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LINKING LAND COVER CHANGES IN THE SUB-ALPINE AND MONTANE BELTS TO CHANGES IN A TORRENTIAL RIVER

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ABSTRACT

Channel changes are the consequence of changes in sediment yield from the slopes and in the connectivity between slopes and channels because of distinct land use and climate impacts. In this study, we investigated the characteristics and evolution of a short reach in the headwater of the Ijuez River, central–southern Pyrenees. Assessment of a series of sedimentary and geomorphic structures confirmed major changes to the valley bottom, mainly related to changes in the intensity of human activity. The oldest sedimentary structure is a terrace level located 3 to 4 m above the current alluvial plain. General deforestation, overgrazing and recurring fires in the montane belt (1100–1600 m a.s.l.) have led to increased soil erosion and connectivity, and to the triggering of debris flows that have been deposited on the fluvial terrace. Woody fragments from within the debris flows were dated using accelerator mass spectrometry ^{14}C radiocarbon techniques (AMS), yielding ages between 100 and 115 cal years BP, which coincides with the period of maximum deforestation and human density in the Pyrenees. Depopulation and farmland abandonment since the beginning of the 20th century has resulted in generalized natural and artificial reforestation, a shrinkage of the eroded areas and a decline in connectivity between slopes and the channel. The most important consequence has been channel incision and narrowing, and the development of a sediment armour layer. Active sediment transport is continuing, although there has been a decrease in sediment yield from the slopes. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS: braided channel; channel incision; land use changes; deforestation; reforestation; debris flows; central Pyrenees

INTRODUCTION

Land degradation is enhanced by a variety of human activities because of population growth and fluctuations in national or international markets, resulting in changes in sediment yield, the hydrological cycle, biodiversity and river morphology (García-Ruiz *et al*., 2011; Asadi *et al*., 2012; Biro *et al*., 2013; Leh *et al*., 2013; Li *et al*., 2013). Rivers are open systems having channel morphology and sediment characteristics that are closely related to runoff and sediment yield from the hillslopes (Schumm, 1977). Thus, the volume of water yielded from a catchment and its temporal variability, as well as the geomorphic activity and the consequent sediment supply, to a large extent explain the main features of the alluvial plain, including its width, gradient, channel morphology, sediment size and downstream fining (Leopold, 1994). Changes in the alluvial plain (termed fluvial adjustments) reflect the complex relationships between hillslopes and channels (Trimble, 1981; Charlton, 2008). A number of recent studies have considered the influence of agricultural activity, deforestation, reforestation, fire, mining and farmland abandonment on fluvial hydrological behaviour and channel morphology, including channel scouring and aggradation, and the rate at which sediment is renewed and carried downstream (Brooks & Brierley, 1997; Kondolf *et al*., 2002; Marston *et al*., 2003; Liébault *et al*., 2005; Gregory, 2006; Bathurst *et al*., 2007; Keesstra, 2007; Picco *et al*., 2014). This implies that changes in land use/land cover modify the alluvial plain in the short term. Changes in climate (particularly the volume of precipitation and rainfall intensity) also have a marked influence on fluvial geomorphology because they affect runoff generation, flood magnitude and frequency, geomorphic processes and sediment accessibility (Benito *et al*., 2008, 2010; Grenfell *et al*., 2014). Changes in all these catchment features have been found in small headwater catchments, where the relationships between hillslopes and channels are easier to observe because of rapid connectivity or coupling (Harvey, 2002, 2012; Benda *et al*., 2005; Fryirs *et al*., 2007). Conversely, these relationships become more difficult to establish as the size and complexity of catchments increase (Rice & Church, 1998).

Mountain areas have been affected by major land use/land cover changes in recent decades, especially in the Mediterranean region (García-Ruiz *et al*., 2013a), where frequent changes in population density and land management have resulted in deforestation, recurring use of fire to manage grasslands, livestock expansion, farming on steep slopes

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and, more recently, forest recovery associated with generalized farmland abandonment (García-Ruiz & Valero-Garcés, 1998; Vicente-Serrano *et al*., 2004; García-Ruiz, 2010). Consequently, different stages of sediment yield and connectivity have been detected, some also related to the occurrence of periods of changing flood magnitude. In most Mediterranean mountains, the maximum human pressure occurred between the middle of the 19th century and the beginning of the 20th century (Collantes, 2005). By that period, a large proportion of the area was cultivated, and large volumes of sediment had been transferred to the fluvial channels, resulting in the development of braided reaches and wandering channels (Beguería *et al*., 2006), and the reactivation of alluvial fans (Gómez-Villar *et al*., 2006). Subsequently, population migration caused generalized farmland abandonment and a decline in the number of livestock, and cultivated areas became restricted to small patches in the valley bottoms. The consequent marked reduction in sediment delivery and transport resulted in scouring and channel narrowing, which is a phenomenon also observed in various European mountains (García-Ruiz & Lana-Renault, 2011; García-Ruiz *et al*., 2011).

Climate records indicate that these changes coincided with the end of the Little Ice Age (LIA), which was one of the most significant abrupt climate changes in the last two millennia; it was characterized in western Mediterranean areas by cold temperatures and increased moisture conditions (Moreno *et al*., 2012). Following the LIA, there was a trend to drier and warmer conditions, although a recent compilation of records for the Pyrenees indicates that there was another period of increase in precipitation and a rapid, short-lived growth of glaciers during the second part of the 19th century, which lasted until the 1920s (Morellón *et al*., 2012). Pollen records from high-altitude lacustrine sequences in the region also show significant changes in plant cover, induced by both climate fluctuations and, particularly, human activity (Pérez-Sanz *et al*., 2011, 2013; Pérez-Obiol *et al*., 2012). Analysis of the combination of palaeo-environmental data from high altitudes and information on fluvial channel dynamics from mid-mountain areas provides the opportunity to identify the causes and consequences of landscape evolution.

