Article:

Llena, M, Vericat, D, Cavalli, M et al. (2 more authors) (2019) The effects of land use and topographic changes on sediment connectivity in mountain catchments. Science of the Total Environment, 660. pp. 899-912. ISSN 0048-9697

https://doi.org/10.1016/j.scitotenv.2018.12.479

The effects of land use and topographic changes on sediment connectivity in mountain catchments

M. Llena, D. Vericat, M. Cavalli, S. Crema, M.W. Smith

PII: S0048-9697(18)35375-0
DOI: https://doi.org/10.1016/j.scitotenv.2018.12.479
Reference: STOTEN 30313

To appear in: *Science of the Total Environment*

Received date: 29 June 2018
Revised date: 12 November 2018
Accepted date: 31 December 2018

Please cite this article as: M. Llena, D. Vericat, M. Cavalli, S. Crema, M.W. Smith , The effects of land use and topographic changes on sediment connectivity in mountain catchments. Stoten (2019), https://doi.org/10.1016/j.scitotenv.2018.12.479

The effects of land use and topographic changes on sediment connectivity in mountain catchments

Llena, M. (1), Vericat, D. (1,2), Cavalli, M. (3), Crema, S. (3), Smith, M.W. (4)

(1) Fluvial Dynamics Research Group, Department of Environment and Soil Sciences, University of Lleida, Lleida, Spain, (2) Forest Science and Technology Centre of Catalonia, Solsona, Spain, (3) Research Institute for Geo-Hydrological Protection, Padova, Italy, (4) School of Geography, University of Leeds, Leeds, UK.

ABSTRACT

Understanding the evolution of sediment connectivity associated with different land use and topographic changes is a prerequisite for a better understanding of sediment budgets and sediment transport processes. We used the Index of Sediment Connectivity (IC) developed by Cavalli et al. (2013) based on the original approach by Borselli et al. (2008) to study the effects of decadal-scale land use and topographic changes on sediment connectivity in mountain catchments. The input variables of the IC (i.e. land cover and topography) were derived from historical aerial photos using Structure from Motion-Multi View Stereo algorithms (SfM-MVS). The method was applied in different sub-catchments of the Upper River Cinca Catchment (Central Pyrenees), representative of three scenarios: (a) Land cover changes; (b) Topographic changes in agricultural fields (terracing); and (c) Topographic changes associated with infrastructure (road construction). In terms of land cover changes, results show that although connectivity is increased in some areas due to the establishment of new field crops, for most of the study area connectivity decreased due to afforestation caused by rural abandonment. Topographic changes due to the establishment of agricultural terraces affected connectivity to a larger degree than land cover changes. Terracing generally reduced connectivity due to the formation of flat areas in step-slopes, but in certain points, an increase in connectivity caused by the topographic convergence produced by terraces was observed. Finally, topographic changes associated with road construction greatly modified surface flow directions and the drainage network, resulting in changes in connectivity that may affect erosional processes nearby. The methodology used in this paper allows to study the effects of real decadal-scale land use and topographic changes on sediment connectivity and also evaluating and disentangling those changes. Furthermore, this approach can be a useful tool to identify potential risks associated with morphological and land use changes, involving road infrastructures.

Keywords: Sediment connectivity, Index of sediment connectivity, land use and topographic changes, Mountain catchments, afforestation, terracing

1. INTRODUCTION

Connectivity is an emergent property of a geomorphic system (Wohl et al., 2018) and can be defined as the degree to which a system facilitates the transfer of water and sediment through coupling relationships among its components (Heckmann et al., 2018). Sediment connectivity represents the potential for a specific particle to move through the compartments of a system at different temporal scales (Hooke, 2003; Bracken and Croke, 2007; Fryirs, 2013). In the particular case of the fluvial system, this term refers to the transfer of sediments from the hillslopes to the channels (lateral connectivity *sensu* Fryirs et al., 2007), and along the channels (longitudinal connectivity *sensu* Fryirs et al., 2007). Sediment connectivity depends on the structural characteristics of the surfaces (e.g. topography, roughness) and the processes driven by the fluxes of water and sediments (e.g. erosion and sedimentation). The interaction of these two components will determine the sediment balance at multiple temporal scales and, consequently, the evolution of landforms and the changes in landscape properties (Bracken et al., 2015). Therefore, connectivity is not static and varies over time and space due to the interaction between the external forcing (mainly precipitation and temperature), landscape properties (i.e. structural connectivity), and the magnitude of the water and sediment fluxes (i.e. functional connectivity), that will ultimately determine the frequency, distribution and magnitude of erosional and sedimentation processes. Additionally, connectivity can be modified by anthropogenic changes that affect these processes and interactions. The significance of these impacts on connectivity will be determined by the geomorphic sensitivity of the landscape: the response of the system to an environmental change or disturbance and its recovery (Brunsden and Thornes, 1979; Harvey 2001; Wohl, 2017).

The assessment of sediment connectivity is particularly relevant in mountain environments because they are characterized by a complex and rugged morphology (Cavalli et al., 2013) and are very sensitive to disturbances by human activities. Population increased in Mountain areas of the Mediterranean region since the end of the 15th century, reaching a peak in the middle of the 19th century. In the case of the Pyrenees, in both the mountain areas and the valley bottoms, population growth was responsible for the progressive expansion of the cultivated area at the expense of forest cover (García-Ruiz and Lopez-Bermudez, 2009). In addition, steep slope areas in this region were gradually transformed into terraced arable lands (Larsen et al., 2016). Agricultural terraces have significant impacts on hydrological and geomorphological processes as they alter the distribution of local slopes and soil properties, and frequently modify the natural drainage patterns of the landscape (Arnáez et al., 2015; Lizaga et al., 2016; Calsamiglia et al., 2017). Terrace construction significantly reduces water and sediment connectivity between the hillslopes and the channels; ultimately, terraces interrupt or delay overland flow and consequently soil erosion and sediment transport (Van Dijk et al., 2005; Bellin et al., 2009).

During the second half of the 20th century, however, the majority of the mountain areas in the Mediterranean region suffered significant land use changes driven by agricultural abandonment as a consequence of the strong depopulation (García-Ruiz and Lana-Renault, 2011; Lopez-Moreno et al., 2011). This abandonment induced an increase in the vegetation cover, both by planting by public administrations (Gracía-Ruiz and Lopez-Bermudez, 2009) and by natural recolonization (Keesstra et al., 2009). The impacts of these land use changes on catchment-scale sediment and water supply, have been intensified by the effects of climate change (Macklin et al., 2012; Buendia et al., 2016; Coulthard and Van de Wiel, 2017). Several studies have pointed to a decrease of the hydrological and geomorphic activity due to climate change (Gallart and Llorens, 2003; Liébault et al., 2005; Beguería et al., 2006; López-Moreno et al., 2009; Garcia-Ruiz, 2010). For instance, Beguería et al., (2006) reported a runoff reduction of around 30% for the past 50 years in the Pre-Pyrenean region, while Buendía et al. (2015) concluded that climate change and afforestation reduced sediment yield by around 8% in a 65 km^2 basin. More recently, Lizaga et al. (2019) analysed the impact of land use changes in soil properties in a catchment of the Pyrenees during the second half of the 20th century, reporting an increase of the soil properties, in terms of soil organic carbon and total nitrogen, related to the afforestation process. In addition to these environmental changes, it is worth considering all direct impacts on hydro-sedimentary processes caused by urbanization and associated constructions (Ferreira et al., 2017). Although the impacts of disturbances due to road construction are very localized (i.e. space and time), they heavily modify the topography and, consequently, connectivity, affecting the fluxes of water and sediment, and, potentially triggering a series of hydrological and geomorphological adjustments well beyond the disturbed zone (Jones et al., 2000, Tague and Band 2001; Bordoni et al., 2018).

The potential of a landscape to be connected has been widely analysed through the application of Sediment Connectivity Indices (e.g. Borselli et al., 2008; Cavalli et al., 2013; Quiñonero et al., 2013; Gay et al., 2015; Heckmann et al., 2018). Raster-based indices provide an opportunity to quantitatively assess the spatial distribution of sediment connectivity. The Index of Sediment Connectivity (hereafter IC) developed first by Borselli et al. (2008), and further modified by Cavalli et al. (2013), has been used in many applications (e.g. Goldin et al., 2016; Lopez-Vicente et al., 2013; Lopez-Vicente et al., 2016; Ortíz-Rodríguez et al., 2017; Persichillo et al., 2018). In mountain environments, Goldin et al. (2016) applied the IC to infer the changes in sediment dynamics as a result of glacier retreat. In terms of land use changes, Lopez-Vicente et al. (2013) and Lopez-Vicente et al. (2016) applied the first version of the IC to analyse changes in connectivity under different scenarios of land uses and land abandonment in two Mediterranean mountain catchments. Results show that erosion rates decrease inversely with the increase of vegetation cover and with the preservation of the agricultural terraces. Quiñonero et al. (2013) developed and applied the Catchment Connectivity Index (hereafter CCI) in a Mediterranean catchment with different land uses and check dam scenarios. Results indicate that the CCI allows identification of landscape properties that have a larger impact on sediment (dis)connectivity at the catchment scale. Persichillo et al. (2018) applied IC in two small catchments in the Apennines (Italy) to investigate three different scenarios of changes induced by human activities related to drainage system, road network, and land use. Results highlighted the changes in the distribution of connectivity as a function of human-induced variations. Finally, in active volcanic areas, Ortíz-Rodríguez et al. (2017) used a modified version of the IC to assess the lateral flow contribution of pyroclastic sediments on the main channels.

This paper analyses the effects of land use changes on sediment connectivity using the IC developed by Cavalli et al. (2013). It is worth noting that IC is primarily a structural sediment connectivity index: it aims to express the control of topography on the potential of the different compartments of a system to be connected. The novelty of the approach used here lies in the dual consideration of both land cover and topographic variations on the assessment of sediment connectivity through time. The previous studies that applied the IC to investigate the effects of land use changes on connectivity (e.g. Lopez-Vicente et al., 2016; Lizaga et al., 2016; Persichillo et al., 2018), simply modified a land-cover based weighting factor that represents the impedance to sediment flux (e.g. *C*-factor or Manning's *n*) implemented in the IC, and topography, another input variable for the computation of the IC, often is assumed to remain unchanged (i.e. a single digital terrain model is used). Therefore, there is a knowledge gap related to studies which analyse changes in the IC through taking into account not just the land cover properties but also the topography (i.e. using the 'real' terrain model in each IC assessment). We argue herein that the use of static topography may not adequately capture the changes in connectivity and, consequently, we have attempted to consider the topography associated to each period under investigation. From the methodological point of view, the novelty of our study lies in the application of Structure from Motion (SfM) photogrammetry using historical aerial photos to obtain historical orthomosaics and topography for quantitative landscape analyses as the bases of the assessment of multi-temporal changes on sediment connectivity.

Specifically, IC maps were produced before and after the *landscape disturbances*. Three different scenarios of land use change were analysed in a representative Pyrenean Mountain catchment (the Upper Cinca). Changes associated with (i) land cover; (ii) terracing; and (iii) road construction were quantified. These three scenarios provide an ideal data set to analyse the sensitivity of the different changes on the potential of the sediment to be transferred through the different compartments of the catchment (i.e. structural connectivity) and, ultimately, to be supplied to the mainstream.

2. STUDY AREA

The Upper Cinca catchment is located in the headwaters of the river Cinca catchment (8300 km^2), in the centre of the south face of the Pyrenees (NE Iberian Peninsula; Figure 1). The upper catchment, above the Mediano Reservoir (435 hm^3), covers a total area of 1565 km^2 and is composed by two sub-catchments: the Ara (715 km^2) and the Cinca (850 km^2). The Upper Cinca catchment is characterized by a complex morphology. The elevation ranges from 522 m.a.s.l. at the outlet to 3375 m.a.s.l. on the Posets Peak at the headwaters (Figure 1A). The climate is typical of Mediterranean mountainous areas with a mean annual precipitation of around 1100 mm, ranging from 800 mm in the lowlands to 1600 mm at high elevations (López-Martín et al., 2007). Strong inter-annual and seasonal variability of precipitation and temperature, and local conditions (e.g. due to relief, lithology and land use) create a highly heterogeneous landscape. Higher parts of the catchment are dominated by bare soil/rock, meadow and scrublands, valley bottoms are mainly used for agriculture, and intermediate elevations covered by woodlands and scrublands comprise the majority of the catchment.

