Is afforestation a driver of change in italian rivers within the Anthropocene era?

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IS AFFORESTATION A DRIVER OF CHANGE IN ITALIAN RIVERS WITHIN THE ANTHROPOCENE ERA?

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Highlights

- A multi-scale diachronous-synchronous approach is used
- Land-use changes at both reach and basin scales drove adjustment in Italian river
- Southern rivers do not undergo floodplain afforestation, although they narrowed
- Similarities and differences between Italian and French river evolutions are found
- Geomorphic diagnosis must consider land-use change effects on river adjustments

Keywords: Multi-scale and multi-temporal analysis, diachronous-synchronous approach, evolutionary trajectories, land cover changes, vegetation encroachment, local controlling factors.

Abstract

For eight rivers situated from northern to southern Italy, the evolutionary trajectories since the middle 19th century and the key controlling factors of channel adjustments were reconstructed using a combined diachronous-synchronous approach, integrating data from catchment- to reach-scale. The analysis takes advantage of multi-temporal GIS analysis of maps, aerial photographs, and orthophotos, and data from literature, archives, and official surveys of population and agrarian censuses. From the middle 19th century to the 1950s, both channel widening and narrowing were observed. These processes were related to land use disturbances (e.g., afforestation versus deforestation) acting at both reach and catchment scales. From the 1950s to 1970s, channel narrowing in some rivers accelerated simultaneously with forest encroachment on fluvial corridors and human abandonment of intense floodplain uses, before the action of any other factors. In southern Italian rivers, channel adjustments were more intense and occurred later than in northern ones, but they remained more active once adjustment ended. Mature floodplain forest establishment is not always observed on these rivers, although they underwent a rural decline that can be explained by drier climatic conditions, maybe exacerbated by dewatering due to channel incision. This also means that upland afforestation and its effects on bedload delivery have been a more critical driver in controlling narrowing than floodplain afforestation, as in this southern context we do not observe floodplain afforestation during the period, but grazing expansion. When forest can establish along the channel, as seen on the Volturno, narrowing is even more important. River widening in the early 2000s–2010s did not compensate for longer term narrowing, demonstrating a shift in river responsiveness that was partly due to upland and floodplain afforestation inducing higher channel resistance to bank erosion and bedload deficit. Such morphological evolution was also observed in southeastern France, but occurred a bit earlier, with stronger similarities with northern Italy and the Apennines. These drivers of change must not be underestimated in geomorphic diagnosis, even if they are more difficult to assess.

1. Introduction

A wide range of human activities (e.g. gravel mining, construction of dams and bank protection, land-use changes) have been considered as the main drivers of channel change in European rivers over the last few centuries (Comiti and Scorpio, 2019). These controlling factors have worked alongside natural drivers such as climate change (Rumsby and Macklin, 1996; Gob et al., 2008) and the occurrence of extreme floods (Arnaud-Fassetta et al., 1999; Uribelarrea et al., 2003). Basin-scale land-use modifications and changes in riparian vegetation composition have been recognized to impact fluvial processes (Sidle and Sharma, 1996; Magilligan and McDowell, 1997; Liébault et al., 2005; Nadal-Romero et al., 2012). In general terms, a decrease in vegetation cover along slopes is associated with increases in sediment production, and vice versa (Liébault et al., 2005; Pisabarro et al., 2019), while vegetation cover on channel banks and floodplains can amplify river corridor roughness and resistance to erosion (Gurnell and Petts, 2002; Liébault and Piegay, 2002; Corenblit et al., 2007; Gurnell et al., 2016).

Several studies in the Spanish Pyrenees (Garcia-Ruiz et al., 1997; Beguería et al., 2006; García-Ruiz, et al., 2010; Sanjuán et al. 2016) demonstrated hydrological and geomorphic effects of land-use changes at a catchment scale. Experimental plots were used to demonstrate that deforestation, the cultivation of steep slopes, overgrazing, and recurrent fires in the montane belt caused high runoff rates and extreme soil erosion during the 18th and beginning of the 19th centuries. As a consequence, channels presented a braided morphology, widespread bare bars, morphological instability, and prevalent bedload transport. Conversely, depopulation of mountain areas and the concentration of most human pressure in the valley bottoms, farmland abandonment, and decreases in livestock pressure during recent decades (following World War II), have caused forest recolonization, reduction of overland flow, and soil erosion, and consequently overall channel narrowing and incision in secondary streams, with the formation of new terraces. The recent development of new fluvial terraces resulting from reforestation has been reported in other Mediterranean mountains, including the southern French Alps (Liébault and Piégay, 2001, 2002; Piégay et al., 2004). In particular, most of those rivers underwent channel aggradation during the 19th century because the basins were subjected to deforestation, erosion, and frequent intense floods.

During the 20th century, channels narrowed progressively because of sediment starvation due to a set of factors including the end of the Little Ice Age, torrent controls, and hillslope afforestation due to grazing decline. From the 1950s to 1970s, channel narrowing accelerated, affecting a large part of the hydrographic network, including branches further downstream from sediment sources. This specific afforestation period is related to the development of hillslope forests and the associated deficit in sediment propagation downstream, as shown by Liébault et al. (2005), but is also affected by activities further downstream such as river margin afforestation and the abandonment of intensive floodplain land-uses such as grazing and riparian forest exploitation, which occurred synchronously with upland abandonment and afforestation (Liébault and Piégay, 2002; Taillefumier and Piégay, 2003; Piégay et al., 2004; Liébault et al., 2005; Lallias-Tacon et al., 2017). Grazing activities and agricultural practices on floodplains contributed to bank instability and erosion (Magilligan and McDowell, 1997), while to the contrary, forested floodplains increased hydraulic roughness conditions, potentially reducing channel shifting, floodplain areal erosion, and chute cut-off frequency, thereby facilitating vegetation establishment on bars (Liébault and Piégay, 2002).

Local factors, especially vegetation development on the floodplains and gravel mining, were considered key factors for explaining the narrowing process and metamorphosis from braided to wandering/meandering patterns that occurred in the Magra river in the northern Apennines (Dufour et al. 2015).

A detailed literature review shows that during the last 20 years, dozens of papers were published analyzing channel adjustments in Italy over the last two centuries (Table 1). Most studies on Italian rivers agree that modifications occurred in three phases, highlighting broad common trends (Fig. 1). The so called “Phase 2” occurred between the 1950s and 1990s, and was characterized by very intense channel narrowing, planform morphology simplification, and bed-level lowering. This phase was widely recognized in all Italian rivers, and was essentially linked to the reduction of sediment supply caused by anthropic factors such as gravel mining, dam closure, channelization, bank protections, and other in-channel works (Table 1). Phase 2 corresponds with a period of huge socio-economic modification of Italian society, new economic processes, and changes in population growth following World War II. This context was characterized by the abandonment of mountain areas and the displacement of both agricultural activities and populations to the valley bottoms and coastal plains, and finally the development of mechanized agriculture.

After the 1980s/1990s, during the so called “Phase 3” (Fig. 1 and Table 1), most rivers underwent an inversion trend, characterized by channel widening, local or widespread bed-level aggradation, and channel planform shifting from a single thread to wandering or even multi-threaded morphologies. Except for a few cases (e.g. the Mareit and Aurino rivers, Fig. 1 and Table 1), where restoration operations were carried out, the occurrence of large floods were observed to be the most common drivers of a rapid and abrupt channel recovery (Table 1). However, in some rivers, channel recovery was instead associated with the cessation of sediment mining (e.g. the Tagliamento, Trebbia, Biferno, and Volturno rivers described in Table 1).

In contrast to the second and third phases, “Phase 1” is less well described and understood. As shown in Figure 1, no common temporal trend in the magnitude and distribution of channel modifications is evident over the entire Italian peninsula. However, it seems that channel stability or trends towards narrowing, and probably slight incision, prevail in the rivers in the northern and central part of Italy (from Aurino to Paglia, Fig. 1), while rivers in southern Italy (from Trigno to Crati, Fig. 1) show more variability or a slight prevalence for widening. These contrasting conditions probably indicate that the rivers in central-northern Italy were previously affected by more consistent in-channel human disturbance, which reduced sediment availability earlier (Scorpio et al., 2015), as is described for some of the rivers (e.g. Mareta, Adige, Piave, Tagliamento, Scrivia, Crati), where deliberate narrowing was caused by the construction of levees and groynes at the end of the 19th century/beginning of the 20th century (Table 1). The general trend of narrowing, especially in the rivers of northern Italy, may be temporarily inverted by the occurrence of extreme flood events that caused remarkable channel widening (see the events affecting the Mareta between the 1920s and 1940s, the Brenta in the 1960s, the Piave in the 1880s and 1960s, and the Magra in the 1940s, Fig. 1).

Finally, there may also be differences in the definition of the evolutionary trajectories, which can be attributed to variations in the accuracy of the maps and temporal variations in scanning, especially in the time span before the 1950s. In particular, long time spans between consecutive maps do not allow the evaluation of whether channel changes occurred consistently over specific periods, or whether the changes showed accelerations and decelerations.

Overall, channel changes in Phase 1 are interpreted as being related to climate changes connected to the end of the Little Ice Age (ca 1850–1880), to the modification of sediment supply coming from slopes because of land-cover modification at the catchment scale, and to the application of soil-erosion control measures on slopes and tributaries (Table 1). Deforestation and soil erosion are well documented between the 19^{th} century and the first decades of the 20^{th} century, whereas increasing afforestation and slope movement stabilizations are described since the 1930s/1950s (Table 1).

The literature overview of the Italian rivers demonstrated that many drivers have interacted over space and time, as is the case in other rivers worldwide (Downs et al., 2013). In most cases, it is not straightforward to establish a clear link between each individual factor and the observed channel condition and its evolution (Dufour et al., 2015), and the role of land use changes at the catchment and reach scales has been addressed only qualitatively in most Italian case studies (see the column ‘Effects of Land use changes at catchment and/or reach scale”, Table 1). The effects of afforestation at a catchment scale were quantified in a few papers (see Table 1: Comiti et al., 2011; Preciso et al., 2012; Ziliani and Surian, 2012; Bollati et al., 2014; Magliulo and Pignone, 2016; Scorpio et al., 2015; Scorpio and Rosskopf, 2016; Fortugno et al., 2017; Marchese et al., 2017), although only six out of 40 considered studies compared land use changes occurring in the corridor area with channel adjustments (Aucelli et al., 2011; Comiti et al., 2011; Dufour et al., 2015; Surian et al., 2015: Picco et al., 2017; Mandarino et al., 2019).

To fill this gap, multiple basins were analyzed, with eight rivers from the north to the south of Italy being considered (Sesia, Stura di Lanzo, Stura di Demonte, Borbera, Nure, Volturno, Trigno, and Fortore rivers). The study was based on a diachronous-synchronous approach carried out at catchment and reach scales and compared channel adjustments and land use changes with the aim of separating the influences of natural and human drivers.

2. Study area

Eight rivers situated within three distinct regions from the north to the south of Italy were analyzed (Fig. 2). The Sesia, Stura di Lanzo, Stura di Demonte, and Borbera rivers are located in the Piemonte Region, in the north-western part of Italy (Fig. 2A); the Nure is located in the Emila-Romagna Region, in northern Italy (Fig. 2A); and the Volturno, Trigno, and Fortore rivers fall in southern Italy (Fig. 2B). From a physiographical point of view, the Sesia, Stura di Lanzo, and Stura di Demonte drain from the Alps, the Borbera and Nure drain from the northern Apennines, and the Volturno, Trigno, and Fortrose drain from the southern Apennines. These rivers were selected as they are characterized by different climatic, geologic, and physiographic characteristics; different fluvial system sizes and morphologies; and different socioeconomic contexts and degrees of human impact. Some of the physiographic and hydrological features are summarized in Table 2.

The catchments of these rivers span a wide range of geological conditions. A prevalence of metamorphic rocks, especially gneiss and serpentinite, characterize the Sesia, Stura di Lanzo, and Stura di Demonte basins, with lower but relevant outcropping of igneous rock (granites) in the Sesia, and sedimentary rocks, especially dolomites, in the Stura di Demonte. The Apennines basins are composed of sedimentary rocks, with some differences between river systems. The Borbera, Nure, and Fortore are underlain by sandstones and mudstones, with outcrops of clay and conglomerates of marine and continental environments in the lower sector of the Fortore River. The Volturno and the upper part of the Trigno catchment are mainly composed of limestone, marly limestones, and flysch deposits. Multi-colored clays and siliciclastic flysch deposits prevail in the middle and lower portions of the Trigno basin. The climate is temperate with rainfall peaks concentrated in the spring and autumn in the Sesia, Stura di Lanzo, Stura di Demonte, Borbera, and Nure basins; and Mediterranean to warm temperate, in the Volturno, Trigno, and Fortore. In particular, the headwater portions of the southern Apennines basins present a temperate–warm humid climate, while the medium and lower sectors are largely represented by a temperate–warm humid climate with warm summers in the Volturno, and very hot and dry summers in the Trigno and Fortore. As a consequence, discharges in the channels show low-flow conditions in spring–summer seasons and high-flow in autumn–winter (Aucelli et al., 2007). The Sesia and Stura di Lanzo have partly ice-fed basins (1% and 12% glaciated areas, respectively).

In the Sesia, Stura di Lanzo, Stura di Demonte, and Nure rivers, channel morphologies - from upstream to downstream - shift from a single sinuous thread or a sinuous morphology with alternate bars, to a multithreaded, wandering and/or braided morphology, before returning to a single-threaded morphology (sinuous and meandering) in the lower plains. The Borbera features a braided planform morphology.

In the Trigno and Fortore, wandering and sinuous channels alternating with bar morphologies feature in the unconfined reaches and upper valleys, respectively, while, sinuous to meandering patterns prevail in the confined reaches and lower/coastal segments. The Volturno presents a prevalence of single-threaded patterns composed of sinuous morphologies with alternate bars in the upper valley, and sinuous and meandering channels in the medium and lower valley.