The Ijuez River basin is an excellent example of land use changes in the southern Pyrenees and their effects on fluvial channel dynamics. Thus, Martínez-Castroviejo & García-Ruiz (1990) studied the sediment characteristics of the alluvial plain in relation to geomorphic activity in the headwater; Bathurst *et al*. (2007) applied the SHETRAN model to assess the possible consequences of deforestation on sediment delivery and transport; Beguería (2006) investigated land cover changes, and the occurrence of shallow landslides and their accessibility to the Ijuez River; and Gómez-Villar *et al*. (2014) studied recent changes in sediment size and the channel morphology of the Ijuez River. The major geomorphic feature of the alluvial plain is the sequence of distinct sedimentary structures (fluvial terrace, large accumulation of debris flows and the active alluvial plain with a wandering channel). These show that the Ijuez River underwent marked changes in channel morphology and sediment supply from the slopes. The main purpose of the present study was to identify and date the various stages of activity in the alluvial plain, and to relate them to land use/land cover changes that occurred in the last 150 years.

MATERIAL AND METHODS

The Ijuez River is a tributary of the Upper Aragón River, in the Central Spanish Pyrenees (Figure 1). The total area of the basin is 45 km^2. The torrential reach selected for the study comprises the headwater, which occupies an area of 4.87 km^2 between 1180 and 2173 m a.s.l., and a length of 4 km from the uppermost zero-order hollow to the first of five check dams built in the streambed to retain the bedload. The bedrock is composed of extremely faulted and folded Eocene flysch, with alternating beds of sandstone and marl. The relief is characterized by the presence of smooth, wide divides and rectilinear slopes, covered by a stony, clast-supported colluvium. The mean gradient is approximately 25°–30°, but most of the catchment is included between 25° and 35°, and a substantial proportion has a gradient >35°. The steepest gradients are mostly concentrated around the headwater ravines. Shallow landslides have occurred throughout the hillslopes and have evolved into debris flows (Lorente *et al*., 2002, 2003; Beguería, 2006; García-Ruiz *et al*., 2010). The river banks are highly unstable because of lateral channel wandering and undermining.

The climate is sub-Mediterranean, with strong oceanic influences. The mean annual precipitation is 874 mm at Jaca, located 8 km south of the catchment, and is approximately 2000–2200 mm in the upper divide (García-Ruiz & Puigdefábregas, 1982). Most precipitation occurs between October and May. The mean annual temperature is 9–10 °C in the lowest sector of the Ijuez basin. A continuous snowpack is present at elevation above 1650 m between November and April. Snowmelt and spring rainfall lead to large discharges in April and May (Lana-Renault

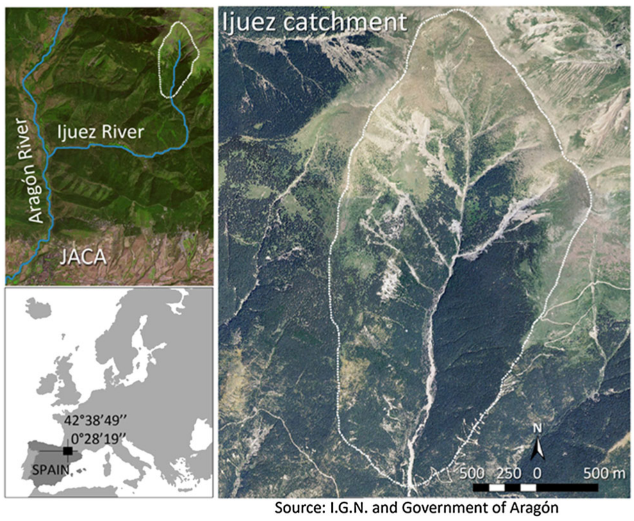

Figure 1. The study area. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

et al., 2010, 2011), whereas summer flows are very low, with some reaches drying up.

Intense rainstorms and large floods are relatively common in this area. For instance, an exceptional hydrological event occurred on 19–21 October 2012 in the Upper Aragón River basin (Serrano-Muela *et al*., 2013), corresponding to a return period of approximately 400–500 years. The discharge of the Aragón River between Canfranc and Jaca increased substantially, probably because of input from the Ijuez River, where signals in tree stems suggested the occurrence of a flood greater than 200 $m^3 s^{-1}$ (approximately 41 $m^3 s^{-1} km^{-2}$).

At elevation less than 1600 m, most of the basin was cultivated on sloping and partially bench-terraced fields during the 19th century (Vicente-Serrano *et al*., 2004; Lasanta-Martínez *et al*., 2005); in many cases, this occurred under shifting agriculture systems, which was a cause of major erosion (Lasanta *et al*., 2006). The five villages in the Ijuez River basin had 656 inhabitants in 1857, 554 in 1900 and 347 in 1950. By 1960, all the human settlements had been abandoned. Farmland abandonment occurred from the beginning of the 20th century, and accelerated in the 1950s, resulting in a complex process of colonization with dense pine (*Pinus sylvestris* L.) forests. During the 1950s, the basin was purchased by the State Administration and partially afforested with *P. sylvestris* and *Pinus nigra* ssp. *salzmannii* to reduce sediment yield and transfer to the Yesa reservoir, which is located 65 km downstream, in the Aragón River. Since that time, the basin has been completely abandoned.