Four small sub-catchments (around 10 km^2) of the Upper Cinca catchment were selected to represent three different scenarios of land use changes: Aran and Soto (Scenario 1: Changes associated with land cover); Pocinos (Scenario2: Changes by terracing); and Fiscal sub-catchments (Scenario 3: Changes by road construction; see the location in Figure 1). In the following sections the main characteristics of the sub-catchments are presented along with the reasons for including each study area in a specific scenario.

Aran sub-catchment

The Aran sub-catchment (9.2 km^2) is located in the upper part of the Ara River. Between 1957 and 2010, forest cover in this basin almost doubled from 43% to 81% of the total surface of the catchment (Figure 3). This increase resulted in a decrease in meadow and pasture areas, mainly located above the timberline, and also a decrease in bare soil areas, such as land crops in the lower parts of the valley, and sediment active areas located in the upper parts of the catchment (i.e. erosional features) and in the valley bottom (i.e. active channels; Figure 3). The increase in forest cover during the second half of 20th century is representative of many Pyrenean mountain catchments and mainly driven by both land crop abandonment and decreasing grazing due to depopulation (e.g. García-Ruiz et al., 1996; Gallart and Llorens, 2003; García-Ruiz and Lana-Renault, 2011; Lopez-Moreno et al., 2011) and climate change (e.g. Lopez-Moreno et al., 2011; Macklin et al., 2012; Buendia et al., 2016; Coulthard and Van de Wiel, 2017).

Soto sub-catchment

The Soto sub-catchment (10.1 km^2) is located in the lower part of the Upper Cinca near the outlet and is characterized by a large bare surface area composed mainly of field crops and badlands. This basin is virtually the only sub-catchment in the Upper Cinca that has not suffered agricultural abandonment during the study period (1957-2010); contrarily, an increase of the area of crop fields has been observed. There was a small decrease in forested areas (from 57 to 51%) and a corresponding increase in bare soil area (from 14 to 20%; Figures 4A and 4B). In 1957 there was a heterogeneous or patchy spatial distribution of the different land uses, sparse forest in the highest parts of the sub-catchment and a few patches of forest cover in the lower parts of the sub-catchment (Figure 4A and 4B). Bare areas composed of small land crops, agricultural terraces, and badlands. However, in 2010 the tree density in the forested areas increased, especially the upper parts. This is mainly due to the decrease of the extensive activities caused by rural abandonment and changes of the main economic activities in mountain areas (García-Ruiz and Valero-Garcés, 1998; Lasanta-Martinez et al., 2005). Badland surface area remained stable throughout the study period. Additionally, the maps indicate that the small crop fields located in the upper parts of the sub-catchment were abandoned and the crop fields in the flatter areas remained, even increasing their surface due to the unification of existing plots or the creation of new ones by means of ploughing and forest harvesting (Tague and Band, 2000; Figure 4A). The abandonment of upland small plots was also driven by the mechanization of the agriculture; except for rare occasions, only the farmlands where (i) machinery can enter, (ii) an access road is available, (iii) a certain slope threshold is not exceeded, and (iv) a size threshold is exceeded, are cultivated (García-Ruiz and Lopez-Bermudez, 2009).

Pocinos sub-catchment

The Pocinos sub-catchment (7.4 km^2), located in the middle part of the Upper Cinca. Most of the surface is covered by agricultural terraces, which due to rural abandonment, have been fully covered by vegetation. The forest surface doubled (from 31% in 1957, to 64% in 2010), while the meadow (from 44% to 18%, respectively) and bare soil (from 25% to 18%) tend to decrease. The main part of the sub-catchment (i.e. 58%) did not undergo significant changes. The rest of the sub-catchment experienced afforestation (i.e. 37%), especially the areas with abandoned terraced fields. Finally, only 5% of the surface suffered deforestation during the study period. These changes are driven by the construction of new roads or the creation of firewalls in the middle part of the sub-catchment and also a little area near to the outlet which was affected by a forest fire in 1991 (Figure 5A).

Fiscal sub-catchment

The Fiscal sub-catchment (15.6 km^2) is located in the middle part of the River Ara catchment. This sub-catchment has also experienced a significant increase in forest cover (i.e. from 50% of the total surface in 1977 to 72% in 2010) and a reduction in meadow and bare surfaces during the study period (Figure 7A and 7B). Furthermore, during the beginning of the 21st century, a road with a length of 5 km and an average width of 20 m was constructed in this sub-catchment. Regarding the impacts of the road construction, Llena et al. (2018) recently analysed the magnitude of the topographic changes along the road, which resulted in a net sediment mobilization of about 900,000 m^3 of material, mainly due to the excavation of material in the slopes (i.e. extraction) and to the infilling in depressions or deep channels (i.e. deposition). Roads influence the overall sediment transfer in two ways, by inducing erosion downslope of the road, and by capturing sediment coming from above the road and delivering them downstream (Wemple et al., 2001). Due to the induced effects on flow paths and consequently on runoff, topographic changes due to roads may have a localised effect on connectivity.

3. METHODS

3.1 Data preparation

Sediment connectivity for the different scenarios was mapped using the Index of Connectivity (IC) developed by Cavalli et al. (2013), which is based upon the original approach by Borselli et al. (2008). This index aims at evaluating, at the pixel scale, potential connectivity between hillslopes and features which act as targets or storage areas (e.g. catchment outlet, channel network). Specific information on the computation of the IC is provided in section 3.3.1. In summary, the inputs needed by the IC are: (i) a Digital Elevation Model (DEM), and (ii) land use maps used to calculate the Weighting factor (obtained from orthophotos, see section 3.3.2 for more information). Input variables to compute the IC are obtained differently for historical and contemporary study periods. In the case of the historical study period, black and white aerial photographs from 1957 and 1977 were used. Structure from Motion and Multi-View Stereo Photogrammetry (SfM-MVS) were applied to produce both orthomosaics and point clouds. The complete SfM-MVS workflow is presented in Llena et al. (2018). The 1957 photographs were obtained from Cartographic and Photographic Centre of the Spanish Army (CECAF), and the 1977 photographs from the National Geographic Spanish Institute (IGN). The use of historical aerial photographs to obtain spatial data through SfM-MVS is influenced by the quality and overlap of photograms and the ground control network (see Micheletti et al., 2015; Bakker and Lane 2017 for additional details). In the particular case of this study, we obtained point clouds with an average spatial resolution of 1 pts/m^2 and an average Standard Deviation Error (SDE) of the elevation of 2 m. Additionally, orthomosaics with a resolution of 1 m and an average Root Mean Square Error (RMSE) less than 1 m were also obtained.

In terms of the contemporary period, information from 2010 was used. For this year, a LiDAR dataset (i.e. point clouds) with a resolution of 0.5 pts/m^2 and an elevation accuracy of less than 0.2 m, and an orthomosaic of 0.5 m resolution were both available from the National Geographic Spanish Institute (IGN).

3.1.1 Image classification: land use maps

A supervised image classification of the multi-temporal orthomosaics for each of the study areas was carried out in order to obtain land use maps to derive the different weighting factors required to compute the IC (see more details in 3.3.2.). Three different classes were identified in terms of land cover: bare, meadow and forest. The identification of these classes was limited by the scale, properties (e.g. black and white) and the quality of the aerial photographs. Forest polygons were also used to filter the point clouds in order to create the DEMs as explained below.

3.1.2 Post-processing point clouds: Digital Elevation Models

Each point cloud (SfM-MVS or LiDAR-based) was regularized to the desired resolution using the ToPCAT algorithm (Brasington et al., 2012), as implemented in ArcGIS through the open source Geomorphic Change Detection extension (GCD, available at http://gcd.joewheaton.org/; Wheaton et al., 2010). This algorithm allowed first defining a regular grid of analysis, second sorting all points in each cell, and finally, calculating a series of elevation statistics for each cell. The mean elevation value in each cell was used as an estimate of the mean ground elevation. The grid resolutions were based on the typology and magnitude of the topographic change in each scenario and in relation to the errors reported below (See section 3.3.2 for more details). Finally, the regularised data representing the mean elevation value per grid cell were interpolated to create the DEMs. For this purpose, we used the Natural Neighbours interpolation method implemented in ArcGIS 10.3. It is worth to mention that, for the 1977 series, we used the polygons associated with forest cover to filter the point cloud before to run ToPCAT. We considered the ground elevation in forested areas not well represented when the point cloud is extracted using SfM-MVS applied to aerial photos. This is a common limitation of this method, not present in the LiDAR data sets where the vegetation is already filtered. Therefore, the SfM-MVS-based topographic observations within those areas were erased before running ToPCAT and creating the DEMs.

3.2 Scenarios of change

The three different scenarios were considered representative of changes in Mediterranean mountain catchments. Figure 2 illustrates each of the scenarios including the data set used.

Scenario 1: Changes in land cover. Land cover changes were analysed in two different sub-catchments (Soto and Aran, Figure 1) during two study periods (1957 and 2010). The Aran sub-catchment, as detailed introduced above, is representative of those where forest cover increased (afforestation) by reducing the area of bare soil, meadows and former cultivate areas. On the other hand, the Soto sub-catchment is considered representative of areas that have not experienced changes in land use during the last 50 years. Only a small increase in crop field areas is observed in this sub-catchment (tillage).

Scenario 2: Terracing: topographic changes in agricultural fields. The effect of terraces on sediment connectivity was analysed in a terraced sub-catchment with an important increase of vegetated area due to the land abandonment during the period 1957-2010. In this scenario, the objective was to compare both the effects of afforestation and of the construction of terraces on sediment connectivity, and evaluate which of them have a more significant role on sediment connectivity (i.e. sensitivity of the IC changes). The effect of terracing (alone) was studied for the Pocinos sub-catchment by analysing the surface with the presence and absence of terraces. The situation of 'terrace presence' was analysed using the contemporary (2010) LiDAR-based DEM. In the case of the situation with the 'absence of terraces', these were filtered out (removed) from the 2010 DEM. The terraces observed in 1957 are actually the same as those observed currently, although almost all the field crops have been abandoned and afforestation took place. Terraces were removed by smoothing the 2010 DEM (see section 3.3.2 for more details). In this case, the same land use map (the one obtained for the year 1957) was used to compute the IC for both conditions: terraces and no-terraces. Therefore, considering that the land uses in 1957 were representative of those before terraces were built, we are able to analyse the effects of these structures on sediment connectivity. Additionally, the effect of just land use changes was assessed with a unique topography (i.e. 2010 DEM containing terraces) but using different land use maps (i.e. 1957 and 2010 respectively) to compute the IC. All these combinations permit analysis of which impacts (terracing vs land use changes in a terraced landscape) have a greater effect on sediment connectivity.

Scenario 3: Road construction: topographic changes associated with infrastructure. This scenario is focused in the Fiscal sub-catchment, where a road was built during the period 2006-2010. We compared the IC maps extracted from the contemporary DEM (i.e. 2010 LIDAR dataset) with the 1977 DEM (i.e. SfM-MVS based dataset). The results for both years could not be statistically compared due to the different accuracy associated to each DEM. However, results permit analysis of the impact of the road on connectivity patterns and identification of areas where changes in connectivity may prompt additional impacts (i.e. potential erosion hot spots).