Forty-three study reaches providing a total length of 165 km were selected (Fig. 2), taking into account evidence of appreciable morphological changes over the past century, while excluding reaches that were confined. For the Nure, Volturno (in the multi-threaded segment in 1954), Trigno, and Fortore (upstream of the Occhito dam) rivers, most of the channel length was analyzed to examine changes in propagation from upstream to downstream over time. To analyze the influence of land-use changes within the river corridors on channel morphology, a further 22 reaches presenting low direct human impacts (gravel mining, bank protection, damming upstream) until at least the 1970s were further selected from the 43 reaches on the basis of the availability of maps and aerial photos, and the technical constrains linked to the quality of the available material (Fig. 2 and Table 3). These reaches were compared with the aim of assessing the effects of catchment-scale vs reach-scale controlling factors.

In all catchments, human activities took place mainly over the second half of the 20th century (Table 4). At the reach scale, the alpine rivers and most reaches in the Nure and Volturno experienced human impacts consisting of gravel mining in the floodplains and the construction of in-channel works since the late 1970s (Table 4). In the Trigno and Fortore, human pressures started in the 1980s, although they were more intense and widespread than in the other rivers (Table 4).

3. Materials and methods

A combined diachronous-synchronous approach integrating data from catchment to reach scale over several time periods was used in this study (Downs and Piégay, 2019). Channel changes were related to different drivers of change, on the bases of the temporal synchronicity and spatial proximity.

3.1. Channel planform changes

Channel changes were estimated by means of a diachronic approach using a set of historical maps, aerial photos, and orthophotos (Table 5). Measurement errors were estimated using the method proposed by Mount et al. (2003). In accordance with previous similar studies in the same or other areas (Winterbottom, 2000; Scorpio et al., 2015; Scorpio and Rosskopf, 2016; Surian et al., 2009b), the maximum error was estimated to be about 35 m for the historical maps and lower than 5 m for the aerial photographs.

Channels were edited as polygons, including the low flow channels and bare alluvial sediments classified as bars, while islands were excluded from the active channel areas. To remove size effects, the active channel width was standardized by the root mean square of the basin area (W* sensu; Piégay et al., 2009). W* is considered as a proxy for the sediment supply.

To allow the comparison of different river reaches, active channel width changes were calculated with respect to the active channel width in 1954 (the oldest aerial photos available for all rivers) using the following equation:

$$\Delta W_{1954}(\%) = (1 - {}^{W}/_{W_{1954}}) * 100 \qquad (1)$$

where W is the average active channel width measured in different years (from 1852 to 2016), and W_{1954} is the average active channel width in 1954. W* and ΔW_{1954} were computed for all the 43 analyzed reaches.

For the 22 selected reaches, the annual rates of channel width variation (expressed in m y^{-1}) were evaluated for four periods: 1954–1970s; 1970s–1980s; 1980s–1998; 1998–2010s.

3.2. Land cover changes

Land use changes were evaluated at both reach and catchment scales. At the reach scale, analyses of land use evolution were carried out for the 22 selected reaches, using a diachronic approach in ArcGis and several sets of aerial photos and orthophotos representative of five periods (1954; 1970s; 1980s; 1990; 2010s; see Table 5 for more details).

To improve uniformity in the interpretation of aerial photos and orthophotos of different resolutions and quality, nine land uses classes were mapped, following the methodology proposed by Dufour, 2005 and Dufour et al., 2015: active channel (wetted channel and unvegetated bars); sparse pioneer vegetation (sparse pioneer vegetation on gravel bar); dense pioneer vegetation (dense pioneer vegetation on the bars, islands, and incipient floodplains); shrub land (units dominated by shrub species); grasslands (units dominated by meadow and herbal species); grasslands with trees and shrubs (units dominated by meadow and herbal species with the presence of sparse trees and shrubs); post- pioneer vegetation (units dominated by mature woodland, usually corresponding with floodplains or recent terraces); agricultural areas; and human activity (roads, gravel mining, housing).

The nine land-use units were mapped within the corridors of historical changes, and within the areas composing the former active channels in previous years that were then abandoned in following years (e.g., land mapped in 1976 within the polygons forming the active channel in 1954, then abandoned in 1976). The historical corridors overlaying the active channels mapped since the 19^{th} century were defined (when maps where available), especially from 1954 to the present.

At the catchment scale, land cover changes were analyzed using data sets from several sources (Table 5), including data from the literature (Di Martino, 1996), official surveys of the National Agrarian Census (http://seriestoriche.istat.it/index.php?id=8), interpretation of orthophotos and maps available on regional websites (http://geoportale.regione.emilia-romagna.it/it/contenuti/database-uso-del-suolo; http://www.geoportale.piemonte.it), and Corine land cover maps obtained from the Italian Ministry of Environment (http://geoportale.isprambiente.it/tematiche_pt/suolo/). The collected sources allowed the reconstruction of land use changes from 1836 to 2012 in the Volturno and Trigno catchments, from 1853 to 2012 in the Nure Catchment, from 1929 to 2012 in the Borbera and Fortore catchments, and from 1960 to 2012 in the Sesia, Stura di Lanzo, and Stura di Demonte catchments. To confirm the trends detected for each catchment and to increase the long-term data for the Stura di Lanzo, Stura di Demonte, and Fortore basins, additional analyses at the province/regional level (Torino province for the Stura di Lanzo, Cuneo province for the Stura di Demonte, and Molise region for the

Volturno, Trigno, and Fortore basins) were carried out for the period 1929 to 2012, using data from the ISTAT website (http://seriestoriche.istat.it/index.php?id=8).

Land uses at the catchment scale were reclassified into the following main types: forested area, pasture and meadow, ploughed land (including crops mainly characterized by cereals), cultivated trees (including crops with cultivated trees), shrub cover, and other (including urban areas, sparsely vegetated areas, bare rock patches, recently burnt areas, and river beds).

3.3. Population and livestock densities

Statistics on population and livestock densities can provide indicators of the anthropogenic pressure on the environment at different scales (Taillefumier and Piégay, 2003). In Italy, 10-yearly population censuses have been conducted regularly since 1861, with the exception of 1891 and 1941. Data on the population composition between 1861 and 2011 were imported from the website ISTAT (http://seriestoriche.istat.it/; http://seriestoriche.istat.it/index.php?id=8) and used to derive statistics and density trends in all analyzed catchments and the municipalities in which the 22 selected reaches are located.

Livestock composition trends were also derived from the ISTAT website, based on a number of surveys between 1908 and 2010. Analysis were carried out at the province level (Torino Province for the Stura di Lanzo River, Cuneo Province for the Stura de Monte River, Piacenza Province for the Nure River) and the regional scale (Volturno, Trigno, and Fortore rivers). Data are referred to 1908, 1930, 1941, 1961, and 2010 for analyses at the province scale, and to 1908, 1930, 1941, 1961, 1970, 2000, and 2010 for the analyses at the regional scale.

3.4. Climate trends and changes in the frequency of floods

Climate changes over the last century were reconstructed from studies on precipitation and temperature trends (Brunetti et al., 2000, 2004a, 2004b).

With the exception of the Stura di Lanzo River at the Lanzo gauging station (Arpa Piemonte, 2012), data on discharge were either unavailable for the studied rivers, or the existing records showed a number of gaps and were not therefore suitable for analysis.

The occurrences of flood events were reconstructed using data extracted from the AVI project (http://avi.gndci.cnr.it) for the Volturno river, from various archives provided by the basin authorities for the rivers Trigno, Biferno, and Fortore, and by the Consortium 'Bonifica della Capitanata' for the Trigno and Fortore rivers.

4. Results

4.1. Channel planform and width changes

Analysis of the W* distribution of all 43 reaches highlights several differences (Fig. 3A). Rivers in the southern Apennines (Volturno, Trigno, and Fortore) and the Borbera and Lavaiana present a high potential for sediment supply (Fig. 3A; W* in all reaches and all years exceeds 1 and goes up to 29.3 in the Fortore in 1954). The Nure and Lardana also show some W* values higher than 1, but the minimum values decrease to 0.24 in the Nure and 0.8 in the Lardana. The Alpine Rivers are characterized by lower W*, ranging between 0.08 and 0.19 in the Stura di Demonte, between 0.16 and 0.41 in the Stura di Lanzo, and between 0.17 and 0.31 in the Sesia (Fig. 3A).

Analysis of the changes in W* over time reveals that before 1954, W* was slightly lower than after 1954 in the Stura di Lanzo (from 0.42 to 0.35; Fig. 3B), Nure (from 1.3 to 1.01 on average; Fig. 3C) and Trigno (from 20 to 19.5 on average; Fig. 3E) rivers, but was slightly higher in the Sesia (from 0.26 to 0.3; Fig. 3B), Stura di Demonte (from 0.16 to 0.19; Fig. 3B), Volturno (from 13.2 to 18.7 on average; Fig. 3D), and Fortore (from 20.8 to 24.2 on average; Fig. 3F) rivers. This suggests a decrease in sediment supply in the Nure and Stura di Lanzo and an increase in the Sesia, Stura di Demonte, Volturno, and Fortore.

Between 1954 and the 1990s, W* decreased in all rivers, with rivers in the southern Apennines showing a sudden decrease between 1954 and the 1970s; while the decline in W* in the other rivers was more gradual and uniform over time (Figs. 3B and 3C). In the Borbera River, W* decreased from 11 to 9 between 1954 and the 1970s, and then oscillated between 9 and 8.5 until the present day (Fig. 3B).

After the 1990s, W* increased in all rivers except the Volturno and Sesia, where it continued to decline (Fig. 3).

Further differences between rivers in northern and southern Italy are highlighted when all 43 reaches are considered (Figs. 4A and 4B). Before 1954, the active channel widths of all rivers were within approximately ± 20% of those in 1954 (Figs. 4A and 4B).

After 1954, active channel narrowing in southern Italy (Fig. 4B) exceeded −60% up to the 1980s/1990s. Maximum narrowing was reached in the Fortore in 1998 (−88% on average) and in the Volturno in 2016 (−89% on average). In the northern Italian rivers, narrowing was lower than −60%, with maximum values being attained in the 1990s or 2010s (up to −46% in the Sesia in 2015; −53% in the Stura di Lanzo in 2015; −55% in the Stura di Demonte in 1996; −26% in the Borbera in 1996; −45% on average in the Nure in 1988; −65% in the Lardana in 1988; −59% in the Lavaiana in 1998; Fig. 4A).

Trends of active channel width changes from upstream to downstream in the same river show a general decrease in channel narrowing in the reaches closer to confluences or to the river mouth (Fig. 4C). Reaches upstream do not present clear and unequivocal trends, especially in the Trigno and Fortore rivers, while narrowing propagated downstream at a decadal time scale in the Nure River (Fig. 4C).

In the 22 selected reaches, several differences in terms of the timing of peak periods and the amounts of average annual active channel width variation are evident (Table 6). High rates of narrowing are shown by the reaches Volt2 and Volt4 in the Volturno River (average annual rates ranging from −4.0 to −4.6 m y^{-1} between 1954 and the 1980s), reaches in the Trigno River in the southern Apennines (Tr5 and Tr9, with average annual rates up to −4.5 and −5 m y^{-1} respectively in the 1980s–1990s), and the Stura di Lanzo (average annual rates up to −4.1 m y^{-1} between 1954 and 1970s), Stura di Demonte (average annual rates up to −3.5 between the 1970s and 1990s) and Sesia (average annual rates up to −3.2 in the 1980s–1990s) in the Alps (Table 6). Rivers in the northern Apennines (Borbera, Nure, Lardana, and Lavaiana) experienced maximum annual rates of narrowing up to −2.0 m y^{-1}, but the average values were lower than −1 m y^{-1}. In the Nure catchment, the upper reach (Nur1) and the reaches in its tributaries (Lar1 and Lav1) presented similar trends over the entire investigated period, with maximum narrowing occurring between 1954 and the 1970s (Table 6). Reaches downstream (from Nur3 to Nur10, Table 6) show a peak period of narrowing in the 1970s–1980s, with higher values in the reach Nur10 (−4.0 m y^{-1}). Trends and rates in the Borbera river (Bor1, Table 6) are similar to those found in the Nure basin.

The Fortore river in the southern Apennines reached peak annual rates of narrowing (up to −1.5 m y^{-1}, Table 6) in the periods 1954–1970s and 1980s–1990s.

In the Stura di Lanzo, Nure, Trigno, and Fortore rivers, some evidence for widening (between +0.3 m y^{-1} in the Fortore to +7.8 m y^{-1} in the Stura di Lanzo, Table 6) is observed, especially after the 1990s.

4.2. Land cover changes at the reach scale

Detailed maps allowing land use characterization in the landscape corridor before 1954 are available for the Volturno in southern Italy and the rivers in the Piemonte Region (Sesia, Stura di Lanzo, Stura di Demonte, and Borbera). In all these rivers, grasslands and semi-natural vegetation (especially pioneer vegetation, shrub lands, and grasslands with trees) prevailed in the middle of the 19^{th} century, with agricultural areas coming second. At that time, riparian forests were almost absent in the Volturno and Sesia, while they were present in a juvenile and sparse phase with discontinuous coverage in the Stura di Lanzo, Stura di Demonte, and Borbera.

After 1954, specific land use typologies are clearly recognizable in the corridor of the historical channel changes of the 22 reaches (Fig. 5).

Post-pioneer vegetation encroachment started from the middle of the 20th century to approximately the 1980s, in the Borbera, Lavaiana, Nure1, Nure3, and Volturno (Fig. 5). In 1954, the Sesia and Stura di Demonte were already well forested (27% and 32% respectively), while the Lardana, although presenting a low coverage of riparian forest (3%), was characterized by juvenile phases presenting sparse (41%) and dense (16%) riparian vegetation, which developed into mature forest over time, especially during the 1970s and 1990s (Fig. 5). In all the rivers mentioned above, channel narrowing occurred with the absence of increasing human pressure (except for the Volturno River) and the increase in post-pioneer vegetation, even though land uses changes did not present the same temporal patterns, as river vegetation encroached earlier in some rivers (Sesia, Stura di Lanzo, Stura di Demonte, Lardana) than in others (Borbera, Volturno, Nure). In the Volturno River (Vol4 and Vol5), forest expansion was possibly limited by increases in agricultural areas and human activities after the 1980s. After a first phase of channel narrowing contemporary with forest expansion in the Stura di Lanzo (between 1954 and 1980s), widening abruptly took place as a consequence of flood events between the 1980s and 1990s (Fig. 5).