The sub-alpine belt (>1600 m a.s.l.) was also deforested (most likely in the Middle Ages; Montserrat, 1992) to enlarge the area of summer pastures. This caused extensive erosion particularly involving shallow landslides (García-Ruiz *et al*., 2010). Declining livestock grazing in the sub-alpine belt has also contributed to the expansion of the forest. Nevertheless, the presence of eroded soil makes rapid recolonization difficult.

A survey based on field and aerial images was carried out to identify distinct depositional environments in the study reach of the Upper Ijuez River. This provided an indication of the main stages in the recent evolution of the torrential reach. Aerial photos from 1957 and orthophotos from 2006 were used to develop land use/land cover maps and to estimate the proportion of the area occupied by different land cover types.

Six woody fragments collected from the alluvial plain were dated following the accelerator mass spectrometry ^{14}C method at the Poznan Radiocarbon Laboratory (Poland); calibration was based on the CALIB 7.0.2 software and the INTCAL 13 curve (Reimer *et al*., 2013). Because of the size and relatively good state of preservation of the woody fragments, it was also possible to prepare sections for microscopic examination, which enabled identification of the tree species. Sections of approximately 20–30 µm were cut using a slide microtone, stained with safranin and mounted in Eukitt mounting medium.

The method of Wolman (1954) was used to measure various parameters of gravels and boulders in the alluvial plain. At selected sampling points, a 25-m tape was placed on the bed, and at each 0.5-m interval, a measurement of the bed material was made to determine its longest axis (a), its shortest axis transverse to the longest axis (b) and its thickness (c). This process was repeated at each sampling point to provide measurements of up to 100 particles (more details are provided by Gómez-Villar *et al*., 2014).

A total of 51 sampling points were selected: (i) 19 in the active channels; (ii) 16 in reorganized debris flows of the active alluvial plain; (iii) 15 in old, non-reorganized debris flows; and (iv) one in the scarp of an old fluvial terrace.

The standard sedimentary index d50 was used for statistical analyses. Regressions were performed between the average size of the particles and the distance from the headwater for each sampling point in the groups (i), (ii) and (iii). Each distance was measured from the uppermost part of the basin to the sampling point. The gradient at each sampling point was measured over a distance of 15 m using a clinometer.

RESULTS

Land Use/Land Cover Changes

Figure 2 and Table I show the spatial distribution of land uses and land cover in 1957 and 2009 in the Upper Ijuez River basin, which is the area drained by the torrential reach in the study. The map for 1957 corresponds to the time when the Ijuez basin had been almost completely abandoned, with only a few cultivated fields remaining in the valley bottom, coinciding with farmland abandonment in rural areas of Spain and the displacement of rural population towards the cities. The effects of a long history of intense human activity are evident in the map, with some abandoned fields and a relatively large area occupied by open forest, corresponding to previously cultivated fields, which had probably been abandoned some decades earlier (Ruiz-Flaño, 1993).

The most notable changes between 1957 and 2006, evident in the land cover maps, are as follows: (i) a generalized

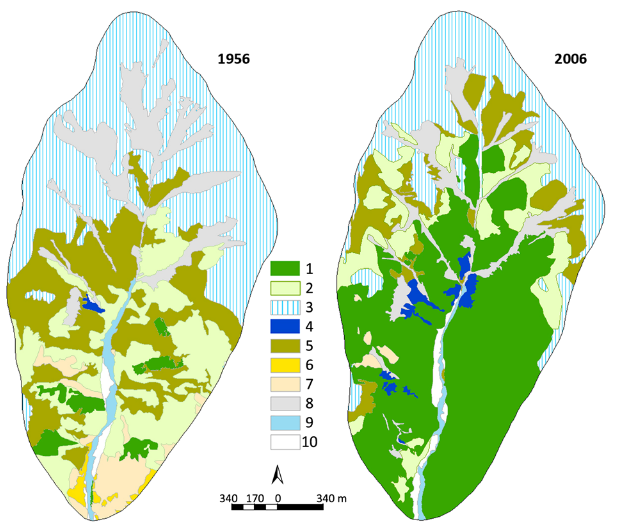

Figure 2. Land use/land cover patterns in the Upper Ijuez basin in 1956 (left) and 2006 (right). 1: dense pine forest; 2: open pine forest; 3: sub-alpine grasslands; 4: deciduous forest; 5: shrubs; 6: cultivated fields; 7: abandoned fields; 8: eroded areas; 9: active alluvial plain; 10: inactive alluvial plain. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Table I. Land cover (1956 and 2006) in the headwater of the Ijuez River basin

	1956		2006	
	Ha	%	Ha	%
Dense pine forest	13·6	2·80	220·4	45·27
Open pine forest	95·2	19·55	55·5	11·40
Sub-alpine grasslands	165·3	33·95	96·9	19·90
Deciduous forest	0·9	0·19	8·3	1·70
Shrubs	113·2	23·24	50·2	10·32
Cultivated fields	4·5	0·92	—	—
Abandoned fields	22·8	4·67	3·0	0·62
Eroded areas	59·7	12·26	41·0	8·42
Active alluvial plain	7·7	1·59	4·6	0·95
Inactive alluvial plain: pines and willows	4·0	0·83	6·9	1·42

expansion of dense pine forests (*P. sylvestris*); (ii) a remarkable decline in the area of sub-alpine grasslands, mainly because of the advance of pine forest towards the upper part of the basin; (iii) a decline in the area occupied by shrubs and open pine forests, which have largely been replaced by dense pine forests; (iv) a decrease in the extent of the eroded areas; and (v) a contraction of the spatial extent of the active alluvial plain.