3.3 Assessment of changes in Sediment Connectivity associated with selected scenarios

3.3.1. Index of Sediment Connectivity (IC)

The Index of Sediment Connectivity (IC) was computed using the software SedInConnect 2.3 (Crema and Cavalli, 2018). The IC is defined as:

$$IC = log_{10}\left(\frac{D_{up}}{D_{dn}}\right)$$

where D_{up} is the upslope component and D_{up} is the downslope component. The upslope component (D_{up}) describes the potential for downward routing of the sediment produced upslope, and is estimated as follows:

$$D_{up} = W\ S\ \sqrt{A}$$

where *W* is the weighting factor (i.e. a proxy of impedance to the sediment flux; dimensionless), *S* is the slope (%) and *A* is the upslope contributing area (m^2). The downslope component (D_{dn}) takes into account the flow path length that a particle has to travel to reach the nearest target or sink. It is expressed as:

$$D_{dn} = \sum_{i} \frac{d_i}{W_i S_i}$$

Where d_i is the length of the flow path along the i^{th} cell, W_i and S_i are the weighting factor and the slope gradient of the i^{th} cell, respectively.

The computation of the IC is mainly based on topography but information on land use cover can be integrated into the analysis by using the weighting factor (e.g. based on *C*-factor as in Borselli et al. 2008 or Manning's *n* as in Brardinoni et al. (2015) and Pesrsichillo et al. (2018). More details on IC can be found in Cavalli et al. (2013) and complemented by the original work by Borselli et al. (2008).

3.3.2. Computing the IC for the different scenarios

In this section we describe the specific methods adopted in each scenario and catchment for the computation of the two main data sets needed for IC computation: (a) Terrain Data (i.e. topography expressed by the DEMs), and (b) Weighting Factor (i.e. land use expressed by the Manning's *n* roughness coefficient).

Terrain Data

Topography determinates the slope and the drainage network characteristics, and both parameters are taken into account in the calculation of the upslope and downslope components of the IC. In the present paper, as explained above (see Figure 2), different DEMs were used based on the objective of each scenario:

Scenario 1: Changes in land cover. A DEM of 5 m resolution was extracted from the 2010 LIDAR dataset with a density of 0.5 pts/m^2. This resolution was considered sufficient to represent the macro-topography at the catchment scale. From the interpretation of the aerial photos we assume that the topographic changes during the study period (1957-2010) would have a minimum effect on the computation of the IC at the targeted scale, therefore the IC was assessed just changing the W factor and using the same terrain data.

Scenario 2: Terracing. First, a DEM of 1 m resolution obtained from the 2010 LIDAR dataset was used. Taking into account that the typical length and width of the terraces in the study area is >2 m, the use of 1 m DEM resolution is considered appropriate to represent the alteration that the terraces caused on the topography. Then, in order to eliminate possible point cloud noise (i.e. interpolation artifacts) a smoothing filter (low pass) was applied to the original 1 m DEM. Finally, to recreate the landscape without terraces the DEM was smoothed in order to eliminate the micro-topography maintaining the macro-topography. To this end, a DEM resampling from 1 m to 5 m (using the Resample ArcGIS 10.3 tool), and a subsequent resampling again to the original resolution of 1 m was performed. The later resampling was performed because maintaining the resolution of the DEM has been considered very important since coarsening implies an increase in the estimated IC value (Goldin, 2015; Brardinoni et al., 2015; Cantreul et al., 2018; López-Vicente and Álvarez, 2018). Therefore, this scenario is evaluated using two DEMs, one representing the landscape without terraces and a second one representing the actual situation, i.e. the landscape with terraces (both at 1 m resolution).

Scenario 3: Road Construction. In the case of the contemporary topography (i.e. after road construction), a DEM of a 10 m resolution derived from the LIDAR 2010 dataset was used. To represent the historical topography (i.e. before the construction of the road) a DEM with 10 m resolution extracted from a 1977 point cloud obtained by means of SfM-MVS applied to aerial historical photos was used. A 10 m resolution was selected to minimize the irregularities observed in the historical point cloud (e.g. bumping surface; Bakker and Lane 2017; Llena et al., 2018). Additionally, this resolution is considered enough to represent the topographic changes associated to the construction of the road, which in some parts were greater than 30 m. Again, this scenario is analysed by means of two DEMs: one representing the landscape before the road was constructed and a contemporary model that contains the road (both at 10 m resolution).

Weighting factor

In the original IC of Borselli et al. (2008), the C-factor based on USLE-RUSLE models was used to parameterize the weighting factor (*W*). In studies like this, where the evaluation of the role of different vegetation cover and land use changes on sediment connectivity is one of the main objectives, an alternative approach to the C-factor using a parameter related to hydraulic roughness. In particular, roughness is needed for a better representation of the impedance to the water and sediment fluxes since the C-factor only refers to cover and management related to erosion. An option is to use the Manning's *n* roughness coefficient (*n*), which represents the resistance to flow, with values varying according to different surface characteristics affecting roughness (Goldin, 2015; Brardinoni et al., 2015; Pesrsichillo et al., 2018). For this study, an image classification of all orthomosaics orthophoto mosaics was performed in order to obtain land use maps. A different Manning's *n* value was assigned to each of land use classes taking into account the *n*-values described in Goldin (2015). Although the study area in Goldin (2015) is located in a different geographical context than the areas studied in this work (i.e. the Italian Alps), the use of *n*-values extracted from this study is justified due to the similarity of the characteristics of the land uses. In spite of this, it is necessary to take into account the simplification that implies the use of the same *n*-value value for each land use class. Evidently, the variability of the *n*-value within each use can be notable although we have considered that this intra-variability has a minor effect on the computation of the IC at the catchments scale. It is important to highlight that the number of land use classes was determined based on the quality (e.g. blurred), characteristics (e.g. number of bands) and resolution (i.e. pixel size) of the aerial images; the images with most limiting conditions (i.e. usually historical images) determined the number of final classes. In this case, we defined three different classes: forest, meadow, and bare (with respective Manning's *n* values of 0.4, 0.1 and 0.05). Finally, the weighting factor W is computed as $W = 1 - n$ (following Goldin et al., 2015; Persichillo et al., 2018). The three land uses classes are representative of the land cover of the study sub-catchments and also of many mountain catchments in the Mediterranean.

IC computation and comparison

Once the IC maps were calculated for each scenario, IC values, as also suggested by Crema and Cavalli (2018), were reclassified into four classes for a better interpretation of the results: Low, Medium-Low, Medium-High and High Connectivity. The mean IC value was used as a limit between the Medium-Low and Medium-High classes, while the mean value plus two times the standard deviation of the IC values was used to define the threshold between the Medium-High and High classes. Finally, the mean value minus two times the standard deviation was the criterion used to establish the limit between the Medium-Low and Low classes. The same criteria were used for the representation of the difference of the IC between the analysed periods.

4. RESULTS AND DISCUSSION

4.1 Changes in sediment connectivity driven by land cover changes (Scenario 1)

In this section, we present two conditions in which land uses can affect sediment connectivity: afforestation and tillage, the latter of which is highly representative of most of the surface of Pyrenean catchments (e.g. García-Ruiz et al., 1996; Lasanta-Martínez et al., 2005), and many mountain catchments in Europe in general (e.g. MacDonald et al., 2000; Liébault et al., 2005) which have undergone afforestation in the last century. In the particular case of the Upper Cinca catchment, afforestation is the main observed change; the areas in which the agricultural activity has been maintained are limited to flat areas located in old terraces or valley bottoms in the vicinity of villages and towns (i.e. <5% of the total surface).

Afforestation: the case of the Aran sub-catchment

Figure 3 presents the land cover (Figure 3A) and IC maps for each year (Figure 3B) and also the comparison of the IC (Figure 3D) and land cover maps (Figure 3C). The old IC map (1957) was subtracted from the more recent (2010) map (hereafter IC Differences map), so that a positive value indicates an increase of connectivity and a negative value a decrease of sediment connectivity. Additionally, by comparing the land cover maps three main processes were determined: afforestation, deforestation and no change. The comparison between the 1957 and 2010 IC maps highlights the general decrease of connectivity in almost all the study sub-catchments (i.e. -0.18 median) that is mainly due to the increase of vegetation occurred during this period (Figure 3A and 3C). These results are in line with the findings of several studies in mountain Mediterranean regions that also show a reduction in sediment connectivity caused by an increase of vegetation cover during the second half of 20th century (e.g. Foerster et al., 2014; Lopez-Vicente et al., 2016; Lizaga et al., 2016; Persichillo et al., 2018). As pointed out by Foertser et al (2014) in the case of the nearby Isábena catchment (Southern Pyrenees), the resulting connectivity map depends not only on the land cover fractions but also on the spatial distribution of vegetation abundances and its proximity to the catchment outlet (i.e. target). In the case of Aran sub-catchment, the majority of the land surface was subject to afforestation (i.e. from bare soil or meadow surface to forest), but the highest decrease in sediment connectivity occurs in the areas where the increase of vegetation is more spatially concentrated and in areas located closer to the outlet (Figures 3C and 3D).

Tillage: the case of the Soto sub-catchment

For almost all the sub-catchment (i.e. 74%) there was a small increase in sediment connectivity (around 1% on average). Only for isolated patches located in the upper part of the catchment did connectivity decrease (i.e. 21% of total surface). These were areas that became forested during the analysed period. Results also indicate that connectivity increased in areas (i.e. 5% of the total surface) characterised by the establishment of farmlands in previously forested areas (Figures 4B and 4D). Although the surface occupied by badlands did not change significantly, it is very important to pay particular attention to these areas because they have because they have the highest values of connectivity. The high dynamism in these landscapes is also clear in the topographic changes observed by Smith and Vericat (2015) for some Badlands of the Soto, and in nearby badlands located in the River Isábena by Vericat et al. (2014). Overall, the median increment of the IC changes during the period 1957-2010 can be considered marginal (i.e. 0.05).

4.2 Changes in sediment connectivity by terracing (Scenario 2)

Two landscape conditions are analysed in this scenario to study the effects of: (a) land cover changes in a terraced landscape on connectivity; and (b) terracing on connectivity. In the former, the landscape is kept the same (i.e. terraced) and land uses are changed while in the later the land uses are kept the same and the landscape is changed (i.e. no terraces versus terraced). These results differ from the results obtained for scenario 1 in the way that they allow inferring the change (land cover or terracing) that affects sediment connectivity most. Areas characterised by a high increase in forest cover have experienced a high decrease in sediment connectivity (e.g. northeast of the sub-catchment, Figure 6). In contrast, in areas where roads and firewalls were built, connectivity increased, while the area affected by a wild fire near to the outlet is the only section that exhibits a high increase of sediment connectivity due to the deforestation associated to the fire (Figures 5A and 6B). The fast increase of forest cover in abandoned terraced landscapes can be explained by the stability of these areas and the favourable soil properties. Terrace abandonment followed by strong scrub or meadow regeneration in humid areas improves soil quality and creates effective protection against soil erosion, ultimately favouring afforestation (Llorens, 1991; Lana-Renault et al., 2014; Lizaga et al., 2016).

In terms of the effect of terracing on connectivity, the comparison of both DEMs shows that the topographic variations caused by the terraces have an amplitude of around 5 m (see longitudinal profiles in Figures 5B and 5C), while terraces increase the local slope (from 5º to 45º). These changes have a direct effect on the estimates of the IC.