The Nure River shows an upstream to downstream gradient in forest cover increase and channel narrowing. Upstream channel changes occur sooner than those downstream (breaking points in channel area change between 1954 and 1970s in Nur1, between the 1970s and 1980s in Nur3, Nur5, and Nure6, and between the 1980s and 1990s in Nur10; breaking points in forest cover change between 1954 and 1970s in Nur1 and Nur3, between 1970s and 1980s in Nur5 and Nur6, and between the 1980s and 1990s in Nur10), denoting a clear downstream propagation probably related to a decrease in sediment supply from upland sources. Overall, post-pioneer vegetation started to become established in the 1970s, and human impacts, similar to the situation for the Volturno river, increased after the 1980s (agricultural area changed from 22%–25% in 1954 to 25%–45% in the 2010s; human activities from 0% in 1954 to 4%–18% in the 2010s, Fig. 5).

The Trigno and Fortore rivers in southern Italy exhibit similar land use changes and configurations, being mainly dominated by agricultural areas, grasslands, and human activities (Fig. 5). Between 1954 and the 2010s, agricultural areas (from 6%–23% in 1954 to 11%–32% in 2010s in the Trigno; from 4%–33% in 1954 to 44%–53% in 2010s in the Fortore) and human activity (from 0 in 1954 to 10%–19% in the 2010s in the Trigno, from 0% in 1954 to 7%–23% in the 2010s in the Fortore) showed increases coincident with the decrease in the active channel. Shrub lands, grasslands, and grasslands with trees and shrubs showed relevant occurrences since 1954, especially in the Trigno. In contrast to all the other rivers, riparian vegetation never particularly developed in the Trigno and Fortore (maximum expansion 7%–22% in the 2010s in the Trigno; 8%–13% in the 2010s in the Fortore), with it starting to only lightly increase since the 1990s, when human activities and agricultural areas declined (Fig. 5).

Similar trends are noted in the progressive abandoned portions of the active channels (Fig. 6). The areas abandoned by the active channel between 1954 and 1970 were mainly encroached by post-pioneer vegetation (exceeding 40% of land uses) in the Sesia, Stura di Demonte, Borbera, and Volturno rivers (Fig. 6A). In the Nure and Lardana, there was a prevalence of pioneer vegetation, while grasslands with the presence of trees and shrubs were widespread in all reaches, but particularly in the Lavaiana (Fig. 6A). The Trigno and Fortore rivers showed especially high levels of grasslands and shrubs, and evidence of human activities and agricultural pressures (Fig. 6A). Between the 1970s and 1980s, pioneer vegetation and secondary post-pioneer vegetation encroached along all the rivers except for the Trigno and Fortore, where human activities prevailed (Fig. 6B). Since the 1980s, riparian forests, pioneer vegetation, shrub lands, and grasslands with trees and shrubs increased along all reaches (Figs. 6C and 6D). Between the 1980s and 1990s, human impacts kept affecting rivers in southern Italy (Trigno and Fortore) and along some reaches of the Nure (Fig. 6C). In some rivers (Stura di Lanzo between 1980s and 1990s and Trigno and Fortore between 1990s and 2010s, Figs. 6C and 6D), previous land uses were substantially eroded and vegetation was rejuvenated by flood events.

In summary, analyses of the land use changes in the corridors of the studied reaches between 1954 and the 2010s have highlighted similarities between the rivers in the Piemonte Region (northern Italy), the Nure, Lardana, Lavaiana, and the Volturno River in southern Italy, especially concerning contemporary afforestation and channel narrowing. For these rivers, phases of vegetation encroachment do not present a synchronous pattern, as the Sesia and Stura di Demonte were already forested in 1954, while in the other rivers, forest expansion started in the 1970s–1980s (e.g., the Volturno, Borbera, Lardana, Lavaiana, and Nur1), or even later in some reaches of the Nure river. In the Fortore and Trigno river (southern Italy), channel narrowing occurred with the increase in human pressure and the permanence of grazing areas.

4.3. Land cover changes at the catchment scale

Historical land use changes play an important role in sediment balance, runoff, and the impacts of rainfall on flow and sediment generation, and consequently on morphological channel evolution. When evaluating channel changes through time, it is therefore important to determine whether land uses were stationary or not, and to consider them in the understanding of channel changes.

Although the data is subject to uncertainty related to the comparisons of maps having different sources and scales, some relevant trends are clearly evident.

The Borbera, Nure (in northern Italy), and Volturno (in southern Italy) rivers present similar general trends, even considering the two sub-periods (before and after the 1960s, Table 7, column trends): a substantial increase in forest areas, especially from the 1930s onwards (from 22% to 64% in the Borbera, from 33% to 52% in the Nure, from 18% to 50% in the Volturno between 1929 and 2012;

Table 7); a slight decrease in pastures and meadows (from 12% to 2% in the Borbera, from 18% to 9% in the Nure, from 26% to 16% in the Volturno between 1929 and 2012; Table 7); large decreases in ploughed lands, especially in the Volturno River (from 19% to 1% in the Borbera, from 33% to 8% in the Nure, from 50% to 7% in the Volturno between 1929 and 2012; Table 7); and marked extension of cultivated trees, particularly after the 1960s (from 6% to 20% in the Borbera, from 0% to 28% in the Nure, from 5% to 23% in the Voltuno between 1929 and 2012; Table 7). Forest cover increased before the 1960s/1970s in the Borbera and Nure basins, and especially after the 1970s in the Volturno (Table 7). In all these basins, forests increased in the upper parts while cultivated trees increased in the lower parts, at the expense of pastures, meadows, and ploughed lands. Analysis suggests the occurrence of a natural regeneration of vegetation after the 1930s, and modification of farming practices from extensive to intensive.

The Trigno and Fortore rivers present some similarities in both sub-periods (Table 7). Forest cover does not present the most interesting change occurring in these basins, as they are characterized by only slight increases, from 15% to 29% in the Trigno River and from 7% to 15% in the Fortore between 1929 and 2012 (Table 7). Notable increases occurred in the cultivated trees between 1929 and 2012, from 5% to 22% in the Trigno and from 4% to 24% in the Fortore (Table 7). Most forest and cultivated trees increases occurred after the 1970s in both catchments. Despite a decrease in ploughed lands from 61% to 30% in the Trigno and from 77% to 55% in the Fortore, especially after the 1970s, they still remain the most widespread land use to the present. In both basins, pasture and meadows cover 10% of the total area until the 1970s, after which they almost disappear. The overall analysis of the land use changes in Trigno and Fortore basins suggests a strong control of agricultural use of the territories.

The Sesia, Stura di Lanzo, and Stura di Demonte rivers are tricky to compare with the other basins, because numerical data are only available from 1960, and for these rivers, only data referring to the second sub-period can be described.

The Sesia already presented very high forest coverage (46%, Table 7) in 1960, with this percentage being comparable with the forests in the Nure and Borbera in the 1960s/1970s, and being higher than that in the Volturno in the 1950s/1970s. In the Stura di Lanzo and Stura di Demonte rivers, forested areas increased from 18% to 33% and from 24% to 28%, respectively.

Pasture and meadow largely decreased in all three rivers, (from 43% to 16% in the Sesia, from 68% to 21% in the Stura di Lanzo, from 44% to 21% in the Stura di Demonte; Table 7).

Ploughed lands are negligible in the Sesia and Stura di Lanzo, while they showed a decrease from 22% to 13% in the Stura di Demonte. Agricultural areas occupied a very low percentage of the basins.

In general, between 1960 and 2012, the Sesia, Stura di Lanzo, and Stura di Demonte land cover was mainly characterized by increases in forest and shrub cover and a decrease in pastures and meadows. Cultivated trees and ploughed land are not prevalent. Increased shrub cover is interpreted as a transitional stage between pastures and meadows or cultivated plots to forest cover.

To compensate for the absence of data before 1960 in the Stura di Lanzo and Stura di Demonte rivers, an analysis at the province scale was performed (Fig. 7A and Fig. 7B). The figures confirm widespread pasture and meadow cover in 1929 that then declines over the 20th century, an increase in forest cover only after the 1970s, while before it was constant. and a decrease in ploughed lands in both provinces, which before 1960 were the most important land cover in the Cuneo Province (Stura di Demonte). The increase in cultivated trees, especially after the 1970s (Fig. 7A and Fig. 7B), is not found in the studied area, maybe because the entire provinces include more plain areas. Furthermore, trends in all the Molise regions (Volturno, Trigno, and Fortore rivers) confirm the trends described for the singular rivers (Fig. 7C), and highlight the higher ploughed and agricultural cover in southern Italy compared with the north (Fig. 7A and Fig. 7B).

4.4. Evolution of population and livestock density

Demographic changes in population and livestock were interpreted as indirect indicators of land use change (Taillefumier and Piégay, 2003) and human pressure at basin and reach scales.

In 1861, the population density in the northern Italian river basins (Fig. 8A) was slightly lower (from 56 inhabitants/km^2 in the Nure to 63 inhabitants/km^2 in the Stura di Demonte and Borbera basins) than that in the southern Italian basins (Fig. 8B, between 78 inhabitants/km^2 in the Volturno river and 88 inhabitants/km^2 in the Fortore river). An exception is represented by the Sesia (Fig. 8A), with 72 inhabitants per km^2. Between 1861 and the beginning of the 1950s, the population slightly increased in most of the basins (e.g. up to 95 inhabitants/km^2 in the Fortore river, up 90 to inhabitants/km^2 in the Sesia river and up to 71 inhabitants/km^2 in the Nure river), while it remained fairly constant in the others. Differing from most catchments, the Borbera underwent a consistent depopulation soon after the 1860s (Fig. 8A).

A rapid depopulation occurred in most of the basins between the 1950s/1960s and 1970s/1980s, with a general migration of the inhabitants to the plain areas. Figures 8C and 8D show stronger decreases in the mountain parts of the basins of all rivers. Depopulation had already started in the 1900s/1920s in some river basins of northern Italy, and started after the 1950s in those in southern Italy. In the Trigno catchment, most of the population moved from the mountain to the coastal area (Fig. 8D). However, the Stura di Lanzo and Stura di Demonte rivers showed a different pattern, with increases in their populations.

After the 1980s, the population density was more stable in the basins of the northern Italian rivers (Fig. 8A) and the Volturno river (Fig. 8B), whereas it continued to decrease in the Fortore and Trigno river basins (Fig. 8B) and the mountain parts of the catchments of all the rivers (Figs. 8C and 8D).

Analysis of the evolution of the demographic density of the population was also performed for the neighboring municipalities of the 22 selected reaches (Fig. 8E and 8F). In all rivers where multiple reaches were analyzed, the derived trends were very similar, and could be represented by a singular trend, as indicated in Figures 8E and F.

The reaches in the Sesia, Stura di Lanzo, Stura di Demonte (Fig. 8E), and Volturno (Fig. 8F) presented similar trends, with human density increasing since the 1860s. The period of stronger population increase occurred in the 1950s/1960s in the rivers of northern Italy, and after the 1970s in the Volturno.

The Nure, Trigno, and Fortore rivers have similar trends, characterized by a population increase followed by a rapid decrease (Fig. 8E and 8F). The historical maximum density occurred in the 1920s in the Nure river (59 inhabitants/km^2), and in the 1950s in the Trigno and Fortore rivers (85 inhabitants/km^2 in the Trigno reaches, 95 inhabitants/km^2 in the Fortore).

At the reach scale, the Borbera showed a different trend, with the population density reaching its maximum in the 1910s/1920s (98 inhabitants/km^2) and its minimum in the 1960s/1970s (77 inhabitants/km^2).

Ovine (sheep) and caprine (goat) breeding is considered an extensive form of breeding that requires little labor and is not wasteful of resources. It is traditionally characteristic of dry mountain areas, where historic fluctuations in the livestock are often linked to economic and political events (Taillefumier and Piégay, 2003).

Overall, the data show that ovine and caprine breeding in northern Italy never took a notable diffusion during the study period (never higher than 0.10–0.15 head of cattle/ha). In these territories, cattle were probably never of great importance, and bovine breeding involved more intensive livestock production in barns. Cattle trends are comparable between the Torino and Cuneo provinces (Stura di Lanzo and Stura di Demonte respectively; Figs. 9A and 9B). Bovine numbers showed a particular increase after the 1960s, while ovine numbers showed notable decreases between the 1940s and the end of the 1950s (Figs. 9A and 9B).

In Piacenza Province (Nure basin, Fig. 9C), the most widespread animal rearing concerned bovines. Ovines decreased in numbers until the 1960s, after which they became of negligible relevance. In southern Italy, different sources indicate a scattered decrease of breeding during the 19th century (Barker, 1995), and the same trend is confirmed during the 20th century by data collected in this study (Fig. 9D).

Ovine and caprine breeding have characterized the river basins of Southern Italy, although the overall density trends show a fast period of decreasing density between the 1940s and 1950s (Fig. 9D). Bovine breeding increased in the southern river basins after the 1930s, but never became of major importance (Fig. 9D).

4.5. Trends in climate and flood frequency

Analysis of the recent studies on precipitation and temperature trends over the last 200 years shows that the Italian climate has become warmer and drier since the 1930s, especially in southern Italy (Brunetti et al., 2000). Annual precipitation and the related number of wet days showed a significant negative trend over all of Italy from 1880 to 2002 (Brunetti et al., 2004a). Some important differences in climate modification over the Italian regions are highlighted. Temperature showed a positive trend in all seasons in southern Italy, and especially in the autumn and winter in northern Italy (Brunetti et al., 2004a), starting from the 1910s and 1920s. Temperatures rose rapidly until the 1950s, and were then constant from 1950 to 1985, with only a slight drop in the period 1970–1980. After 1985, they began to rise again in all seasons. As a consequence, dry conditions became stronger in the southern regions. Total precipitation showed no trend in the northern regions, but a significant negative trend in southern regions, with the number of rainy days decreasing in all regions, with the greatest decreases occurring from the 1930s to 1940s, and from the 1960s to 1980s (Brunetti et al., 2004b). Significant positive trends in precipitation intensity were registered in the northern part of Italy because of the strong decrease in the number of rainy days, while in southern Italy, no significant changes in precipitation intensity were found, because both total precipitation and the number of rainy days significantly decreased (Brunetti et al., 2004b). In northern Italy, the increase in precipitation intensity caused an increase in heavy precipitation events, while at the same time, droughts particularly affected the southern regions, causing problems for agriculture during the summer.