Sequence of Geomorphic Structures in the Alluvial Plain

The Upper Ijuez River shows initially a very steep gradient (19º) and runs in a narrow incised channel that includes steps related to the geomorphic structure (sandstone outcrops). Then the river flows over a 60-m waterfall, beyond which the longitudinal gradient abruptly reduces to 9° and then progressively declines to 6°–7°. Several tributary ravines having gradients between 28° and 31° join the main channel.

Figure 3 shows detailed views of a short stretch (1.09 km) of the study reach in the Upper Ijuez River in 1956 (left) and 2009 (right). By 1956, the alluvial plain occupied most of the valley bottom; the image shows the presence of several shifting channels and unstable islands within a typical braided fluvial morphology. The entire alluvial plain appears to be active, given the almost complete absence of vegetation. Most of the riverbanks show the effect of intense erosion because of river channel wandering. The small, slightly darker areas were probably sites of relatively old sedimentation (perhaps only a few years before). By 2009, the torrential reach had substantially narrowed. The image shows that part of the reach had become colonized by trees and shrubs, and although the river was still wandering, it was not directly contacting and eroding the rocky banks, thus decreasing sediment supply.

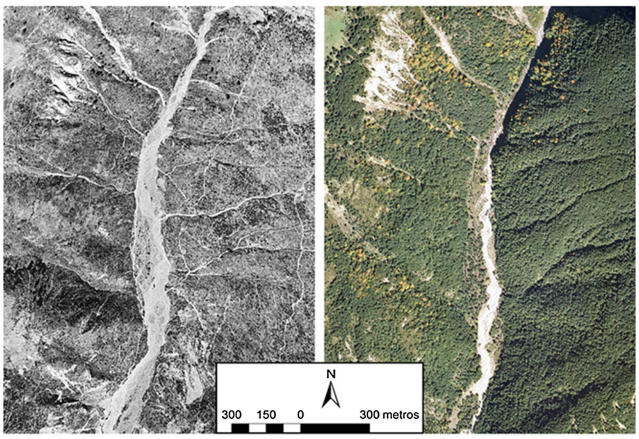

Figure 3. Images showing a selected reach of the Upper Ijuez River in 1956 (left) and 2006 (right). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Four types of geomorphic and sedimentary structures were identified in the current alluvial plain during the summer of 2013 (Figure 4):

(i) The active channel is 2–3 m wide and wandering, with subdivisions being relatively common. The channel is incised approximately 1–1.5 m into the active alluvial plain, with frequent riffles caused by the presence of large boulders and woody debris. The active channel clearly changes in position during large floods, particularly because of scouring, lateral erosion and the transport of large volumes of sediment, which occasionally blocks the water flow.

(ii) The active alluvial plain is composed of a large sediment accumulation with boulders and cobbles derived from remobilized debris flows. With the exception of a short reach, where the Ijuez River flows into a deep narrow canyon (approximately 8 m wide), the active alluvial plain is 80–100 m wide and is characterized by a braided-like morphology and chaotic accumulation of coarse materials (Figure 5). No fine sediment is visible on the surface, or in trenches excavated by channel scouring, and consequently the structure is clast or boulder supported.

(iii) A small fluvial terrace is apparent, particularly on the right side of the valley bottom. It shows a short lateral development (<5 m at the starting point, up to 150 m in at some downstream sites) and directly contacts the hillslope of the valley. The terrace has a matrix-supported structure (Figure 6). It is 3 m above the alluvial plain in the uppermost sector of the study reach (immediately downstream of the waterfall), where a localized 1.5-m-high sub-terrace is also evident. In the lower sector of the study reach, the fluvial terrace is almost 4 m high. The incision that caused

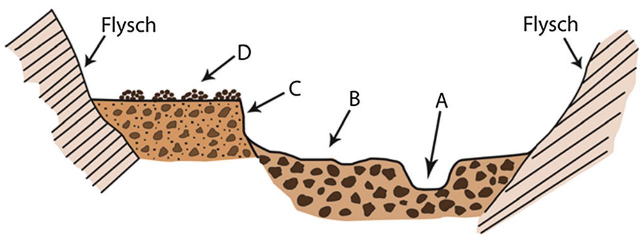

Figure 4. Idealized organization of the sedimentary environments in the upper torrential reach of the Ijuez River. A: active channel; B: active alluvial plain; C: fluvial terrace; D: debris flow deposits. The width of the valley bottom is approximately 150 m. The difference in height between the fluvial channel and the upper part of the terrace is 4 m. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Figure 5. Sediment accumulation in the active alluvial plain of the Ijuez River. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

the development of the terrace also disconnected the tributaries from the main channel, such that the tributaries appear to be perched 3 m above the alluvial plain; no incision has occurred in the tributaries to form a direct connection to the main channel (Figure 7).

(iv) The fluvial terrace appears to be covered by debris flows that are characterized by the chaotic deposition of cobbles and boulders arranged in convex lobes, the upper parts of which are approximately 2–3 m above the terrace surface (Figure 6). The cobbles and boulders are covered by black patina, which indicates that remobilization has not occurred since deposition. The terrace has been recolonized by *P. sylvestris* between the debris flows, although no tree is more than 30 years old. The debris flows have a boulder-supported structure. Figure 6 shows the large structural differences between the fluvial terrace and the debris flows. Both sedimentary bodies are sharply separated, with paleosoil evident in between.