The maps of IC show a general large decrease of sediment connectivity in all the areas with the presence of terraces (Figure 6B). Topographic conditions in terraced landscapes have a direct influence on infiltration and surface runoff; infiltration tends to increase while surface runoff is typically delayed, resulting in reduced peak flows and a subsequent decrease of connectivity (Garcia-Ruiz, 2010; Preti et al., 2018). Lesschen et al. (2009) also found that the presence of (maintained) terraces largely determines hydrological connectivity at the catchment scale. Inside the terraced landscape areas, connectivity increased locally, mainly due to the convergence caused by artificial structures (e.g. walls, forest roads; Figure 6B). This increase is typically explained by the abandonment of terraced areas triggering localized landslides and wall failures, resulting in a localized increase in connectivity even in areas with dense vegetation (e.g. Garcia-Ruiz and Lana-Renault, 2010; Lopez-Vicente, 2013; Tarolli et al., 2014; Tarolli and Sofia, 2016). In particular, Calsamiglia et al. (2017) observed a high correlation between the failure of terrace walls and the increase in erosion and sediment connectivity (structural and functional) in a small Mediterranean catchment. Note that in our case the non-terraced landscape was reconstructed by smoothing the 2010 DEM (see methods). This was mainly due to the limitations provided by the quality of the 1957 topography data (i.e. errors around 2 m). Therefore, no further details on the effects of wall failures on connectivity were able to be performed. Our results, however, allow studying the combined effect of terracing and land use changes and the effect of the different topography related just to the presence\absence of terraces. In summary, after isolating the effect of land cover changes on a terraced landscape, and those driven by topographical changes due to terracing, the presence of terraces has a greater effect on sediment connectivity in the whole sub-catchment. Specifically, the IC median reduction due to terracing is more than twice the reduction computed when different land cover conditions are analysed (i.e. IC median reduction of 5 and 2% of respectively).

Although the (re)creation of a DEM without terraces can be considered a landscape simulation, this can be a useful approach to estimate the effect on sediment connectivity before the construction and after the failure of terraces in Mediterranean mountain catchments. In addition, if IC maps are computed based on these terrain models, they can help to better estimate and understand historical sedimentary dynamic providing important indication for its future evolution.

4.3 Changes in sediment connectivity driven by road construction (Scenario 3)

The IC maps of the Fiscal sub-catchment show low values of connectivity in the areas with a high increase of the forest cover. A large part of these areas corresponds to the zones covered by steep slope field crops in 1977. These crops were abandoned and, consequently, covered by scrubs and forest (north part of the sub-catchment; Figure 7A and 7B). The south part of the sub-catchment also shows a decrease of sediment connectivity related to the increase of forest cover. In this case, the increment is due to an increase of tree density due to the decrease of extensive forest exploitation activities caused mainly by depopulation and also climate change (see IC maps in Figure 7A and 7B).

In terms of stream-road intersections (e.g. Figure 7B and 7D), the road artificially cut the drainage network producing a localized increase in connectivity in the upslope area and a decrease in the potential connectivity downslope. As a consequence, the morphological variation due to road construction led to an increase of erosional activities uphill, triggering in some cases localised landslides (Figure 7D). The IC map also suggests that the sediment involved in the landslide now has a lower probability of reaching the target (i.e. outlet of the catchment) because of the effect of the road in trapping the material produced upslope.

Tarolli and Sofia (2016) analysed how roads could trigger landslides in two different case studies in a mountain watershed in the United States of America. Their results described whether or not the sediment produced by the slides can contribute to the total sediment of the watershed at the outlet. In one of their study cases, when the slide was produced above the road, the road disconnected the source area from the channel network, but move the flows downstream, thus increasing the probability of delivering the sediment to the watershed outlet by changing the path. Other studies analysed the interactions between roads and sediment (dis)connectivity. For instance, Kalantari et al (2017) recently used the IC, among other indicators, to try to quantify the flood probability in road-stream intersections, demonstrating that the use of the IC as input variable improved the accuracy of a data-driven spatial-statistical model for road flood probability. In a different geographical context, Persichillo et al (2018) observed a high correlation between the occurrences of shallow landslides with areas with high connectivity caused by the presence of roads in a Mediterranean catchment of the north of Italy. All these studies, both the study case, are good examples of the use of IC as a useful tool to assess potential risks associated with such infrastructure (e.g. identifying hot spots) and to inform also, at a broad spatial scale, those responsible for watershed and road infrastructure management.

General Trends and Limitations

The analyses of land use changes and topographical changes in different scenarios allow us to quantify the effect of these changes on Sediment Connectivity and to estimate what types of change have the greatest effect. Figure 8 summarises the changes associated with each of the scenarios analysed in this study. The increase or decrease of the vegetation cover had a clear effect on the IC (Figure 8) by increasing or decreasing connectivity respectively. If topographic changes, such as the associated with terrace construction, are also taken into account, the impact of these on connectivity can be even higher than the driven by land use changes. This is clearly observed in the results obtained for the Pocinos catchment. In this case, the percentage of the area in which connectivity highly decreased is 22% when the land use changes are analysed, and 35% when the topographic changes are considered. Moreover, in this latter case, the degree of IC increase is magnified (2.2% of the landscape suffered a high increase in connectivity while only the 0.1% in the case of the analysis just isolating the land use changes).

It is also interesting to note the patterns obtained in catchments where, although no significant general changes are observed (a mean change of the IC around 1% is obtained in the Soto sub-catchment), locally, (i) the unification of existing field crops or the creation of new ones by means of ploughing and forest harvesting, and (ii) patchy afforestation may increase or decrease connectivity. In this case, two main processes can be observed. First, connectivity may change on bare surfaces attributed to topographic changes. These changes, although may be relevant to study changes on connectivity at smaller (detailed) scales, cannot be depicted at the scale analysed in this paper (they are out of the scope of this study). Secondly, land use changes may decrease connectivity locally in those areas where field crops are abandoned or bare surfaces are vegetated (7% of the catchment area of the Soto experimented this change), or may increase in those areas where new field crops are developed or by the unification of existing ones (6% of the Soto). Finally, topographic changes associated with road construction can modify, not only the general IC values but also the patterns and distribution of these (Figure 8), in much more detail than the ones associated with land use changes.

As stated in the methods section, the limits between the different IC classes (including the IC changes) were calculated based on the mean values and the standard deviation of these. In this way, the significance of changes is a relative expression that depends on the distribution of the data of each of the scenarios. In the same way, the values of IC were directly conditioned by the main inputs to calculate the IC: the weighting factor and the topography. On one hand, the selection of the roughness or *n*-values as a weighting factor parameter was based on values presented in the literature (Goldin, 2016). It is very important to take into account the criteria when assigning the different values of *n*, since the variation of these values could lead to completely different IC maps. On the other hand, the resolution of the topography has an inverse effect on the total values of IC (e.g. Cantreul et al., 2018; López-Vicente and Álvarez, 2018), mainly driven by the smoothing of the landscape as the resolution decreases. In this study, the different resolutions were based on the typology and magnitude of the topographic change analysed in each scenario in relation to the errors.

5. CONCLUSIONS

Sediment Connectivity Indices are very valuable to analyse the potential of a landscape to transfer sediments through its main compartments; that is to assess structural sediment connectivity through time. The role of land use and topographic changes on sediment connectivity in representative mountain catchments has been analysed for three different scenarios, representative of the main changes observed in many mountain areas. The main findings of the study can be summarized as follows:

- Land cover changes have a direct effect on the impedance to water and sediment fluxes. We identified areas with a slight increase in sediment connectivity due to the establishment of new field crops; however, most of the study area has undergone afforestation which resulted in a decrease of sediment connectivity and potential reduction of sediment supply to the main channel network.
- Terraces affect connectivity to a much greater extent than changes in land cover. The establishment of terraces has a double effect: (a) generally reducing connectivity due to the establishment of flat areas between slopes, and (b) increasing connectivity locally due to the convergence produced by the different human-made structures such as walls or the collapse of terraces due to abandonment. Results indicate that the use of the IC may detect areas of

terraced landscapes where further monitoring is required for a better management of such structures, as for instance in vineyards areas where terraces are key for their stability and productivity.

- Topographic changes associated with road construction modify slope, surface flow directions and, consequently, the drainage network. Altogether, this leads to changes in connectivity that could affect erosional processes in the neighbouring areas with a direct impact on the stability of the road and on the transfer of sediments downstream. In this context, the IC is a useful tool to map hot spots, i.e. critical areas where further attention or monitoring would be required for a better maintenance of such infrastructures.

Finally, we argue that the study of historical changes in sediment connectivity due to land use variations, especially if addressed considering also topographic changes, may provide valuable information to understand sediment supply dynamics. This information coupled with hydrological and sediment transport numerical modelling can help understanding of how this has or is affecting the channel adjustments that are observed in many mountain rivers that have experienced land use changes in their headwaters during the 20th century. The novelty of our work lies in the development of an approach to assess multi-temporal changes in sediment connectivity by considering both changes in topography and land use. The methodology we used in this paper allows not just studying the effects of real decadal-scale land use and topographic changes on sediment connectivity, but also evaluating and disentangling those changes. Furthermore, the assessment of connectivity at multiple temporal scales can be also a useful tool to identify potential risks associated with morphological and land use changes, involving road infrastructure.

6. ACKNOWLEDGEMENTS

This research was carried out within the framework of two research projects funded by the Spanish Ministry of Economy and Competitiveness and the European FEDER funds: MORPHSED (CGL2012-36394) and MORPHPEAK (CGL2016-78874-R). The first author has a grant funded by the Spanish Ministry of Education Culture and Sports (FPU016/01687). The second author is a Serra Húnter Fellow at the University of Lleida. This manuscript has benefited from the work carried out during a Short Term Scientific Mission funded by the EU Cost Action Connecteur (ES1306: Connecting European Connectivity Research), and all discussions during the different meetings the Working Group 2 and 4 of this Action organised. The first and second authors are part of the Fluvial Dynamics Research Group-RIUS, which is a Consolidated Group recognized by the Generalitat de Catalunya (2017 SGR 459645). We also acknowledge the support of the CERCA Program of the Generalitat de Catalunya.

7. REFRENCES

Arnáez, J., Lana-Renault, N., Lasanta, T., Ruiz-Flaño, P., Castroviejo, J. 2015. Effects of farming terraces on hydrological and geomorphological processes. A review. *Catena*. 128, 122-134.

Bakker, M., Lane, S.N. 2017. Archival photogrammetric analysis of river floodplain systems using Structure from Motion (SfM) methods. *Earth Surface Processes and Landforms*. 42, 1274–1286.

Beguería, S. 2006. Changes in land cover and shallow landslide activity: A case study in the Spanish Pyrenees. *Geomorphology*. 74, 196-206.

Bellin, N., van Wesemael, B., Meerkerk, A., Vanacker, V., Barbera, G.G. 2009. Abandonment of soil and water conservation structures in Mediterranean ecosystems. A case study from south east Spain. *Catena.* 76, 114-121.

Bordoni, M., Persichillo, M.G., Meisina, C., Crema, S., Cavalli, M., Bartelletti, C., Galanti, Y., Barsanti, M., Giannecchini, R., D'Amato Avanzi, G. 2018. Estimation of the susceptibility of a road network to shallow landslides with the integration of the sediment connectivity. *Natural Hazards and Earth System Sciences*. 18, 1735-1758.

Borselli, L., Cassi, P., Torri, D. 2008. Prolegomena to sediment and flow connectivity in the landscape: A GIS and field numerical assessment. *Catena.* 75, 268–277.

Braken, L.J., Tumbull, L., Wainwright, J., Bogaart, P. 2015. Sediment connectivity: a framework for understanding sediment transfer at multiple scales. *Earth Surface Processes and Landforms*. 40, 177-188.

Braken, L.J., Croke, J. 2007. The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. *Hydrological Processes*. 21, 1749-1763.

Brardinoni F., Cavalli M., Heckmann T., Liebault F., Rimbock A., 2015. Guidelines for assessing sediment dynamics in Alpine basins and channel reaches. Final project report (WP4), Alpine Space Programme – SedAlp Project. 177 pp.

Brasington, J., Vericat, D. Rychkov I. 2012. Modelling river bed morphology, roughness, and surface sedimentology using high resolution terrestrial laser scanning. *Water Resources Research*. 48, 1-18.

Brunsden, D., Thornes, J.B., 1979. Landscape sensitivity and change. *Transactions of the Institute of British Geographers.* 4, 463–484.

Buendia, C. Batalla, R., Sabater, S., Palau, A., Marcé, R. 2015. Runoff trends driven by climate and afforestation in a Pyrenean basin. *Land Degradation and Development*, 27, 823-838.