Trends of flood discharge are continuous only for the studied reach in the Stura di Lanzo (station Stura di Lanzo at Lanzo town Fig. 10A). The data show a notable increase in channel width during the 2000s, which was concurrent with the occurrence of large floods (Fig. 10A). According to the data extracted from the AVI project for the Volturno Rivers (Fig. 10B), a significant increase in the frequency of flood events occurred during the 1990s, although these floods did not cause any appreciable channel changes. The increase in channel width in the Fortore and Trigno rivers during the 2000s is related to the occurrence of floods in 2003, 2009, and 2015 (Scorpio et al., 2016b). In the Nure catchment, significant channel width changes were documented in 2015 because of a flood event that occurred in September 2015 (Scorpio et al., 2018c).

5. Discussion

5.1. A very clear regional difference in the narrowing process

This study has revealed a variety of processes influencing channel responses during the last century. The analysis allowed us to identity three main groups of rivers with similar cause-effect interactions between channel behavior and controlling factors. The similarities and dissimilarities in the factors controlling channel changes also varied over time. Overall, the evolutionary trajectories became more similar over time, even between rivers located in different regional contexts, with the main differences being related to the chronology of driver occurrences and associated channel changes.

In the Sesia, Stura di Demonte, and Stura di Lanzo rivers (Alpine rivers in the Piemonte region), channel width declined with the encroachment of vegetation in the corridors and along the hillslopes (Figure 11). In general, these rivers already presented higher percentages of forest cover than the other rivers in the 1950s/1960s, at both reach and catchment scales, with this probably being related to wetter and cooler climatic conditions and lower human impacts caused by the earlier abandonment and depopulation of the mountain areas (which had already started in the 19th century).

The Apennine rivers (Borbera, Nure, and Volturno) present a slight delay in afforestation and vegetation recruitment compared with the Alpine rivers, with this being related to the extent of human exploitation in the upper part of the basins until the middle of the 20th century (Figure 11), and the considerable human pressure in the reaches. Data shows that the northern Apennine rivers and the Volturno followed a similar trend, although with different timelines for the intensity of the processes.

The Trigno and Fortore rivers in southern Italy present a different story (Figure 11). For these, channel narrowing was particularly related to the decrease in high human pressure at the catchment scale (especially before the 1950s, with ovine breeding and farming decline in the uplands), whereas no afforestation occurred at the reach scale.

Narrowing seems to have occurred on most of the rivers before direct human impacts on channel reaches, such as gravel mining and the construction of in-channel works (Italian and French rivers between 1970s and 1990s), and therefore, land-use change must be taken into account in geomorphic analysis to interpret channel changes in Italy, as is also the case in France and Spain (Garcia-Ruiz et al., 1997; Liébault & Piégay, 2001, 2002; Piégay et al., 2004 ; Beguería et al., 2006; García-Ruiz, et al., 2010; Sanjuán et al. 2016). Major land-use change has contributed to reductions in sediment supply and an increase in floodplain resistance, leading to bed level incision and pattern shifting to single-thread morphologies in downstream reaches and regressive erosion upstream.

5.2. The initial 19th century widening

Between the 19th century and the 1950s, active channel width changes occurred in all rivers, although they were not associated with relevant planform morphology modification, as all reaches maintained their original multithreaded pattern (braided or wandering). Because of the gap between historical maps and the first aerial photos, accurate analysis of the timing of channel width changes is not feasible within this period. Despite climate data indicating drier conditions in the rivers of southern Italy, several similarities are found between rivers located in different geographical areas.

Overall, an evident trend of channel widening was found in the Sesia, Stura di Demonte, Volturno, and Fortore (on average +20%), while narrowing was detected for the Stura di Lanzo and Nure (on average −20%). In most basins, demographic pressure and economic needs induced farmers to maximize production, cultivating as much land as they could. Ploughed lands were widespread at the expense of forests and shrubs, despite unfavorable environments (Figure 11). Human pressures active at the catchment scale, such as population growth, overgrazing, and deforestation for the purpose of cultivation, increased runoff rates, soil erosion, and sediment supply to rivers. At the reach scale, low resistance within floodplains due to the prevention of vegetation encroachment and increased soil resistance through overgrazing resulted in channel widening. Most of the large active channels observed during the first part of the 19th century in northern Italy and southeastern France were the result of human pressures on uplands and river corridors. At that time, channels presented multi-threaded morphologies, especially braided patterns, and were characterized by high rates of bedload transport and low bank resistance. Because of this high pressure on land and its potential effects on flow regime and bedload delivery, it is difficult to really assess the effects of the Little Ice Age and its ending, as it is overwhelmed by other factors.

Limits on the available data make it difficult to isolate the causes of channel changes, although overall, it is clear that human pressure along hillslopes had more impact on the southern rivers than on the rivers of northern Italy, particularly in relation to the higher population density, higher breeding of goats and sheep, and higher percentage of ploughed land in the catchments (Figure 11). In the rivers experiencing widening, intense human activity was constant or increased between the middle of the 19th century and the 1950s, whereas those rivers that experienced narrowing were already impacted by rural population decline and the transformation of agricultural systems. Between the 19th century and the 1950s, population density in the Volturno catchment exceeded 75 inhabitants/km^2, the forest cover had not yet started to increase considerably, and the hillslopes were particularly exploited, with ploughed land reaching 50% of total cover (Figure 11). During this period, factors controlling the Volturno dynamic were more comparable to those in other rivers in southern areas than to northern ones. As for the other rivers in southern eastern Italy, the Fortore underwent channel widening, while a specific trend is not clearly highlighted for the Trigno. Their basins are characterized by many similarities in term of climate, average precipitation, orientation, bedrock, mass-wasting processes, and general socio-economic contexts. In the Fortore, widening is probably related to higher rates of sediment supply coming from slopes, which were caused by the increased population density, especially in the mountain areas (Fig. 11), as also confirmed by the higher percentage of ploughed lands in the catchment (Table 8 and Figure 11). In the Trigno, mountains areas had already started suffering depopulation before the 1950s, owing to migration to the coastal areas (Fig. 8D). The trends described for the channels find an indirect confirmation in the evolution of the river mouths. Mouth trends show a significant shoreline retreat in the Trigno (Aucelli and Rosskopf, 2000), which can be interpreted as an indication of a reduction in sediment transport, probably related to the end of the Little Ice Age, and a moderate retreat coupled with lateral migration in the Fortore (Scorpio and Rosskopf, 2016; Fig. 12), which can be interpreted as an indication of significant sediment supply caused by higher human impact in the catchment.

In the Nure and Stura di Lanzo catchments, channel narrowing is chronologically linked to afforestation along the hillslopes and the depopulation of the mountain areas that started before the 1950s.

In contrast to the good availability of data for investigating controlling factors at the catchment scale, information on the possible human impacts on channels at the reach scale is scarcer for the period before 1950. It is probable that positive trends in population density in the proximity of the rivers (Figs. 8E, F, and Fig. 11) caused increases in direct human pressure, as shown for the Volturno River, where maps in 1885 and 1909 display floodplains clearly colonized by semi-natural and pioneer vegetation, while in 1954 they were occupied by arable cultivations reaching the channel banks. Forested floodplains were very infrequent in the 1950s, except for the Sesia and the Stura di Demonte rivers, where they represented 26% and 33% of land cover in the respective river corridors (Figure 11).

Channel narrowing (on average −20%) was also documented for most rivers in southern France (Liébault and Piégay, 2001, 2002; Taillefumier and Piégay, 2003; Piégay et al., 2004; Liébault et al., 2005). Two phenomena were observed to complicate the chronology of changes: i) depopulation occurred before upland and corridor afforestation (depopulation began in the 1830s, in contrast to upland and corridor afforestation, which began in the 1930s–1950s), demonstrating that a certain depopulation was needed before a noticeable effect on land use and then channel response occurred. Such findings allow the disentangling of the end of the Little Ice Age effects (end of the 19th century) from land-use change effects (mid-20th century); ii) earlier afforestation was observed in intra-mountain areas, and was interpreted as a political strategy to control erosion in the Sardes kingdom (Upper Savoy) in the case of the Giffre river, or the combined effects of torrent works that were built during between 1860 and 1920 in the French catchments, such as in the Ubaye river in the southern French Alps.

5.3. The mid-20th century big narrowing

The data available after 1954 allow us to gain a full picture of the cause-effect relationships between channel changes and influencing factors. This analysis allowed us to highlight differences and similarities between rivers located in different regions. All channels suffered narrowing or an acceleration in narrowing between the 1950s and 1990s. The rates for channel narrowing were already elevated over the 1950s–1970s, when activities such as gravel mining and the construction of in-channel works were not yet widespread (Figure 12).

Similar to the situation in Italy, in southern France, narrowing was documented in large rivers of the piedmont and intra-montane valley between the 1950s and 1970s, as well as small mountain streams, notably in the Prealps (Liébault and Piégay, 2001, 2002; Piégay et al., 2004; Liébault et al., 2005). As explained in section 5.2, these rivers were already experiencing narrowing since the 19th century, and between the 1950s and 1970s they suffered a new accelerated phase of narrowing (on average −60% compared with the 1950s). Narrowing took place without any increase in direct human impacts on channels or any relationship with a period of changes in the frequency and magnitude of smaller floods (Liébault and Piégay, 2002). In France, narrowing was interpreted to be a result of the interaction of human and climatic controls, with the former overwhelming the latter. Sediment supply from the slopes showed a decrease in relation to the depopulation that had already started in the 19th century, involving the abandonment of agricultural practices on the hillslopes, afforestation, replacement of ploughed lands with open shrub land and meadows, and decreases in livestock pressure (Taillefumier and Piégay, 2003). In the 1930s, some French rivers (to the contrary to the 19th century, when floodplain forests were infrequent and arable areas were interfaced with active channels) started to host forested riparian vegetation, or shrublands colonized former grazed areas (Piégay et al., 2004). This was the case with the Ubaye River, where riparian vegetation started to encroach from the early 1920s, and was well established in 1948 (Liébault and Piégay, 2002).

In Italy, it seems that Alpine Italian rivers also underwent afforestation at a catchment scale sooner than the Apennine rivers, and this afforestation can be locally associated with torrential works that were conducted during the first part of the 20th century, and in some catchments (Stura di Lanzo, Stura di Demonte, Borbera), to the depopulation of mountain areas (Figure 11). Depopulation in southern Italy (Volturno, Trigno, and Fortore rivers) took place only after 1950, some decades later than in northern Italy and France. In all catchments in Italy, depopulation and the abandonment of farmland and ploughed lands accelerated after World War II, causing less sediment production from the slopes and the spontaneous colonization of pastures by shrub formations. In Italy, riparian vegetation started to encroach on the river corridors at different times: before the 1950s in some rivers of northern Italy (Sesia, Stura di Demonte, Lardana), and between the 1950s and 1980s in the Stura di Lanzo, Borbera, Nure, and Volturno (Fig. 11). Riparian vegetation was characterized by mature phases of post-pioneer vegetation in the Sesia (up to 73%), Borbera (up to 41%), and Stura di Demonte (up to 42%), and by pioneer stages of forest growth composed of riparian forests, sparse riparian vegetation, and grasslands with shrubs and trees in the Nure, Stura di Lanzo, Lardana, and Lavaiana. The primary role of riparian forests and semi-natural vegetation in driving channel narrowing between the 1950s and 1970s was also observed by Mandarino et al. (2019b) in the Scrivia River, and by Dufour et al. (2015) in the Magra River (northern Apennines, see Fig. 2A for location).

In the Nure River (northern Apennines), an upstream-to-downstream gradient in forest cover increase and in-channel narrowing was found, similar to that shown by Liébault et al. (2005) with a dendrochronological method. In light of these studies, the combination and comparison of such studies between different rivers and along channel gradients is shown to be very valuable for validating and establishing the importance of potential causes.

In both France and Italy, it became clearly evident that channel narrowing in some rivers (e.g. the Drôme, Ain, and Ardéche rivers in France, and the rivers in northern Italy and the Volturno river in southern Italy) occurred simultaneously with riparian vegetation encroachment on channel bars and floodplains. Lallias-Tacon et al. (2017) asserted that long-term narrowing of the Bouinenc torrent until 1975 resulted in a well-developed vegetated floodplain that was for the most part composed of mature units. As confirmation, Liébault and Piégay (2002) presented the case of the Doubs River, the channel of which remained stable from 1940 to 1996. The encroachment of riparian vegetation onto the Doubs's floodplain was inhibited by the continuation of land exploitation and intense livestock grazing.

In conclusion, controlling factors for channel narrowing between the 1950s and 1970s were referred to overlaps between catchment-scale (depopulation and afforestation) and reach-scale factors (riparian vegetation encroachment). At the reach scale, most intensive floodplain land uses were abandoned (Liébault and Piégay, 2002), with the consequent rapid riparian forest expansion occurring concurrently with the abandonment of agriculture and grazing in riparian zones.

