke and Rendell (2000) as well as Piccarreta and others (2006), analyzing erosion processes in Basilicata (Italy), found that land-use practices had a greater effect than rainfall changes. In the Alps, Meusburger and Alewell (2008) showed that land use affected the spatial distribution of landslides and created new landslide risk areas, clearly highlighting the relevance of anthropogenic impacts on landslide hazard. According to Tarantino and others (2007), "It seems well known that land-use changes are among human-induced predisposing factors to landslides." In another aforementioned study in Southern Italy, Clarke and Rendell (2006) found that landslide frequency decrease with time following a roughly parallel trend to decrease in extreme rainfall events, and probably also responding to hazard-mitigation practices.

The effect of roads on landslides in a forested area of Oregon was analyzed by Rice (1977), who found that landslide frequency was 315 times greater in areas affected by roads than in those without roads. Similar, but less spectacular effects have been described in Washington (Jensen and Cole 1965) and Idaho (Rothacher and Glazebrook 1968), where 90 % of the failures studied were associated with roads. Road cuts and fills as well as diversion and concentration of runoff are considered by those authors to be the main factors leading to enhanced landslide occurrence. Roads are the single most important anthropogenic cause of landslides on Vancouver Island (Guthrie 2002; Borga and others 2005). These authors point out that road building overloads and oversteepens slopes, and that "some road segments intercept subsurface flow, route it to ditches and thence on previously unchanneled hillslopes, altering the hillslope flow paths and the potential for shallow landsliding." Based on the findings of several analyses (Howes and Sondheim 1988; Rollerson 1992; Rollerson and others 1998; Jakob 2000; Guthrie 2002; Guthrie and Evans 2004; Chatwin 2005), Guthrie (2005) points out that "Forest harvesting and road building are recognized as increasing the landslide frequency several times." Sidle and others (2006) have demonstrated that the density of landslides associated with road construction in mountainous terrains is one and in some cases two orders of magnitude greater than for other land-use changes. Petley and others (2007) also found that trends in landslide occurrence in Nepal were strongly influenced by roads. Finally, the importance of changes related to urbanization has been stressed by Wright (2004), who pointed out that increased human activity is a major factor leading to increasing susceptibility to landslides in the future.

Wasowski (1998) analyzed the relative role of rainfall–landslide relationships in an area of Italy concluding that slope instability is determined to a great extent "by man-made processes, which may modify the relationships between rainfall events and landslide occurrence." The relative role of human actions and climate changes on landslide activity has also been discussed by Crozier (2010), who indicated that the former could presently be the main cause of increasing landslide occurrence.

Thus, data reported by the authors above are consistent with the results we have obtained here as well as those described in recent contributions (Bonachea and others 2010; Bruschi and others 2012). They all point to human-driven geomorphic change as a significant factor for the observed increase in land instability.

Conclusions

The results presented here, although not conclusive, do suggest a relationship between changes affecting land surface as a result of human activities, and land instability (landslides, denudation, and sediment generation). Landslide density in both the Lower Deva Valley and the Deva and Elgoibar subareas was clearly greater in areas affected by changes from other types of land cover into farmlands (including artificial pasturelands) and to a lesser extent in areas which remained as farmlands during the period covered, the latter obviously the result of older land-use changes. When landslide rates through time are considered, the oldest period covered always presents lower frequency. If the first and last periods analyzed in each study area or subarea are compared the latter has higher rates, despite the fact that rainfall data show a decrease in total precipitation or frequency of intense rainfall episodes. Infrastructure also appears to have an effect on landslide occurrence, as shown by the decrease of landslide density with distance to roads in two different periods. In this same area, landslide frequency is also greater in the more recent period. The comparison of different indicators of land cover change and sedimentation rates in the Rioturbio study area also suggests a relationship between human-induced changes and the latter, but this relationship is less clear.

As expected, there is no evidence of earthquakes as a triggering factor of landslides in the region. Data obtained indicate that—as is well known—intense rainfall is an important landslide trigger, but do not satisfactorily account for the increasing trend observed in the indicators of land instability studied. The intense rainfall episode of 1983, well known in the region for its effects on landslide activity, is reflected in the maxima observed in the Deva and Elgoibar subareas during the period 1969–1985. Also but less clearly defined the one of 1996.

The overall results presented suggest that the resilience of the surface layer to triggering agents in the study areas

decreased with time. Data presented here are coherent with those of former works (Cendrero and others 2009; Bonachea and others 2010; Bruschi and others 2012), as well as with those reported by a number of authors in different parts of the world. They suggest that there is a general trend toward the intensification or acceleration of geomorphic processes that cannot be explained on the basis of climate change. Rather, it appears that human activities like the ones analyzed in this region (and probably others as well), which alter geomorphic characteristics and/or terrain resilience, are the main underlying cause of the intensification observed. As the type of people-driven alterations described here are taking place in most regions of the world, it is not unreasonable to assume that the process could have a global extent, representing a "global geomorphic change" that appears to be significantly changing surface geologic processes.

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