Calsamiglia, A., Fortesa, J., García-Comendador, J., Lucas-Borja, M.E., Calvo-Cases, A., Estrany J. 2018. Spatial patterns of sediment connectivity in terraced lands: Anthropogenic controls of catchment sensitivity. *Land Degradation and Development.* 29, 1198-1210.

Cantreul, V., Bielders, C., Calsamiglia, A., Degré, A. 2017. How pixel size affects a sediment connectivity index in central Belgium. *Earth Surface Processes and Landforms*. 43, 884-893

Cavalli, M., Trevisani, S., Comiti, F., Marchi, L. 2013. Geomorphometric assessment of spatial sediment connectivity in small Alpine catchments. *Geomorphology*. 188, 31–41.

Crema, S., Cavalli, M., 2018. SedInConnect: a stand-alone, free and open source tool for the assessment of sediment connectivity. *Computational Geosciences*. 111, 39–45.

Coulthard, T.J., Van De Wiel, M.J. 2017. Modelling long term basin scale sediment connectivity, driven by spatial land use changes. *Geomorphology*. 277, 265-281.

Ferreira, C.S.S., Walsh, R.P.D., Blake, W.H., Kikuchi, R., Ferreira, A.J.D. 2017. Temporal Dynamics of Sediment Sources in an Urbanizing Mediterranean Catchment. *Land Degradation and Development*. 28(8), 2357-2369.

Foerster, S., Wilezok, C., Brosinsky, A., Segl, K. 2014. Assessment of sediment connectivity from vegetation cover and topography using remotely sensed data in a dryland catchment in the Spanish Pyrenees. *Journal of Soils and Sediments*. 14, 1982-2000.

Fryirs, K.A., Brierley, G.J., Preston, N.J., Kasai, M. 2007. Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. *Catena*. 70, 49-67.

Fryirs, K., 2013. (Dis)Connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem. *Earth Surface Processes and Landforms*. 38, 30–46.

Fryirs, K.A. 2017. River sensitivity: a lost foundation concept in fluvial geomorphology. *Earth Surface Processes and Landforms*. 42, 55-70.

Gallart, F., Llorens, P. 2003. Catchment Management under Environmental Change: Impact of Land Cover Change On Water Resources. *Water International*. 28, 334-340.

García-Ruiz, J.M. 2010. The effects of land uses on soil erosion in Spain: A review. *Catena*. 81, 1-11.

García-Ruiz, J.M., Lasanta, T., Ruiz-Flaño, P., Ortigosa, L., White, S., González, C., Martí, C. 1996. Land-use changes and sustainable development in mountain areas: a case study in the Spanish Pyrenees. *Landscape Ecology*. 11(5), 267-277.

García-Ruiz, J.M., Valero-Garcés, B. 1998. Historical geomorphic processes and human activities in the Central Spanish Pyrenees. *Mountain Research and Development*. 18 (4), 309-320.

García-Ruiz, J.M., López-Bermúdez, F. 2009. La erosión del suelo en España. *Cuaternario y Geomorfología*. 23 (3-4).

García-Ruiz, J.M., Lana-Renault, N. 2011. Hydrological and Erosive Consequences of Farmland Abandonment in Europe, with Special Reference to the Mediterranean Region—A Review. *Agriculture Ecosystems & Environment*. 140(3), 317-338.

Gay, A., Cerdan, O., Mardhel, V., Desmet, M. 2015. Application of an index of sediment connectivity in a lowland area. *Journal of Soils and Sediments*. 16(1), 280-293.

Goldin, B. 2015. *Geomorphometric Analysis And Sediment Dynamics In Mountainous Basins: Spatial And Temporal Scales*. Doctoral Thesis. Università degli Studi di Padova.

Goldin, B., Rudaz, B., Bardou, E. 2016. Application of a sediment connectivity GIS-based index in a basin undergoing glacier retreat: the case study of the Navizence catchment. *Rendiconti Online Società Geologica Italiana*. 6, 35-38.

Grohmann, C.E., Smith, M.J., Riccomini, C. 2011. Multiscale Analysis of Topographic Surface Roughness in the Midland Valley, Scotland. *IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING.* 49(4), 1200-1213.

Harvey, A.M. 2001. Coupling between hillslopes and channels in upland fluvial systems: implications for landscape sensitivity, illustrated from the Howgill Fells, northwest England. *Catena*. 42, 225-250.

Heckmann, T., Cavalli, M., Cerdan, O., Foerster, S., Javaux, M., Lode, E., Smetanová, A., Vericat, D., Brardinoni, F., 2018. Indices of sediment connectivity: opportunities, challenges and limitations. *Earth-Science Reviews*. (In press).

Hooke, J. 2003. Coarse sediment connectivity in river channel systems: a conceptual framework and methodology. *Geomorphology.* 56, 79-94.

Jones, J. A., Swanson, F. J., Wemple, B.C., Snyder, K.U. 2000. Effects of Roads on Hydrology, Geomorphology, and Disturbance Patches in Stream Networks. *Conservation Biology*. 14(1), 76-85.

Kalantari, Z., Cavalli, M., Cantone, C., Crema, S., Destouni, G. 2017. Flood probability quantification for road infrastructure: Data-driven spatial-statistical approach and case study Applications. *Science of the Total Environment*. 581-582.

Keestra, S.D., van Dam, O., Verstraeten, G., van Huissteden, J. 2009. Changing sediment dynamics due to natural reforestation in the Dragonja catchment, SW Slovenia. *Catena*. 78, 60-71.

Lana-Renault, N., Ruiz-Flaño, P., Llorente, J.A., Arnáez, J. 2014. Respuesta hidrológica de una cuenca de bancales abandonados (Camero Viejo, La Rioja). In: Arnáez, J., González-Sampériz, P., Lasanta, T., Valero-Garcés, B. (Eds.) *Geoecología, cambio ambiental y paisaje*. CSIC-Universidad de La Rioja.

Larsen, A., Robin, V., Heckmann, T., Fülling, A., Larsen, J.R., Hans-Rudolf, B. 2016. The influence of historic land-use changes on hillslope erosion and sediment redistribution. *The Holocene*. 26(8), 1248-1261.

Lasanta-Martínez, T., Vicente-Serrano, S.M., Cuadrat-Prats, J.M. 2005. Mountain Mediterranean landscape evolution caused by the abandonment of traditional primary activities: a study of the Spanish Central Pyrenees. *Applied Geography*. 25, 47-65.

Lesschen, J.P., Cammeraat, L.H., Nieman, T. 2009. Erosion and terrace failure due to agricultural land abandonment in a semi-arid environment. *Earth Surface Processes and Landforms*. 33, 1574-1584.

Liébault, F., Gomez, B., Page, M., Marden, M., Peacock, D., Richard, D., Trotter, M. 2005. Land-use change, sediment production and channel response in upland regions. *River Research and Applications.* 21, 739-756.

Lizaga, I., Quijano, L., Palazón, L., Gaspar, L., Navas, A. 2016. Enhancing Connectivity Index to Assess the Effects of Land Use Changes in a Mediterranean Catchment. *Land Degradation and Development*. 29(3), 663-675.

Lizaga, I., Quijano, L., Gaspar, L., Ramos, M. C., & Navas, A. (2019). Linking land use changes to variation in soil properties in a Mediterranean mountain agroecosystem. *Catena, 172*, 516-527.

López-Martín, F., Cabrera-Millet, M., Cuadrat, J.M., Saz-Sánchez, M.A., Martín, S., Serrano, V. 2007. *Atlas climático de Aragón*. Gobierno de Aragón. Spain

López-Moreno, J.I., Vicente-Serrano, S.M., Morán-Tejeda, E., Zabalza, J., Lorenzo-Lacruz, J., García-Ruiz, J.M. 2011. Impact of climate evolution and land use changes on water yield in the Ebro basin. *Hydrology and Earth System Sciences*. 15, 311-322.

López-Moreno, J.I., Zabalza, J., Vicente-Serrano, S.M., Revuelto, J., Gilaberte, M., Azorin-Molina, C., Morán-Tejeda, García-Ruiz, J.M., Tague, C. 2014. Impact of climate and land use change on water availability and reservoir management: Scenarios in the Upper Aragón River, Spanish Pyrenees. *Science of the Total Environment*. 493, 1222-1231.

López-Vicente, M., Poesen, J., Navas, A., Gaspar, L. 2013. Predicting runoff and sediment connectivity and soil erosion by water for different land use scenarios in the Spanish PrePyrenees. *Catena*. 102, 62–73.

López-Vicente, M., Nadal-Romero, E., Cammeraat, E.J.H. 2016. Hydrological Connectivity Does Change Over 70 Years of Abandonment and Afforestation in the Spanish Pyrenees. *Land Degradation and Development*. 28(4), 1298-1310.

López-Vicente, M., Álvarez, S. (2018). Influence of DEM resolution on modelling hydrological connectivity in a complex agricultural catchment with woody crops. *Earth Surface Processes and Landforms. 43*(7), 1403-1415

Llena, M., Cavalli, M., Vericat, D., Crema, S. (2018). Assessing changes in landscape associated to anthropic disturbances by means of the application of Structure from Motion photogrammetry using historical aerial imagery. *Rendiconti Online della Società Geologica Italiana.* (In press).

Llorens, P. 1991. *Resposta hidrològica i dinàmica de sediments en una petita conca perturbada de muntanya mediterrània*. Tesis doctoral. Universitat de Barcelona, Barcelona.

MacDonald, D., Crabtree, J.R., Wiesinger, G., Dax, T., Stamou, N., Fleury, P., Gutierrez-Lazpita, J., Gibon, A. 2000. Agricultural abandonment in mountain areas of Europe: Environmental consequences and policy response. *Journal of Environmental Management*. 59, 47-69.

Macklin, M.G., Lewin, J., Woodward, J.C. 2012. The fluvial record of climate change. *Philosophical Transactions of The Royal Society*. 370, 2143-2172.

Micheletti, N., Lane, S.N., Chandler, J.H. 2015. Application of Archival Aerial Photogrammetry to Quantify Climate Forcing of Alpine Landscapes. *The Photogrammetric Record*. 30, 143-165.

Ortíz-Rodríguez, A.J., Borselli, L., Sarocchi, D. 2017. Flow connectivity in active volcanic areas: Use of index of connectivity in the assessment of lateral flow contribution to main streams. *Catena*. 157, 90-111.

Persichillo, M.G., Bordoni, M., Cavalli, M., Crema, S., Meisina, C., 2018. The role of human activities on sediment connectivity of shallow landslides. *Cartena*. 160, 261–274.

Preti, F., Guastini, E., Penna, D., Dani, A., Cassiani, G., Boaga, J., Deiana, R., Romano, N., Nasta, P., Palladino, M., Errico, A., Giambastiani, Y., Trucchi, P., Tarolli, P. 2018. Conceptualization of Water Flow Pathways in Agricultural Terraced Landscapes. *Land Degradation and Development.* 29(3), 651-662.

Quiñonero-Rubio, J.M., Boix-Fayos, C., de Vente, J. 2013. Desarrollo y aplicación de un Índice Multifactorial de Conectividad de Sedimentos a escala de cuenca. *Cuadernos de Investigación Geográfica*. 39(2), 203-223.

Smith, M.W., Vericat, D. 2015. From experimental plots to experimental landscapes: topography, erosion and deposition in sub-humid badlands from Structure-from-Motion photogrammetry. *Earth Surface Processes and Landforms*. 40, 1656-1671.

Tague, C., Band, L. 2001. Simulating the impact of road construction and forest harvesting on hydrologic response. *Earth Surface Processes and Landforms.* 26(2), 135-151.

Tarolli, P., Preti, F., Romano, N. 2014. Terraced landscapes: From an old best practice to a potential hazard for soil degradation due to land abandonment. *Anthropocene*. 6, 10-25.

Tarolli, P., Sofia, G. 2016. Human topographic signatures and derived geomorphic processes across landscapes. *Geomorphology*. 255, 140-161.