Focusing in more detail on the rivers of southern Italy (Volturno, Trigno, and Fortore), it appears clear that narrowing between the 1950s and 1970s was more intense (on average between –40% in the Trigno and more than –50% in the Volturno and Fortore rivers, Fig. 4A and 4B) than in the rivers of northern Italy (between about 20% in the Nure and 50% in the Lardana, Fig. 4A and 4B). Channel narrowing was not supported by climate data (which highlighted a relatively wet climate and higher flood frequency until the mid-1970s) (Scorpio et al. 2015), but by human impacts, because as previously stated, southern Italy was impacted by a set of socio-economic transformations between the 1950s and 1970s, transformations that had already occurred several decades before in northern Italy. Narrowing in the south seems to be mainly linked to bedload delivery decline, rather than increased bank resistance following reach afforestation. We may expect that grazing also declined in the floodplain area, and that grass and shrub establishment may have had a resistance effect. This first narrowing step was then exacerbated by local pressures (e.g.

gravel mining and the construction of in-channel works) inducing a second narrowing phase after the 1970s–1980s (Figure 11). On the Magra River, Dufour et al. (2015) did not interpret any downstream shift in change in a comparison of two reaches, and concluded that local factors were the primary drivers of the narrowing (encroachment, not afforestation, and mining). They showed a two-step evolution in the downstream reach, similar to that we observed in the Trigno and Fortore, but not in their upstream reach. This fact may potentially allow the separation of local factors (notably mining) from upstream ones, and allow discussion of upstream versus local control. Because upstream and downstream land-use change results from the same drivers, they also have the same chronology, and it is therefore difficult to distinguish the effect of each from the historical data. In the case of France, the Doubs river was interesting in the sense that it showed that narrowing did not occur on a reach that was not afforested, giving credit to a reach-scale afforestation effect on narrowing. However, this observation is in contradiction with the southern Italian cases.

Even if controlling factors at the catchment scale evolved similarly in the three rivers in southern Italy (Volturno, Trigno, and Fortore), there were still some differences evident in the land uses spreading in their fluvial corridors. Fluvial corridors were mainly affected by an increase in grassland and grassland with scrubs and trees in the Trigno, and by grassland and agricultural areas in the Fortore, denoting high human pressure (Figure 11). To the contrary, narrowing in the Volturno river occurred with rates that were relatively much higher than those in the Fortore and Trigno (Fig. 4B; Table 6), and together with the encroachment of mature riparian forest, similar to the rivers in northern Italy (post-pioneer vegetation from 46% to 67%, Figure 11). This difference in adjustment may be explained by the differences in vegetation encroachment, afforestation, increasing floodplain resistance, and the induction of slightly more narrowing.

The difference between the Volturno and the Trigno and Fortore requires some interpretation. Two factors seem to play noticeable roles. i) Wetter climatic conditions are observed for the Volturno than for the Trigno and Fortore (Aucelli et al., 2007). Dry climates significantly slowed down forest encroachment dynamics along these latter two rivers. No real afforestation occurred, because conditions were too dry compared with the west side of the Apennines, and the dryness may even be exacerbated by climate change as showed. ii) Channel bed lowering over the last decades in the Trigno river was faster and more intense than in the other rivers, especially the Volturno (on average exceeding 3 m). As a consequence, the former channel evolved rapidly into terraces, without turning into floodplains. Differences in elevation did not allow the newly terraced surfaces to be affected by periodic floods able to deposit fine sediments, and therefore soil did not become well-developed, and the sparse riparian vegetation was composed of pioneer species adapted to the marked circumstances of soil aridity. Similar evolutions are described in France for the Bès River (Lallias-Tacon et al., 2017) and the Drome River at Luc-en-Diois (Liébault et al., 2005). Conversely, data for the Volturno river indicate moderate incision that was able to maintain hydrological connectivity between the channel and floodplain system. Current floodplains in the Volturno river are located 1–2 m above the active channel, and present overbank deposits able to preserve wet soil conditions favoring mesophytic woodland (Aucelli et al., 2011).

5.4. Are these new ecosystems a proof of renaturation or of human disturbance?

Narrowing was until recently considered to be a result of human disturbance and was interpreted as a problem with the progressive disappearance of braided wide river systems. The perception of this change is strongly discussed, because i) we understand that the 19th and even 18th century conditions cannot be a pristine reference, and ii) the narrowing corresponds to a significant renaturation of the valleys. Lallias-Tacon et al. (2017) analyzed the example of the Bouinenc torrent, and explained that in long-term narrowing rivers, floodplains evolve with well-developed forest composed of mature units. Similarly, high floristic diversity and good development in the zonation of the riparian vegetation were observed in the Volturno river (Aucelli et al., 2011). For this river, any floods able to cause appreciable channel widening and vegetation erosion were recorded in the last decades (Fig. 10). Human disturbances can be considered in terms of incision and floodplain disconnection, disrupting the recovery processes, as indicated earlier.

The Trigno River is characterized by being less species-rich, and is especially poor in woody species in the floodplains, and although the herbaceous and pioneer communities in the channels and onto the floodplain show high floristic richness (Aucelli et al., 2011). As described above, the Trigno was affected by many erosion processes related to human pressure and recent flood events that caused bank retreat and vegetation fragmentation. Lower woody species diversity and high floristic richness in pioneer communities can also be considered to be an indication of channel dynamics, as asserted by Dufour et al. (2015), who showed that higher activity rivers present lower landscape diversity due to the domination of bar units with fewer vegetation units.

After the 1990s, all rivers widened as a consequence of flood events, except for the Volturno, Borbera, and Sesia rivers, which presented with wider and more developed riparian forest. In most cases, the widening processes after the 1990s do not counteract the 20th century narrowing. The Volturno and Sesia have probably reached a new equilibrium, being less responsive and more resistant to pulse disturbances than what they were during the 19th century.

The only exception is represented by the Borbera River, whose channel width and planform morphology have remained almost constant since the 1970s (Figures 3B and 11). For the Borbera, both local factors (land uses in the river corridor, human pressure in terms of the population density near to the channel) and catchments factors controlling channel morphology have not changed over the last few decades (Figure 11). In addition, immediately upstream of the study reach, the Borbera presents confined or partly confined valley setting characteristics, with hillslopes frequently affected by gravitational processes connected to the channel and able to provide a sediment supply, showing that this river is still very responsive and one of the most active of the piedmont region and even the western Alps (Bizzi et al. 2019); an Anthropocene river in a sensitive geological setting exacerbated by human pressures.

6. Conclusions

This study compared channel evolutionary trajectories in eight rivers situated from the northern to the southern part of Italy, and spanning a range of climatic, physiographic, geometric, and socioeconomic characteristics. A combined diachronous-synchronous approach integrating data from catchment to reach scale over several time periods was used.

Although there were some exceptions, most rivers demonstrated narrowing between the 19th century and the end of the 20th century. Channel adjustments were more marked in southern than in northern Italy. Human disturbances, with deforestation and maximization of cultivated lands during the 19th century, rural system transformations, the construction of torrent works, in-channel works, and gravel mining during the 20th century, have driven the channel dynamics. A clear synchronicity between vegetation encroached on the floodplains and channel narrowing was found in the Volturno in southern Italy and the rivers in the Alps and northern Apennines between the 1950s and 1970s. Post-pioneer vegetation encroachment did not present the same temporal patterns in all rivers, as it commenced earlier in some rivers (Sesia, Stura di Lanzo, Stura di Demonte, Lardana) than in others (Borbera, Volturno, Nure). Such morphological evolution was also observed in southeastern France, but occurred a bit earlier, with strong similarities with northern Italy and the Apennines. In the Nure River (northern Apennines), an upstream-to-downstream gradient in forest cover increase and in-channel narrowing was observed.

This paper raises a question over how natural and in equilibrium with erosive conditions were the channels in the 1950s. In fact, when aerial photos taken in the 1950s are examined, floodplains are seen to be completely anthropized with arable lands and crops, while riparian forests that are known to provide the most ecological benefits were very infrequent. Even the mid-19th century riverscapes were human-driven by higher sediment delivery upstream and low channel resistance due to local pressure, both of which maximized channel responsiveness.

This paper supports the idea that reconstruction of the evolutionary trajectory of fluvial systems and their responses to past human and natural variability is a fundamental requirement for the correct management of river corridors and the implementation of restoration projects, and although past conditions will not be repeated exactly the same in the future (Brierley and Fryirs, 2016), it allows assessment of future trends and provides information on their responsivity and sensitivity to changes.

The findings of this study strengthen the need to perform analyses at catchment scales and to seriously consider land-use changes both upstream and within valley corridors in the interpretation of channel changes, because they definitely played a role prior to the intense channel mining, damming, and rectification in the 1960s. As the chronology of the depopulation of mountainous areas varies, as well as the river basin sensitivity to changes and vegetation adjustment, it seems that there is a fairly complex mosaic of patterns along the Italian rivers. A potential north–south gradient seems nevertheless accurate, with changes occurring much earlier in the north than in the south, but also slighter changes occurring in the north, because the northern systems were less sensitive to changes, both in terms of activation and deactivation.

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Captions

Figure 1. Chronology and intensity of the morphological changes in the Italian rivers. For references see Table 1. Rivers are ordered from north to south.

Figure 2. Location maps of the studied rivers. Catchment limits and studied reaches in northern Italy: Sesia, Stura di Lanzo, Stura di Demonte, Borbera, and Nure (A); and in southern Italy: Volturno, Trigno, and Fortore (B).

Figure 3. Changes in W* for all 43 analyzed reaches, all rivers, and all years (A). W* changes from 1952 to 2010s in the Alpine rivers (Sesia, Stura di Lanzo, Stura di Monte, Borbera) and the two tributaries of the Nure river (Lardana and Lavaiana) (B). W* changes in all reaches of the Nure river from 1877 to 2015 (C). W* changes in all reaches of the Volturno river from 1885 to 2016 (D). W* changes in all reaches of the Trigno river from 1878 to 2016 (E). W* changes in all reaches of the Fortore River from 1870 to 2015 (F).

Figure 4. Channel width variations over the past 170 years in the studied rivers in northern Italy (A) and southern Italy (B), using the channel width variation $\Delta W_{1954}\%$ in respect to the channel

width in 1954. ΔW_{1954} % from upstream (reach 1) to downstream in the Nure, Volturno, Trigno, and Fortore rivers (C).

Figure 5. Historical changes in land use trends in the corridors of the 22 reaches.

Figure 6. Land cover changes in the studied reaches between 1954 and the 1970s (A); 1970s and 1980s (B); 1980s and 1990s (C); and 1990s and 2010s (D). Negative values in C and D indicate land uses eroded during flood events.

Figure 7. Land use changes between 1929 and 2012 in the Torino Province (Stura di Lanzo basin, represents 13% of the province) (A); Cuneo Province (Stura di Demonte basin represents 21% of the Province) (B); and between 1910 and 2012 in the Molise Region (Volturno, Trigno, and Fortore river catchments represent 23%, 28%, and 7% of the territory of the region respectively) (C).

Figure 8. Evolution of the demographic population density in the studied catchments in northern Italy (A); southern Italy (B); and the mountain catchments of the rivers in northern Italy (C). Comparison of the demographic trends in all the Trigno catchment and the coastal area (D). Evolution of the average demographic population density of the 22 selected reaches in northern Italy (E); and southern Italy (F).

Figure 9. Demographic evolution of livestock in the: Torino province for the Stura di Lanzo basin (catchment represents 13% of the province, A); Cuneo province for the Stura di Demonte basin (catchment represents 21% of the province, B); Piacenza province for the Nure basin (catchment represent 17% of the province, C); and Molise region for the Volturno, Trigno, and Fortore rivers (catchments represent 23%, 28%, and 7% of the territory of the region, respectively, D).

Figure 10. Maximum annual discharge at the Lanzo gauging station and W* trend in the Stura di Lanzo river (A). Frequency of flood events from the 1910s to 2000s and comparison with W* within the Volturno river.

Figure 11. Evolutionary trajectories in comparison with the degree and timing of anthropic and natural control factors at reach and catchment scales. key: GM = gravel mining; ICW = in-channel work (groynes, bank protection, levees).

Figure 12. Shoreline changes in the Trigno and Fortore mouth areas between the 19^{th} to the 1990s. Modified from Aucelli and Rosskops, 2000 and Scorpio and Rosskopf, 2016.

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Figure 1

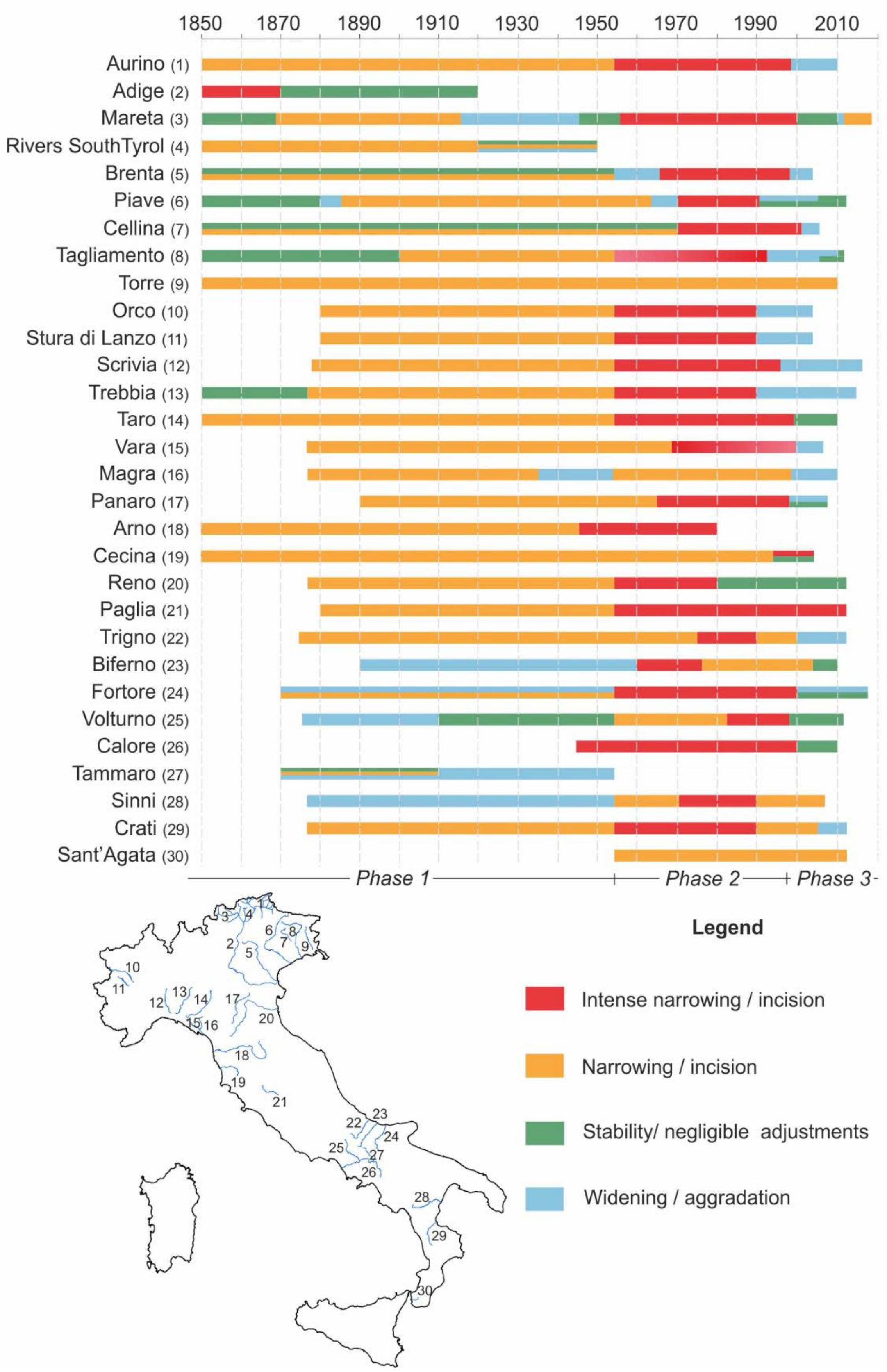

1850
1870
1890
1910
1930
1950
1970
1990
2010
Aurino (1)
Adige (2)
Mareta (3)
Rivers SouthTyrol (4)
Brenta (5)
Piave (6)
Cellina (7)
Tagliamento (8)
Torre (9)
Orco (10)
Stura di Lanzo (11)
Scrivia (12)
Trebbia (13)
Taro (14)
Vara (15)
Magra (16)
Panaro (17)
Arno (18)
Cecina (19)
Reno (20)
Paglia (21)
Trigno (22)
Biferno (23)
Fortore (24)
Volturno (25)
Calore (26)
Tammaro (27)
Sinni (28)
Crati (29)
Sant'Agata (30)
Phase 1
Phase 2
Phase 3
Legend
Intense narrowing / incision
Narrowing / incision
Stability/ negligible adjustments
Widening / aggradation