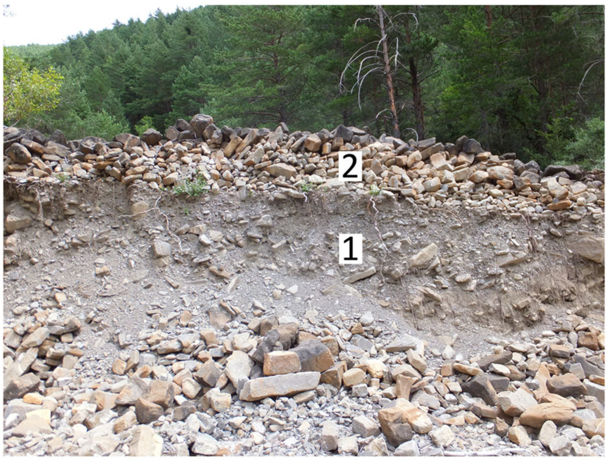

Figure 6. The fluvial terrace (1) and the debris flows (2). The direction of stream flow is from left to right. Note the completely different structures of the terrace and the overlying debris flows. Both the terrace and the debris flows are an important sediment source for the alluvial plain. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Figure 7. Mouth of one of the tributary ravines, showing recent incision of the Ijuez River and the absence of incision in the tributary. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

All of the sedimentary environments show a predominance of large particles, with the (a) axis of many exceeding 100 cm. Figure 8 shows the grain size distribution in relation to distance from the headwater, in the channel, the active alluvial plain and the old debris flows. There was a clear and statistically significant decrease in grain size for the (b) axis along the channel ($r^2 = 0.694$; $p = 0.000$) and the alluvial plain ($r^2 = 0.436$; $p = 0.005$) in the study reach, indicating the effects of both sorting and abrasion. Nevertheless, the analysis showed that there was wide dispersion of the points around the regression lines. In general, the average grain size at each sampling point was greater in the channel than in the alluvial plain. For the old debris flows, the grain size distribution did not show any relationship to distance, indicating chaotic organization of the particles and the absence of reorganization by water flow following sedimentation.

It is noteworthy that the values for both the (a) and (b) axes of particles in the channel are higher than reported by Martínez-Castroviejo & García-Ruiz (1990) for similar sampling points in the same study reach of the Ijuez River. In both cases, the relationships between grain size and distance yielded significant coefficients of determination ($r^2 = 0.694$ for 1990; and $r^2 = 0.660$ for 2013; $p = 0.000$ in both cases). The regression line for the current channel showed a slightly steeper gradient (Figure 9).

The Woody Fragments and the Radiocarbon Dates

Six woody fragments from the study reach were dated using the accelerator mass spectrometry ^{14}C procedure (Table II). The samples were collected from within the sedimentary bodies, five in the old debris flows (samples 2–6) and one in the trench of the 1.5 m fluvial terrace (sample 1). Samples 2–5 were from relatively large wood pieces, whereas samples 1 and 6 were obtained from well-preserved stems. The samples were identified as being of *P. sylvestris* type (García & Guindeo, 1988; Schweingrüber, 1990). This type includes *P. sylvestris*, *Pinus uncinata Mill.* and *Pinus nigra*, which are difficult to distinguish, especially in charcoalified

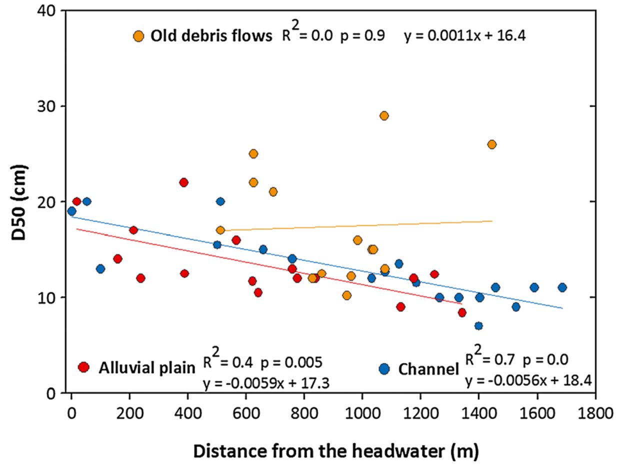

Figure 8. Grain size distribution (d50, (b) axis) as a function of distance along the channel, the alluvial plain and the old debris flows. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

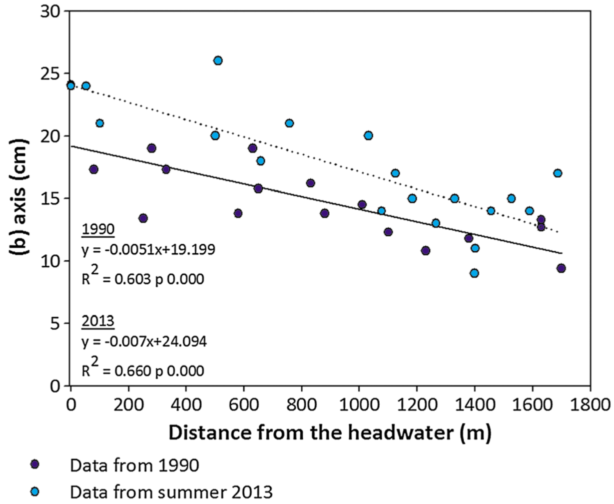

Figure 9. Comparison of the grain size distribution with distance from the uppermost sector of the headwater in 1990 and 2013. Data for 1990: Martínez-Castroviejo & García-Ruiz (1990). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

remains (Roiron *et al.*, 2013). However, the presence of features typical of *P. sylvestris* (i.e. thin-walled epithelial cells in axial and radial resin ducts, and concrescent to reticulate tooth-shaped walls in radial tracheids) point to *P. sylvestris* as the most likely species. This species is currently the most common conifer in the montane belt of the southern Pyrenees. It is noteworthy that the dates obtained for the fragments were in the range 100–115 cal years BP, with sample 6 being the youngest (107 ± 25 cal years BP) and sample 3 the oldest (115 ± 30 cal years BP).