Van Dijk, A.I.J.M., Bruijnzeel, L.A., Vertessy, R.A., Ruijter, J. 2005. Runoff and sediment generation on bench-terraced hillsides: measurements and up-scaling of a field-based model. *Hydrological Processes*. 19, 1667-1685.

Van Nieuwenhuyse, B.H.J., Antoine, M., Wyseure, G., Govers, G. 2011. Pattern-process relationships in surface hydrology: hydrological connectivity expressed in landscape metrics. *Hydrological Processes*. 24, 3760–3773.

Vericat, D., Smith, M.W., Brasington, J. 2014. Patterns of topographic change in sub-humid badlands determined by high resolution multi-temporal topographic surveys. *Catena*. 120, 164-176.

Wemple, B.C., Swanson, F.J., Jones, J.A. 2001. Forest roads and geomorphic process interactions, Cascade Range, Oregon. *Earth Surface Processes and Landforms.* 26(2), 191-204.

Wheaton, J.M., Brasington J., Darby, S.E., Sear, D. 2010. Accounting for Uncertainty in DEMs from Repeat Topographic Surveys: Improved Sediment Budgets. *Earth Surface Processes and Landforms*. 35, 136-156.

Wohl, E. 2017. Connectivity in rivers. *Progress in Physical Geography*. 41(3), 345–362.

Wohl, E., Brierley, G., Cadol, D., Coulthard, T.J., Covino, T., Fryirs, K.A., Grant, G., Hilton, R.G., Lane, S.N., Magilligan, F.J., Meitzen, K.M., Passalacqua, P., Poeppl, R.E., Rathburn, S.L., Sklar, L.S. 2018. Connectivity as an Emergent Property of Geomorphic Systems. *Earth Surface Processes and Landforms*.

FIGURE CAPTIONS

Figure 1.Upper Cinca river catchment and study sub-catchments

Figure 2. (A) Representation of the three scenarios of change analysed in the Upper Cinca catchment: (a) Changes in land cover; (b) Topographic changes on agricultural fields (i.e. terracing) and (c) Topographic changes associated with infrastructures (i.e. road construction). (B) Maps and DEM's used for each of the scenarios.

Figure 3. Changes on sediment connectivity associated land cover changes (afforestation): (A) Land use maps for the two study periods (1957-2010). (B) Map of the Connectivity Index (IC) for the two study periods. (C) Maps of land cover changes between the two study periods where 3 main processes can be observed (afforestation, deforestation and no change). (D) Maps of the difference of the ICs between the two study periods. (E) Example of an area in which there has been a decrease in connectivity due to the increase in forest.

Figure 4. Changes on sediment connectivity associated with land cover changes (tillage): (A) Land use maps of the Soto sub-catchment for the two study periods (1957-2010). (B) Map of land cover changes between the two study periods (afforestation, deforestation and no change). (C) Connectivity Index (IC) maps for the two study periods. (D) Maps of the difference of the ICs between the two study periods. (E) Photograph showing an example of an area in which there has been a large increase of sediment connectivity due to the creation of new cropland.

Figure 5. Changes in sediment connectivity associated with terracing: (A) Land cover maps for both study periods (i.e. 1957 and 2010) and map of land cover changes between the two study periods (afforestation, deforestation and no change) in a terraced landscape. (B) Hillshade model of the DEMs with no terraces (left) and with the presence of terraces (right). (C) Two profiles (i.e. a-b, c-d) showing the variation of elevation and slope for no terraced (red lines) and terraced (black lines) DEMs.

Figure 6. Changes in sediment connectivity associated with terracing: (A) IC maps for different catchment conditions: (i) IC map assessed from the DEM without terraces and a weighting factor (W) extracted from the 1957 land use map; (ii) IC map obtained from the DEM with terraces (2010) and a W extracted from the 1957 land use map; and (iii) IC map assessed from the DEM with terraces (2010) and a W extracted

from 2010 land cover map. (B) Difference of the IC maps comparing the effect of terracing on connectivity (i.e. terraces; left); and the effect of land cover changes on connectivity in a terraced landscape (right).

Figure 7. Changes on sediment connectivity associated to road construction: (A) IC maps obtained using the 1977 DEM and land cover map (before road construction) and by the 2010 DEM and land cover map (after road construction). (B) IC maps for both study periods showing the spatial distribution of the IC values and the changes caused by the construction of the road. (C) Map of land cover changes between the two study periods (afforestation, deforestation and no change). (D) Zoom on a hot spot where the morphological variation due to road construction led to an increase of erosional activities on the upslope side of the road (i.e. a landslide); this is also observed by looking at the changes on the IC (indicated with a black rectangle).

Figure 8. Changes in Sediment Connectivity (IC) for each one of the scenarios analysed in this study: Afforestation; Tillage; Terracing; Afforestation in a terraced landscape and Road Construction.

TABLES AND TABLE CAPTIONS

Table 1. Main characteristics of the four study sub-catchments

Catchment	Catchment Area (km^2)	Minimum and maximum elevation (masl)	Mean slope (º)	Percentage of forested cover (%)
Fiscal	15.6	750 - 1925	29	72
Arán	9.2	1045 - 2025	17	81
Pocinos	7.4	758 - 2013	28	52
Soto	10.1	540 - 1046	30	51

HIGHLIGHTS

- Land cover changes have a direct effect on sediment connectivity.
- Changes caused by terraces are inferred from the recreation of the terrain without these structures.
- Terraces had a larger impact on sediment connectivity than land use change
- The Index of Connectivity is a useful tool to map hot spots in areas where roads are constructed.
- Changes on historical sediment connectivity may help understanding catchment-scale sediment supply dynamics

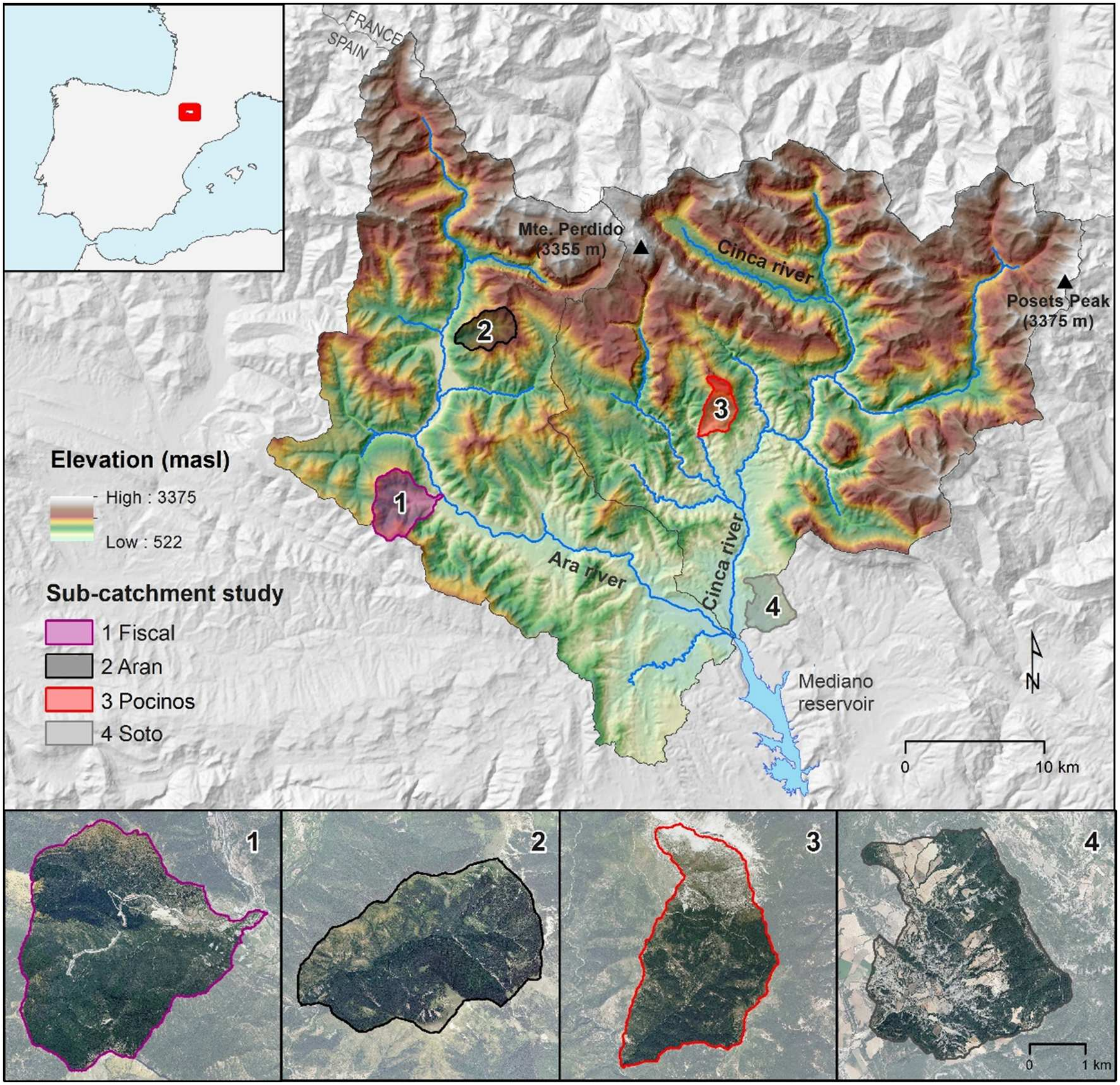
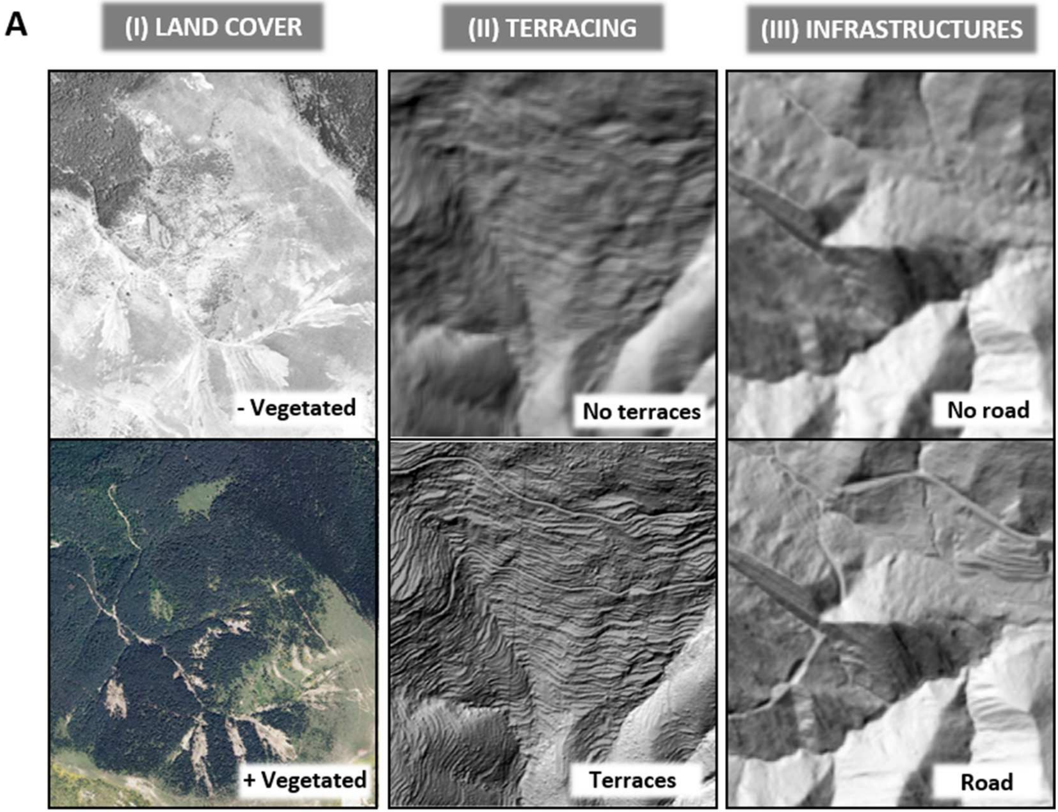