Figure 2

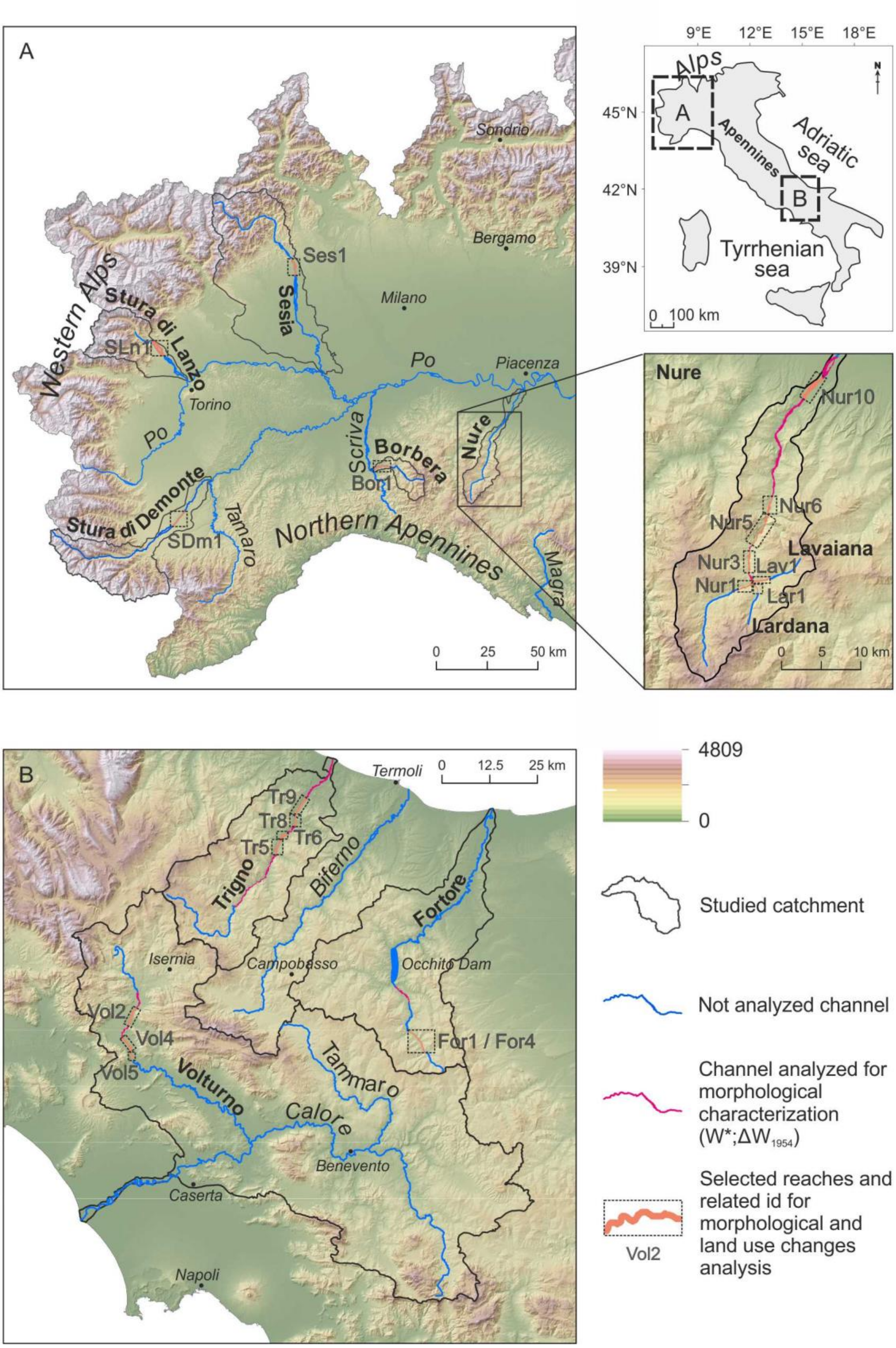

A
B
9°E
12°E
15°E
18°E
45°N
42°N
39°N
Alps
Apennines
Adriatic sea
Tyrrhenian sea
0 100 km
Sondrio
Bergamo
Milano
Piacenza
Torino
Ses1
Sesia
Western Alps
Stura di Lanzo
SLn1
Po
Scriva
Borbera
Bor1
Nure
Stura di Demonte
SDm1
Tanaro
Northern Apennines
Magra
0 25 50 km
Nure
Nur10
Nur6
Nur5
Nur3
Nur1
Lav1
Lar1
Lavaiana
Lardana
0 5 10 km
4809
0
Termoli
0 12.5 25 km
Tr9
Tr8
Tr6
Tr5
Trigno
Biferno
Fortore
Isernia
Campobasso
Occhito Dam
Vol2
Vol4
Vol5
For1 / For4
Volturno
Tammaro
Calore
Benevento
Caserta
Napoli
Studied catchment
Not analyzed channel
Channel analyzed for morphological characterization (W*;ΔW1954)
Selected reaches and related id for morphological and land use changes analysis
Vol2

Figure 3

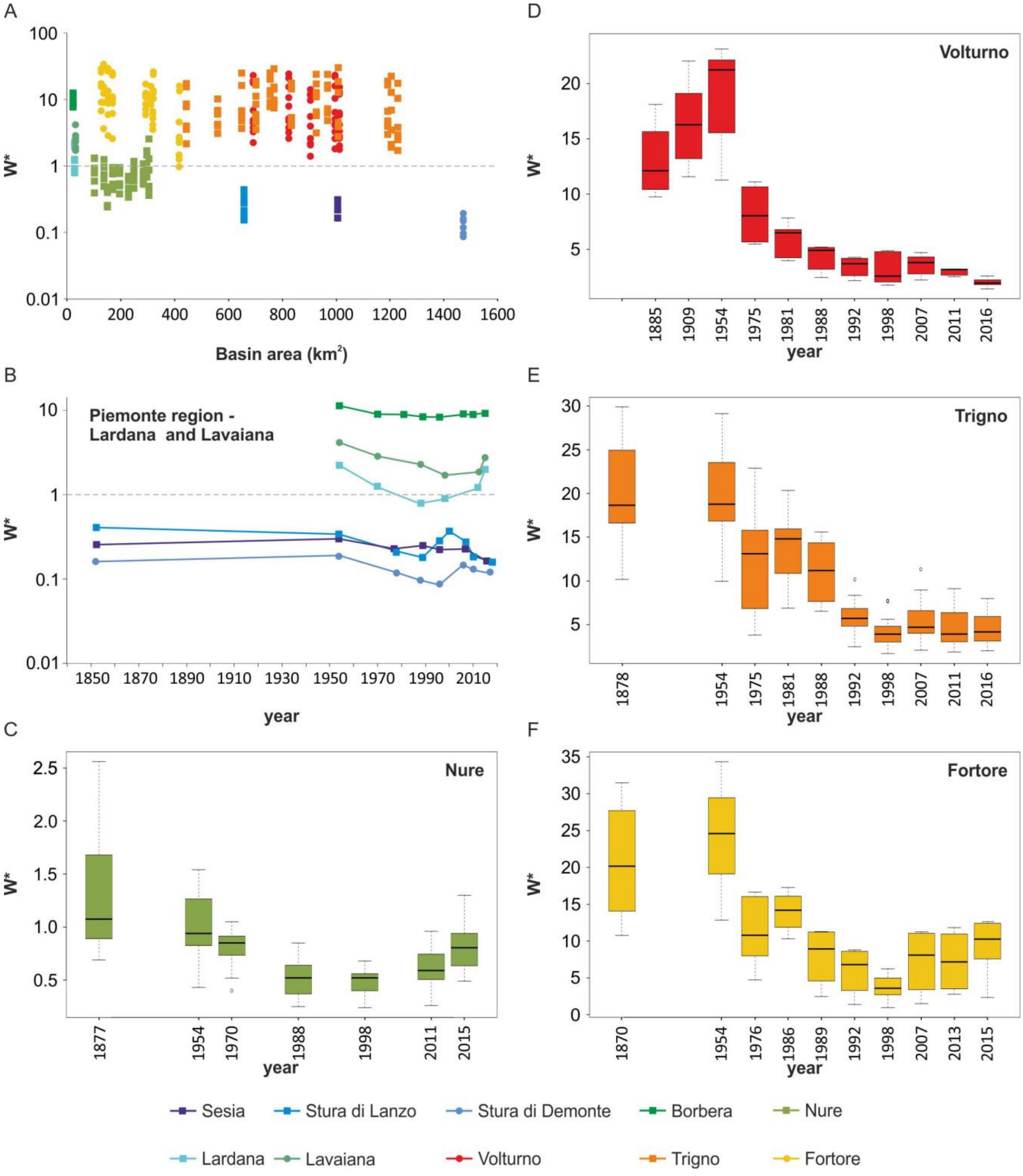
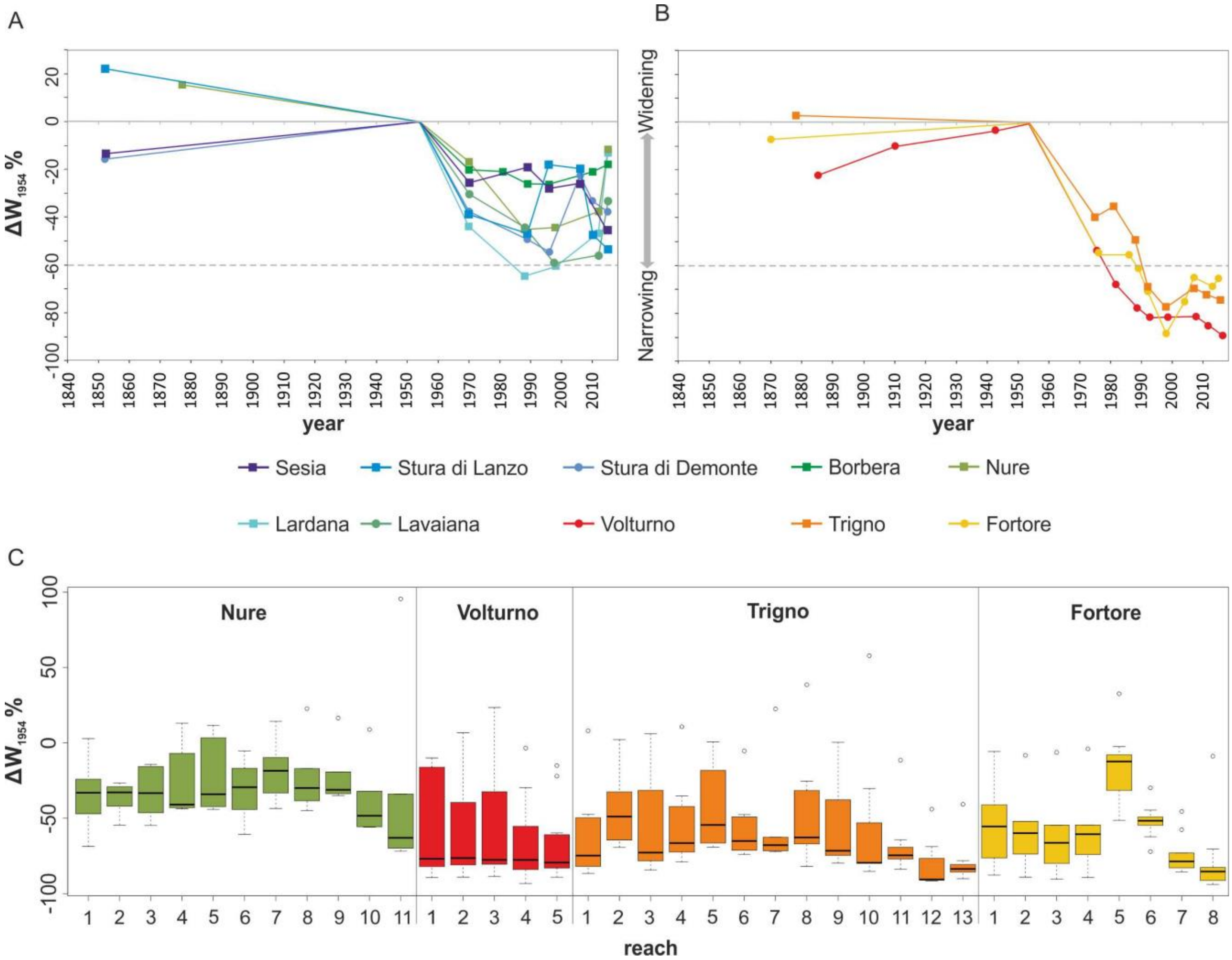