Nevertheless, one of the samples comprised diffuse porous wood with solitary or occasionally clustered pores and had simple perforation plates, large simple ray-vessel pits, and uniseriate and biseriate heterogeneous rays. All these features suggest an arboreal member of the genus *Salix* (Schweingrüber, 1990), which in this context indicates a tree living on the alluvial plain.

DISCUSSION

The Upper Ijuez River has a braided-like morphology, which is characterized by the presence of accumulated coarse sediment, a steep longitudinal gradient, a wandering and changing channel, and large volumes of sediment supplied by tributaries and river banks. These factors explain most of the sediment characteristics, particularly the abundance of cobbles and boulders and the irregular spatial organization of the grain size distribution (Rice & Church, 1998; Hoey & Bluck, 1999; Gómez-Villar *et al.*, 2014). The development of a braided morphology is a common characteristic of rivers that cross the flysch sector of the southern Pyrenees, as a consequence of the typical high sediment yield and delivery from the hillslopes (García-Ruiz & Puigdefábregas, 1982; Gómez-Villar & García-Ruiz, 2000; Lorente *et al.*, 2002; Gómez-Villar *et al.*, 2014). Natural erosion processes were favoured and enhanced by deforestation related to intense human activity. Cultivation of steep slopes, frequently under shifting agriculture systems (Lasanta *et al.*, 2006), the occurrence of human-induced fires to control the expansion of thorny shrubs and overgrazing are considered the main reasons for the development of gullies and shallow landslides, which evolve into debris flows (Lorente *et al.*, 2002, 2003).

Four distinct geomorphic and sedimentary environments have been found in the valley bottom: a fluvial terrace, debris flows over the terrace, the currently active alluvial plain and the current channel. This suggests the occurrence of changes in sediment supply, geomorphic processes in the hillslopes and flood intensity. The oldest sedimentary structure is a fluvial terrace perched 3–4 m above the current alluvial plain. This terrace shows a fluvio-torrential character, as suggested by the presence of cobbles within a matrix-supported structure. The presence of a relatively abundant fine matrix is consistent with the occurrence of floods in a context of partial deforestation, with erosion in some parts of the basin. There is no information on the age of the terrace, although deforestation processes have been recorded in various high-altitude paleo-environmental sequences formed before and since the Middle Ages (Montserrat, 1992; Pérez-Sanz *et al.*, 2011; Pérez-Obiol *et al.*, 2012), with drops in arboreal (AP) pollen proportions, which probably indicate an expansion of transhumant livestock. The moister conditions that occurred during the LIA (AD 1300–1850) in the Pyrenees (Morellón *et al.*, 2012) are also consistent with the development of shallow landslides and gullies that produced a mixture of fine and coarse sediments able to form the terrace. Nevertheless, in the absence of accurate chronological control, uncertainty remains about the causes (human–climate interactions) and time of formation of the deposit.

The 1956 land cover map of the basin confirmed that deforestation was a generalized feature and that a large proportion of the slopes (including very steep areas) was

Table II. Accelerator mass spectrometry radiocarbon dates for woody fragments found in the Upper Ijuez River

Site name	Location	Laboratory Code	Material type	Radiocarbon date (^{14}C AMS year BP)	Calibrated dates (2 sigma cal year BP)	Median probability (2 sigma cal year BP)
Ijuez 1	Fluvial terrace	Poz-57793	Wood	100 ± 25	23–264	110
Ijuez 2	Debris flows	Poz-57796	Wood	105 ± 25	21–266	112
Ijuez 3	Debris flows	Poz-57797	Wood	110 ± 30	12–269	115
Ijuez 4	Debris flows	Poz-57798	Wood	100 ± 30	15–268	112
Ijuez 5	Debris flows	Poz-57799	Wood	100 ± 25	23–264	110
Ijuez 6	Debris flows	Poz-57800	Wood	90 ± 25	26–259	107

cultivated until some decades ago. Eroded areas appeared very active, with some incised ravines in the sub-alpine belt and gullies incising on the old cultivated open forest areas. The most important consequences of this erosion have been soil degradation on the hillslopes, with an increase of soil stoniness and loss of the most fertile soil horizons (Bathurst *et al*., 2007), and the development of a braided pattern mostly induced by extremely high sediment supply. By 1956, the braided morphology occupied most of the valley bottom, where coarse sediment accumulated. Much of the sediment reached the alluvial plain in the form of debris flows. This is a very recent process that occurred approximately at the end of the 19th century or the beginning of the 20th century, as deduced from the age of the debris flows that cover the fluvial terrace. This estimated age is quite convincing because all of the woody samples yielded similar dates. This coincided with the period of maximum population density in the Ijuez basin and presumably with the greatest intensity of deforestation, cultivation of steep slopes, human-induced fires and overgrazing, as is recorded in various palynological sequences from diverse regional lakes including Estaña Lake (670 m a.s.l.; Riera *et al*., 2004; Morellón *et al*., 2011), Montcortés Lake (1027 m a.s.l.; Rull *et al*., 2011) and Basa de la Mora Lake (1914 m a.s.l.; Lasheras-Álvarez *et al*., 2013; Pérez-Sanz *et al*., 2013). Deforestation at the end of the 19th century probably affected all the altitudinal belts, as is suggested by regional pollen records and the presence of *P. sylvestris* woody debris within the debris flow deposits in the Ijuez alluvial plain, which indicates that the montane belt (1100–1600 m a.s.l.) would have been one of the most affected areas. The absence of woody debris of *P. uncinata* suggests that the sub-alpine belt had been deforested some centuries before.