FRANCE
SPAIN
Mte. Perdido
(3355 m)
Cinca river
Posets Peak
(3375 m)
Elevation (masl)
High : 3375
Low : 522
Sub-catchment study
1 Fiscal
2 Aran
3 Pocinos
4 Soto
1
2
3
4
Ara river
Cinca river
Mediano
reservoir
N
0
10 km
1
2
3
4
0
1 km

Figure 1



B

Scenario	(I)	(II)	(III)
DEMs (resolution and time)	5x5 m 2010	1x1 m 2010 and 2010 modified	10x10 m 1977 and 2010
LAND USE MAPS (time)	1957 and 2010	1957 and 2010	1977 and 2010

Figure 2

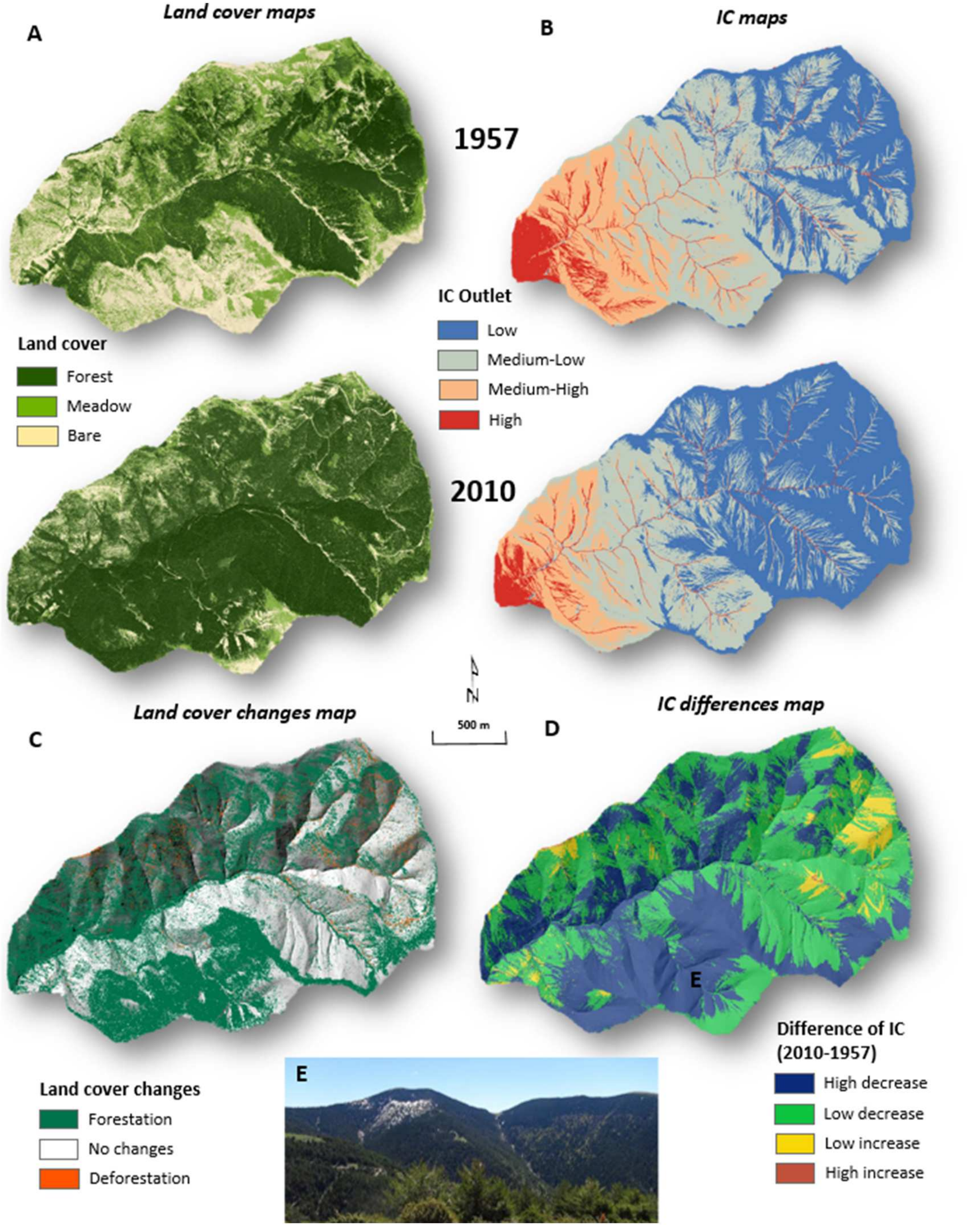

Land cover maps
A
IC maps
B
1957
2010
Land cover
Forest
Meadow
Bare
IC Outlet
Low
Medium-Low
Medium-High
High
N
500 m
Land cover changes map
C
IC differences map
D
E
Land cover changes
Forestation
No changes
Deforestation
E
Difference of IC (2010-1957)
High decrease
Low decrease
Low increase
High increase

Figure 3

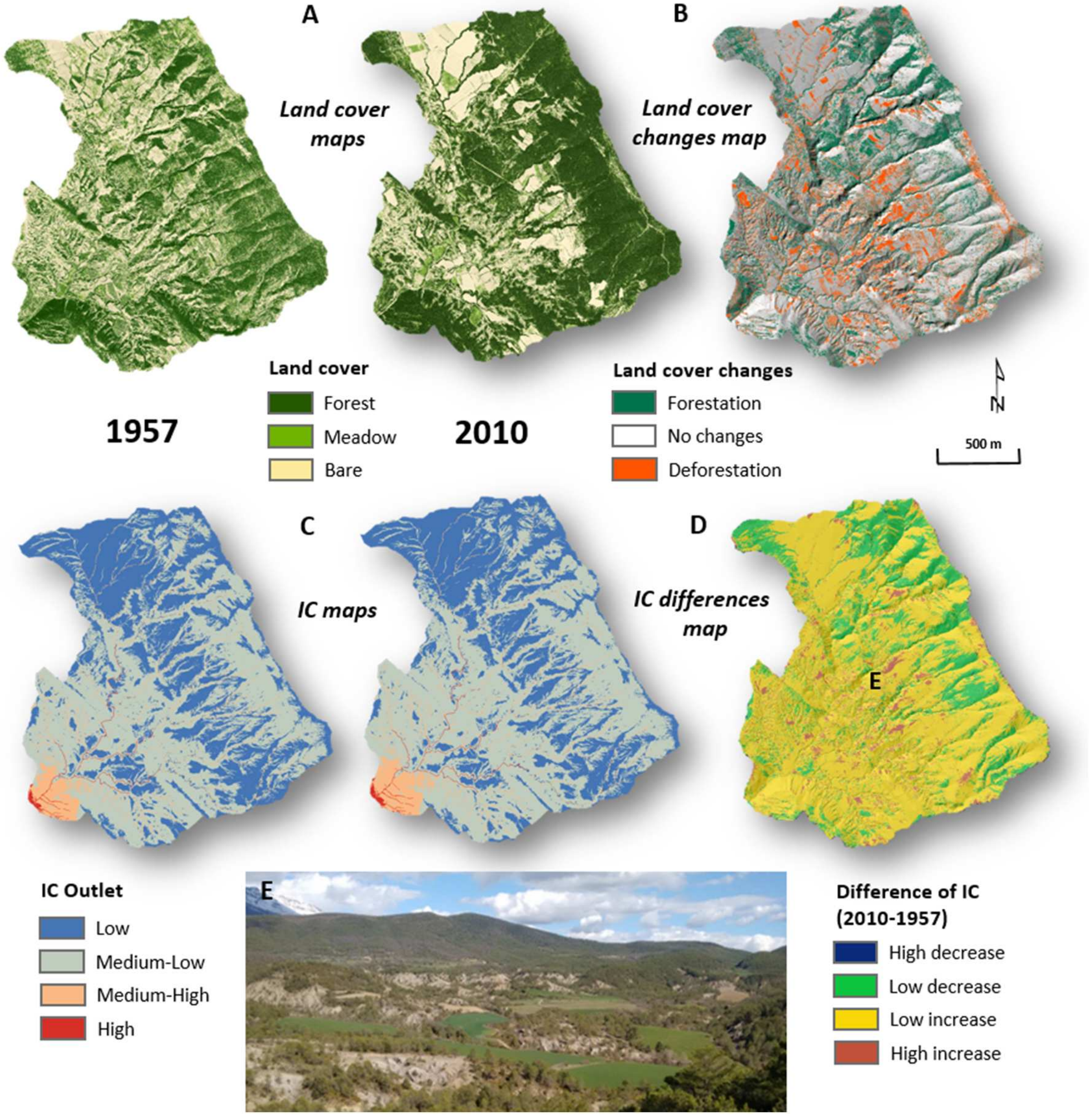

A
Land cover maps
B
Land cover changes map
1957
2010
Land cover
Forest
Meadow
Bare
Land cover changes
Forestation
No changes
Deforestation
N
500 m
C
IC maps
D
IC differences map
E
IC Outlet
Low
Medium-Low
Medium-High
High
E
Difference of IC (2010-1957)
High decrease
Low decrease
Low increase
High increase