A
W*
Basin area (km²)
B
Piemonte region -
Lardana and Lavaiana
W*
year
C
Nure
W*
year
D
Volturno
W*
year
E
Trigno
W*
year
F
Fortore
W*
year
Sesia
Stura di Lanzo
Stura di Demonte
Borbera
Nure
Lardana
Lavaiana
Volturno
Trigno
Fortore

Figure 4



A
B
C
ΔW1954 %
year
reach
Widening
Narrowing
Sesia
Stura di Lanzo
Stura di Demonte
Borbera
Nure
Lardana
Lavaiana
Volturno
Trigno
Fortore

Figure 5

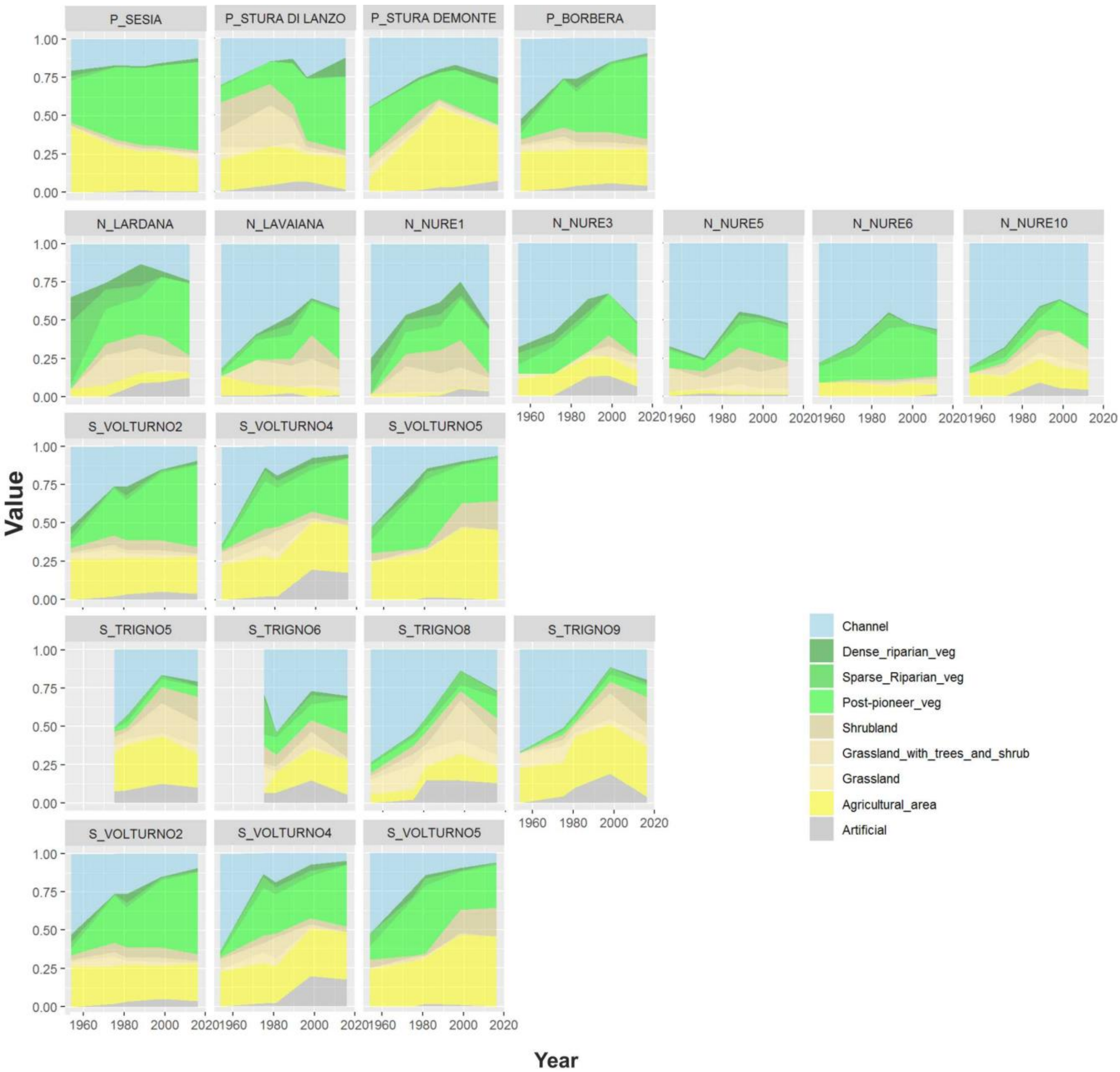

P_SESIA
P_STURA DI LANZO
P_STURA DEMONTE
P_BORBERA
N_LARDANA
N_LAVAIANA
N_NURE1
N_NURE3
N_NURE5
N_NURE6
N_NURE10
S_VOLTURNO2
S_VOLTURNO4
S_VOLTURNO5
S_TRIGNO5
S_TRIGNO6
S_TRIGNO8
S_TRIGNO9
S_VOLTURNO2
S_VOLTURNO4
S_VOLTURNO5
Value
Year
Channel
Dense_riparian_veg
Sparse_Riparian_veg
Post-pioneer_veg
Shrubland
Grassland_with_trees_and_shrub
Grassland
Agricultural_area
Artificial

Figure 6

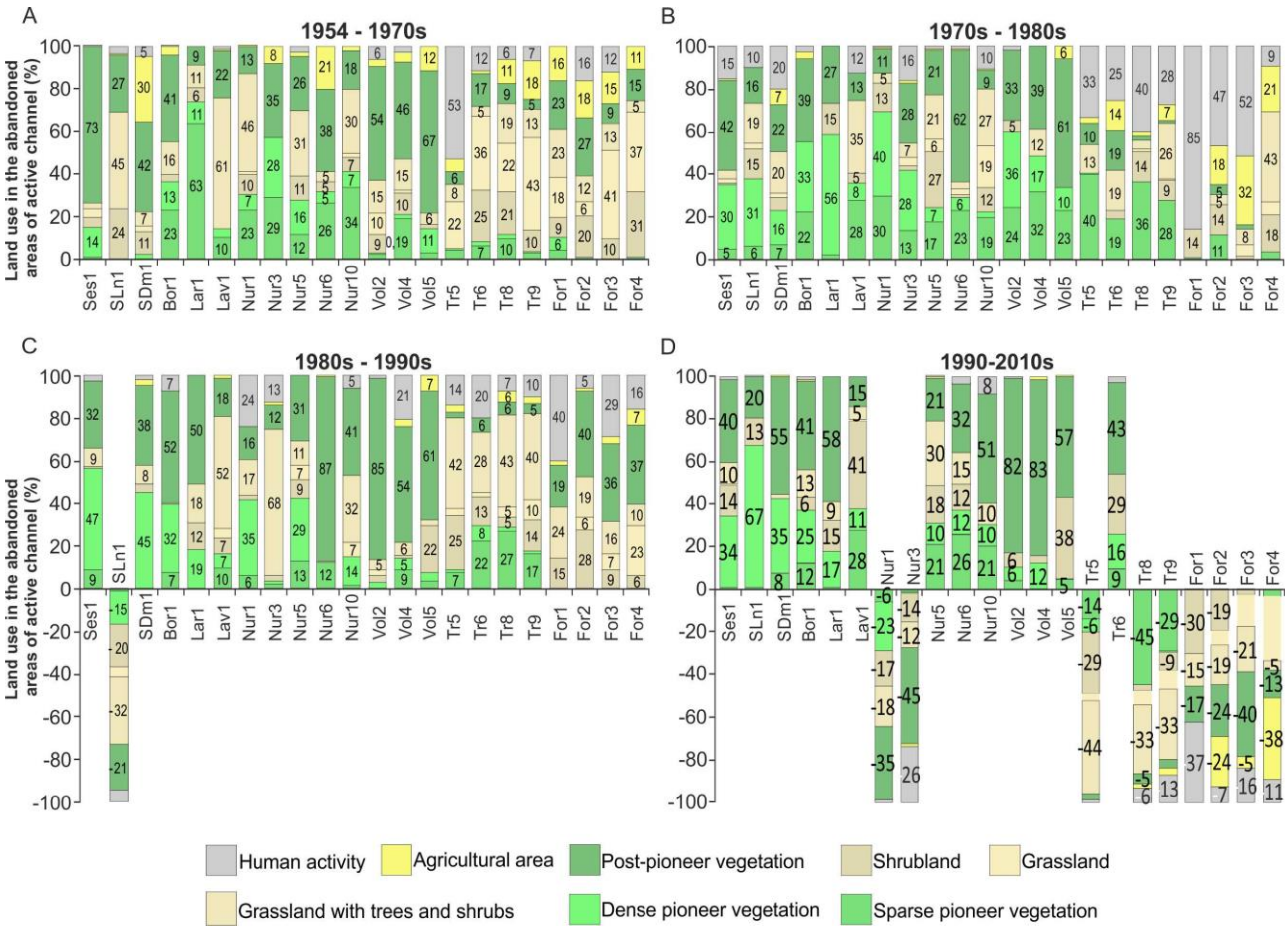

A
1954 - 1970s
B
1970s - 1980s
C
1980s - 1990s
D
1990-2010s
Land use in the abandoned areas of active channel (%)
Human activity
Agricultural area
Post-pioneer vegetation
Shrubland
Grassland
Grassland with trees and shrubs
Dense pioneer vegetation
Sparse pioneer vegetation

Figure 7

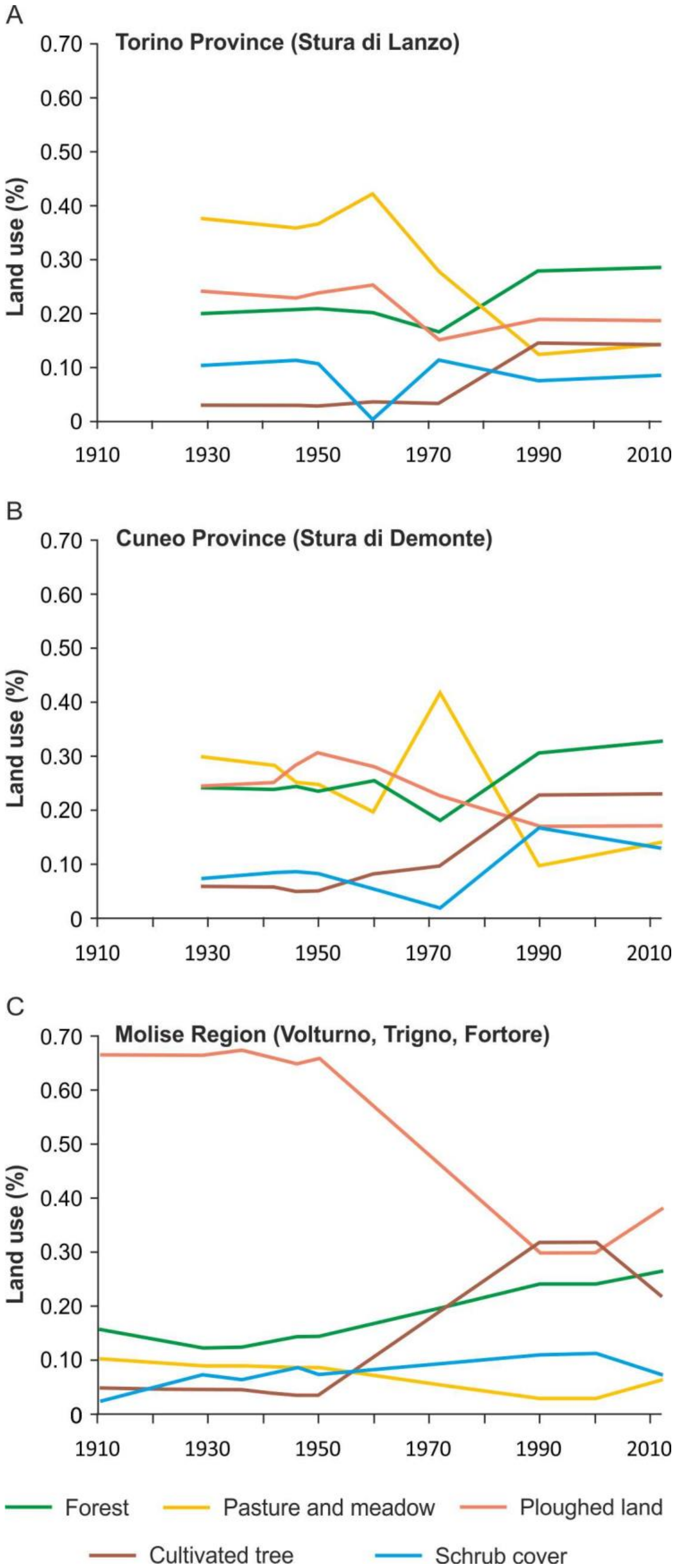

A
Torino Province (Stura di Lanzo)
B
Cuneo Province (Stura di Demonte)
C
Molise Region (Volturno, Trigno, Fortore)
Land use (%)
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0
1910
1930
1950
1970
1990
2010
Forest
Pasture and meadow
Ploughed land
Cultivated tree
Schrub cover