The occurrence of an abrupt change in the sedimentation regime from the fluvial terrace to the debris flows indicates a sudden change in flood magnitude and sediment yield, with the arrival of large volumes of sediment from the hillslopes (Martínez-Castroviejo & García-Ruiz, 1990). This indicates a dramatic transition or threshold (Church, 2002) from a fluvial or fluvio-torrential regime to one dominated by massive sediment transport without any fluvial reorganization. The application of the SHETRAN model to the Ijuez basin confirmed that deforestation was responsible for the occurrence of many debris flows that were the main sediment sources (Bathurst *et al*., 2007). A large number of studies worldwide have demonstrated that deforestation lowers the rainfall threshold necessary to initiate debris flows, such that they can be generated by rainstorms corresponding to low return periods (Cannon *et al*., 1997, 2001; Nyman *et al*., 2011; García-Ruiz *et al*., 2013b). This is particularly true in the flysch regions, where dense faulting delivers large volumes of sediment and increases the instability of poorly sorted material (Lorente *et al*., 2002). Moody & Martin (2001) reported severe erosion following wildfires, with an approximately 200-fold increase in erosion rates that resulted in aggradation of alluvial fans. Rapid changes in the relationships between slopes and channel were also very common immediately following European settlement in North America, Australia and South Africa, because of extensive clearing that caused complete transformation of river morphologies (Brooks & Brierley, 1997; Liébault *et al*., 2005; Phillips *et al*., 2007; Foster *et al*., 2012). Gómez-Villar *et al*. (2006) attributed the development of alluvial fans in the Iberian Range (Spain) to deforestation and intense human activity, and Beguería *et al*. (2006) noted that most of Pyrenean rivers had braided morphologies at the beginning of the 20th century, which coincided with the maximum extent of cultivated areas and the highest numbers of livestock. Barreiro-Lostres *et al*. (2013) found a marked relationship of the development of the transhumance system, deforestation and agriculture with high sedimentation rates during the Middle Ages in a small lake in the Iberian Range (eastern Spain). Furthermore, several reports show that in other Iberian mountains *P. sylvestris* has been very sensitive to human activities during the last two millennia (Rubiales *et al*., 2010, 2012). Nevertheless, as noted earlier, climate variability must also be taken into account. A clear glacier re-advance occurred in the Pyrenees during the decades at the end of the 19th century and the beginning of the 20th century (Morellón *et al*., 2012), suggesting conditions of increased moisture. In this context, the influence of the unusually large number of catastrophic floods that occurred between 1877 and 1898 cannot be ruled out as the trigger for debris flows, as has been reported by Machado *et al*. (2011) for southeast Spain. Benito *et al*. (2010) suggested that these floods were enhanced by land use changes, particularly deforestation, highlighting the complexity of human–climate interactions (García-Ruiz *et al*., 2008; Serrano-Muela *et al*., 2008).

Farmland abandonment, reforestation and afforestation since the middle of the 20th century resulted in rapid recovery of dense pine forests in the basin, which caused a reduction in the area of the shrub and sub-alpine grassland, and a significant decline in the area affected by erosion. The most important consequences were a decline in sediment yield and a decline in connectivity between the hillslopes and channels, as reported in many areas worldwide (Nadal-Romero *et al*., 2012; Quiñonero-Rubio *et al*., 2013). In our study area, the major tributary ravines are still very active, although their source areas have been reduced, and many others are currently covered with pines and do not have any direct connection with the main channel. The contribution of debris flows to total sediment transport has been estimated to be only 13% (Bathurst *et al*., 2007). Beguería (2006) also detected a decline in the occurrence of debris flows and their contribution to sediment yield, although some debris flows have developed in the most degraded areas, even though they were protected by forest (Lorente *et al*., 2002).

The progressive incision of the active channel and the relatively recent development of a terrace level seem to be related to a decline in sediment yield from the headwater, resulting in scouring of the channel to a depth of at least 1 m in relation to the active alluvial plain. The latter has also been incised to 3–4 m below the terrace level. Scouring is a process common to many rivers in the Mediterranean (García-Ruiz & Lana-Renault, 2011; Ibisate *et al*., 2013; Segura-Beltrán & Sanchis-Ibor, 2013; Sanchís-Ibor & Segura-Beltrán, 2014) and alpine regions, and is a consequence of a decreased sediment supply following farmland abandonment and forest recolonization (Kondolf *et al*., 2002; Marston *et al*., 2003; Liébault *et al*., 2005; Beguería *et al*., 2006; Boix-Fayos *et al*., 2007; Keesstra, 2007; Surian & Cisotto, 2007). Natural vegetation rehabilitation is also responsible for a substantial decline in sediment yields and general landscape changes in the Loess Plateau, China (Zhao *et al*., 2013). This situation can also be deduced from palynological sequences, given that clear increases in the AP proportions, an upward displacement of the forest tree line and decreases in anthropogenic indicators (ruderals, cultivated plants) were commonly recorded during the last decades of the 20th century (Pérez-Sanz *et al*., 2013), suggesting less human pressure.