Figure 4

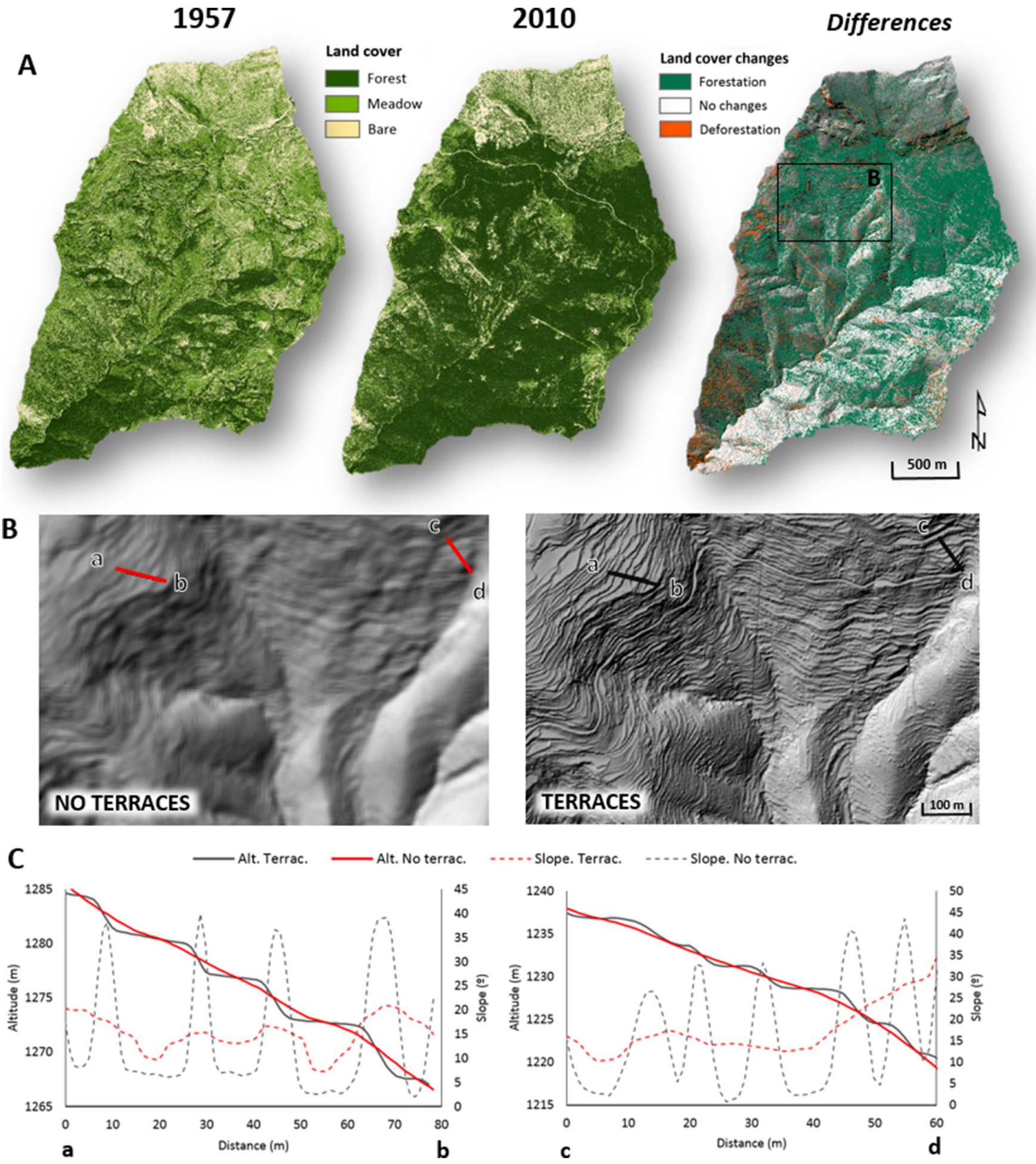

1957
2010
Differences
A
Land cover
Forest
Meadow
Bare
Land cover changes
Forestation
No changes
Deforestation
B
N
500 m
B
a
b
c
d
NO TERRACES
TERRACES
100 m
C
Alt. Terrac.
Alt. No terrac.
Slope. Terrac.
Slope. No terrac.
Altitude (m)
Slope (º)
1285
1280
1275
1270
1265
45
40
35
30
25
20
15
10
5
0
0
10
20
30
40
50
60
70
80
Distance (m)
a
b
1240
1235
1230
1225
1220
1215
50
0
10
20
30
40
50
60
Distance (m)
c
d

Figure 5

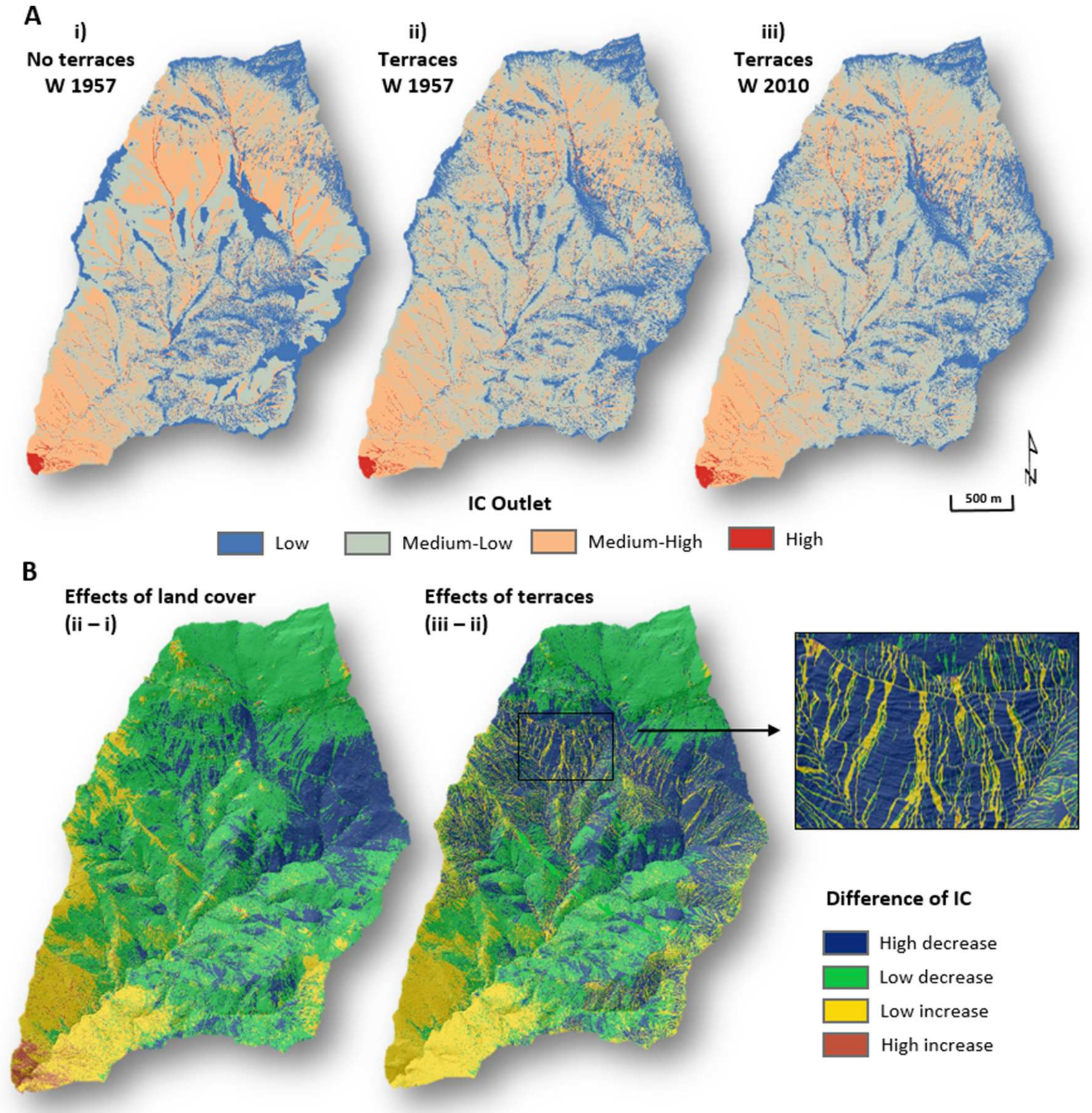

A
i)
No terraces
W 1957
ii)
Terraces
W 1957
iii)
Terraces
W 2010
N
500 m
IC Outlet
Low
Medium-Low
Medium-High
High
B
Effects of land cover
(ii – i)
Effects of terraces
(iii – ii)
Difference of IC
High decrease
Low decrease
Low increase
High increase

Figure 6

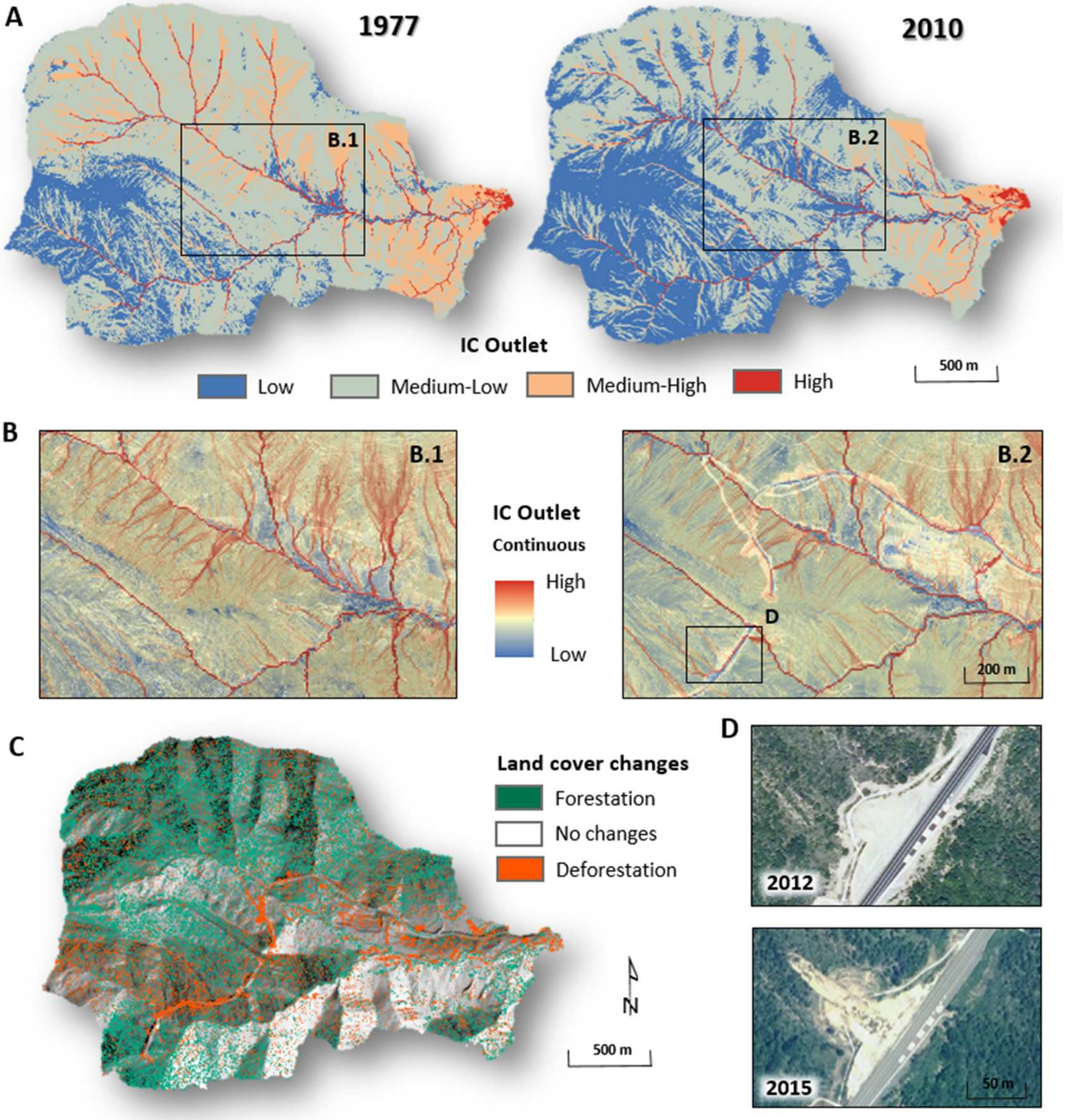
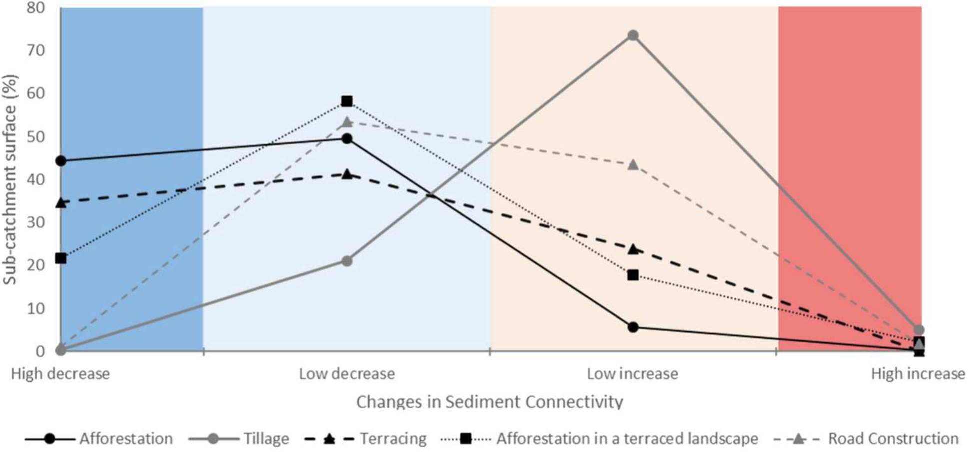

A
1977
2010
B.1
B.2
IC Outlet
Low
Medium-Low
Medium-High
High
500 m
B
B.1
IC Outlet
Continuous
High
Low
B.2
D
200 m
C
Land cover changes
Forestation
No changes
Deforestation
N
500 m
D
2012
2015
50 m

Figure 7



80
70
60
50
40
30
20
10
0
Sub-catchment surface (%)
High decrease
Low decrease
Low increase
High increase
Changes in Sediment Connectivity
Afforestation
Tillage
Terracing
Afforestation in a terraced landscape
Road Construction

Figure 8