Nevertheless, some studies have indicated that a decrease in sediment supply from the hillslopes does not necessarily result in a decrease in bedload transport in the channel, because channel scouring and lateral erosion compensate for the deficit in sediment yield by becoming local sediment sources. In such cases, bank erosion becomes the main sediment source (Surian & Cisotto, 2007), as was observed in the Ijuez River, where the terrace and the old debris-flow deposits directly contribute sediment to the alluvial plain. Consequently, bedload outputs from a catchment are not always a good indicator of its geomorphic activity (Trimble, 1999), because some slope sediment sources can be substituted by other sources in the alluvial plain.

The incision of the Ijuez River is a recent process. Aerial photos from 1956 show a wide active alluvial plain occupying most of the valley bottom. At that time, forests represented a small proportion of the total area; the hillslopes were affected by intense gullying, shallow landsliding and sheet wash erosion; and a number of ravines were connected directly to the fluvial channel. This indicates that incision has occurred in the last few decades, coinciding with a decline in sediment yield and delivery from the hillslopes as a consequence of farmland abandonment and reforestation. The recent development of fluvial terraces resulting from reforestation has been reported in other Mediterranean mountains, including the southern Alps (Liébault & Piégay, 2001, 2002; Piégay *et al*., 2004), the Tatra Mountains (Lach & Wyzga, 2002), the southern Appenines (Garfi *et al*., 2007) and the Balkans (Keesstra *et al*., 2005). For instance, Piégay *et al*. (2004) reported that the Drôme River (French Prealps) underwent channel aggradation between 1835 and 1945 because the basin was subjected to deforestation, erosion and frequent intense floods. More recently, spontaneous reforestation following farmland abandonment led to a decline in sediment yield (particularly bedload), which caused channel degradation. In the same area, Liébault & Piégay (2002) observed channel narrowing resulting from a combination of climate change following the LIA and basin reforestation following rural depopulation. In a study of the Dragonja River (Slovenia), Keesstra *et al*. (2005, 2009) reported a similar change in the streambed between 1954 (29% of forest cover) and 2002 (73%), with a 68% decrease in channel width and the development of a terrace, and a 69% decline in the total hillslope sediment delivery. A similar trend towards channel narrowing and incision, including a change from braiding to single-thread channels, was reported to have been caused in Italian rivers by gravel mining, reforestation and flood control works (Surian *et al*., 2010). Thus, a series of river channels in northeastern Italy underwent substantial adjustment during the last century, including narrowing by 76% and incision by up to 8.5 m, mainly because of in-channel mining. There is general agreement that gravel-bed rivers draining reforested watersheds are affected by a marked narrowing and scouring (Liébault *et al*., 2005). This contributes to the partial colonization of the alluvial plain by riparian vegetation, as indicated by the decline in the area occupied by the active channel in the Ijuez River.

A noteworthy result was obtained from a comparison of the current grain size distribution with that calculated more than 20 years ago, following the same sampling method in the same stream reach. This showed that mean grain size in the active channel is larger than in 1990, and an armour layer has developed in a process similar to that reported for other southeastern rivers in France (Liébault & Piégay, 2001). This does not necessarily mean that geomorphic processes in the hillslopes are more active now or are characterized by greater energy. Most probably, it is related to decreased sediment yield from the hillslopes and the consequent channel incision, which has carried out most of boulders except for the largest, and consequently the mean grain size has increasing.

CONCLUSIONS

The presence of distinct sedimentary and geomorphic environments in the valley bottom of the Ijuez River indicates changes in sediment yield and delivery from the hillslopes, and in sediment connectivity between the hillslopes and the channel. These changes seem to be particularly related to land cover changes since the mid-19th century.

(i) A fluvio-torrential terrace that is located 3–4 m above the current alluvial plain is the oldest sedimentary structure in the valley bottom. It has a matrix-supported structure, with abundant fine particles. The sedimentation process that formed the terrace probably corresponds to a period when most (if not all) of the catchment was still covered with forests. No detailed information exists on the sediment age.

(ii) Above the terrace, there are a number of debris flows that represent a sudden change in the geomorphic and sediment transport regimes. The debris flows are composed of cobbles and boulders arranged in a chaotic manner, with a cobble-supported structure. A thin paleosoil layer is occasionally apparent between the terrace and the debris flows. The debris flows were dated at 100–115 cal yr BP, which coincides with the end of the LIA, and the period of the highest population density and the greatest human pressure on the montane and sub-alpine belts. Deforestation was the main consequence of intense human activity, accompanied by the recurring use of fire and cultivation on steep slopes, which resulted in extensive soil erosion. This period probably coincided with the occurrence of several exceptional floods, as reported in other sites on the Iberian Peninsula, which could have triggered debris flows that covered (entirely or partially) the alluvial plain.

(iii) Depopulation and farmland abandonment, followed by reforestation of the past cultivated areas and a reduction in the area affected by erosion, led to a decline in erosion and sediment transport. The consequence was a progressive and relatively rapid incision and narrowing of the active alluvial plain. Channel incision contributed to the development of an armour layer, so that the grain size on the surface tends to be greater now than it was 20 years ago. The occurrence of very active incision and bank erosion suggests that bedload transport is still very active in the headwater of the Ijuez River, even though the connectivity between the hillslopes and the channel has declined, reducing the supply of bedload. As bedload output is not always a good indicator of the geomorphic activity of a catchment, it is crucially important to develop a regional contextualization of the past climate and to assess the vegetation evolution that occurred at different altitudes in the area.

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