Figure 8

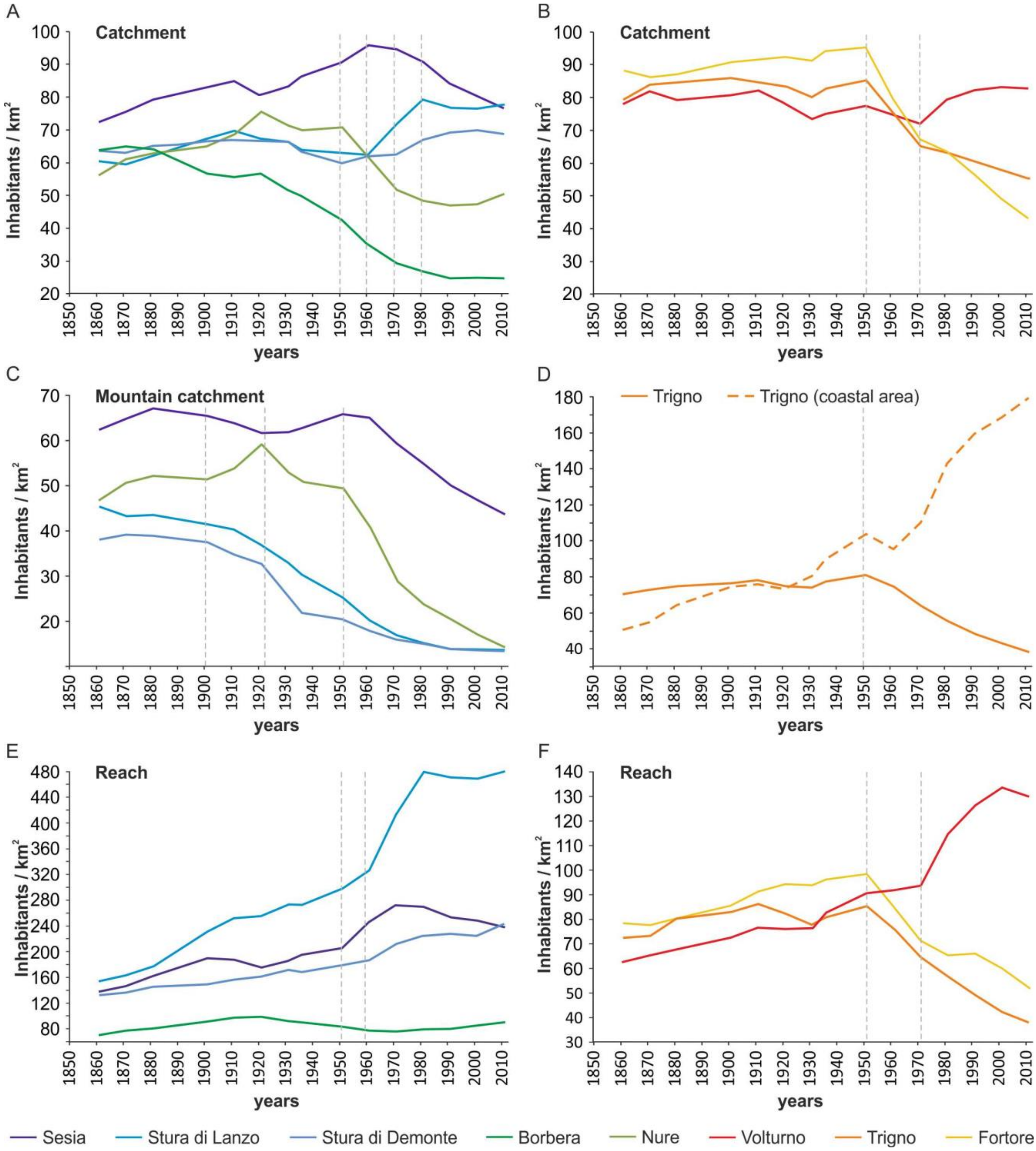

A
Catchment
Inhabitants / km²
years
B
Catchment
Inhabitants / km²
years
C
Mountain catchment
Inhabitants / km²
years
D
Trigno
Trigno (coastal area)
Inhabitants / km²
years
E
Reach
Inhabitants / km²
years
F
Reach
Inhabitants / km²
years
Sesia
Stura di Lanzo
Stura di Demonte
Borbera
Nure
Volturno
Trigno
Fortore

Figure 9

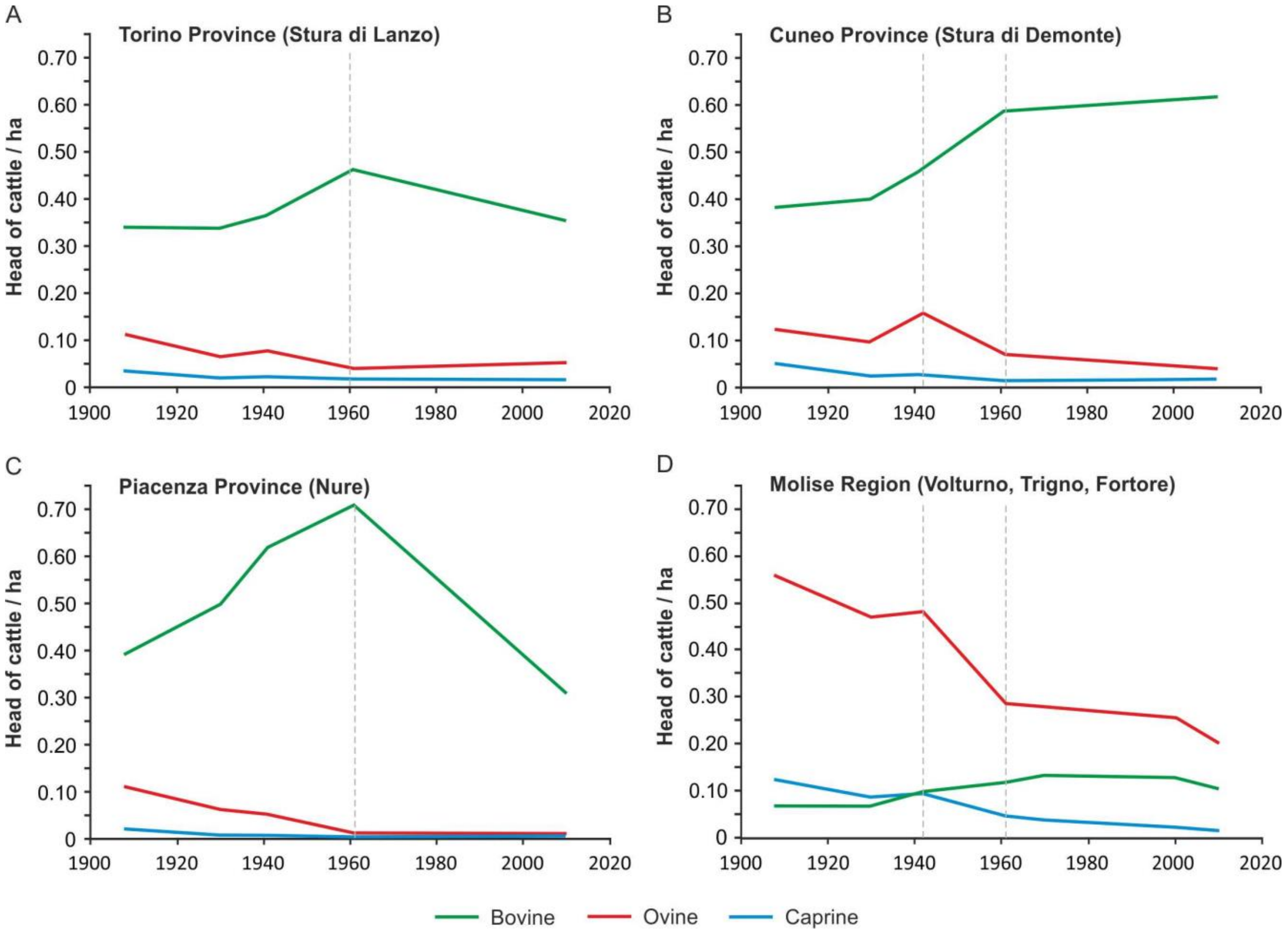

A
Torino Province (Stura di Lanzo)
B
Cuneo Province (Stura di Demonte)
C
Piacenza Province (Nure)
D
Molise Region (Volturno, Trigno, Fortore)
Head of cattle / ha
0
0.10
0.20
0.30
0.40
0.50
0.60
0.70
1900
1920
1940
1960
1980
2000
2020
Bovine
Ovine
Caprine

Figure 10

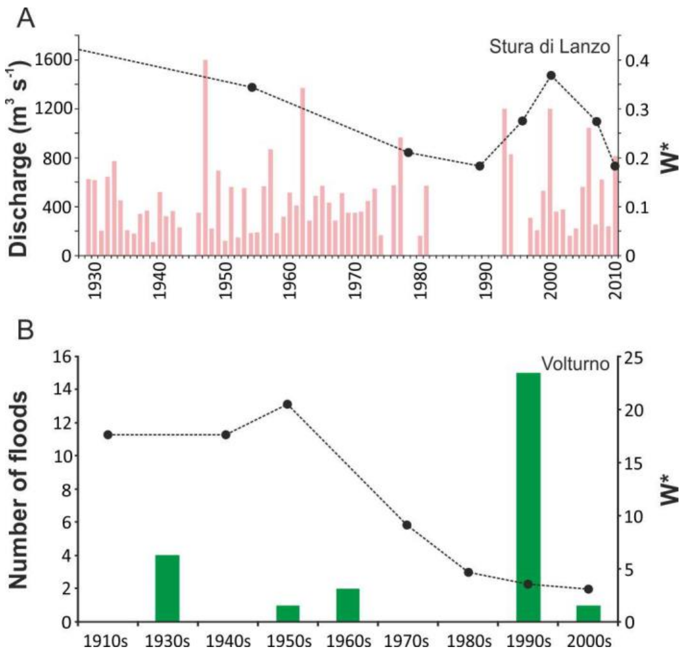
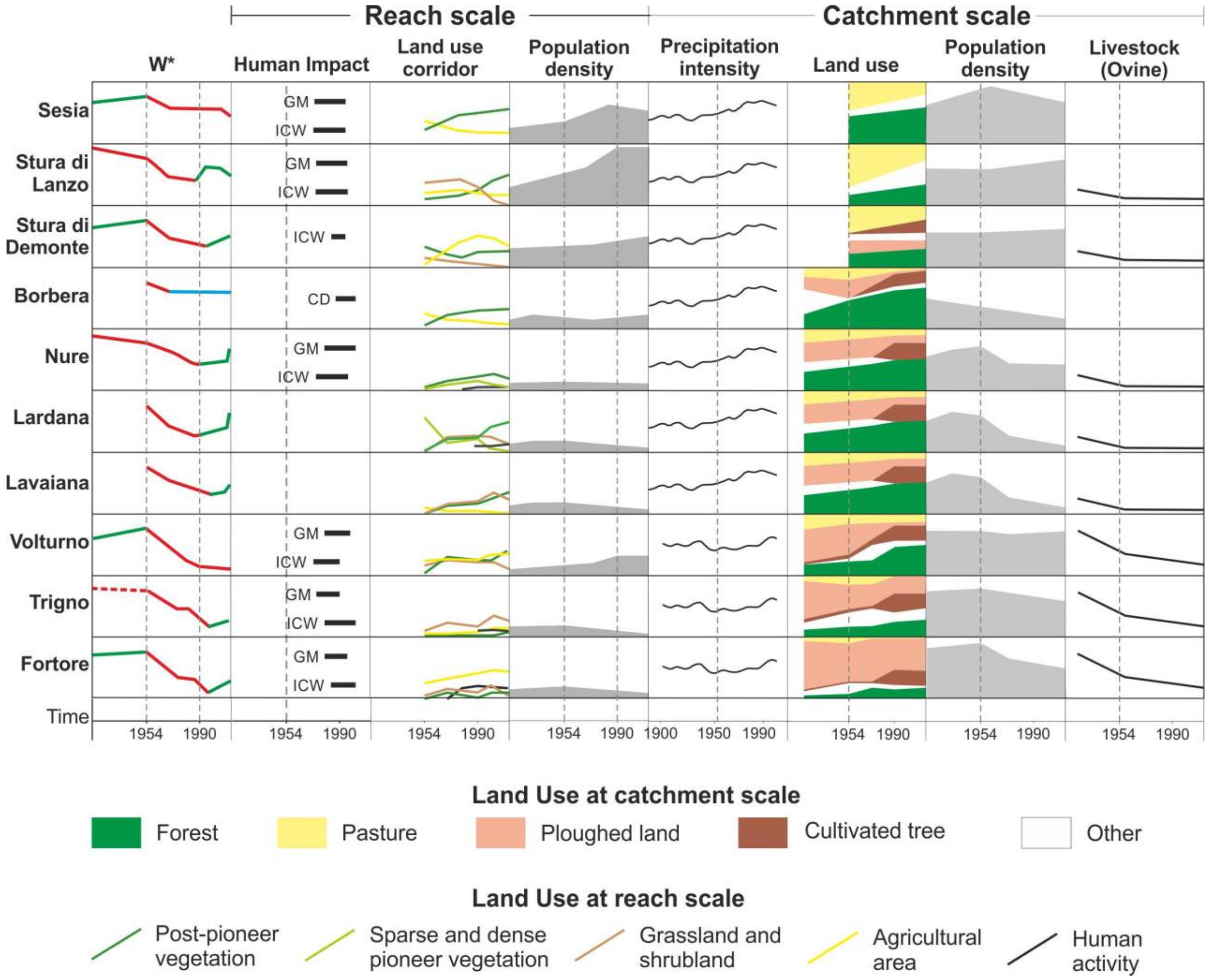

A
Stura di Lanzo
Discharge (m3 s-1)
W*
1600
1200
800
400
0
0.4
0.3
0.2
0.1
0
1930
1940
1950
1960
1970
1980
1990
2000
2010
B
Volturno
Number of floods
W*
16
14
12
10
8
6
4
2
0
25
20
15
10
5
0
1910s
1930s
1940s
1950s
1960s
1970s
1980s
1990s
2000s

Figure 11



Reach scale
Catchment scale
W*
Human Impact
Land use corridor
Population density
Precipitation intensity
Land use
Population density
Livestock (Ovine)
Sesia
Stura di Lanzo
Stura di Demonte
Borbera
Nure
Lardana
Lavaiana
Volturno
Trigno
Fortore
GM
ICW
CD
Time
1954
1990
1900
1950
Land Use at catchment scale
Forest
Pasture
Ploughed land
Cultivated tree
Other
Land Use at reach scale
Post-pioneer vegetation
Sparse and dense pioneer vegetation
Grassland and shrubland
Agricultural area
Human activity

Figure 12

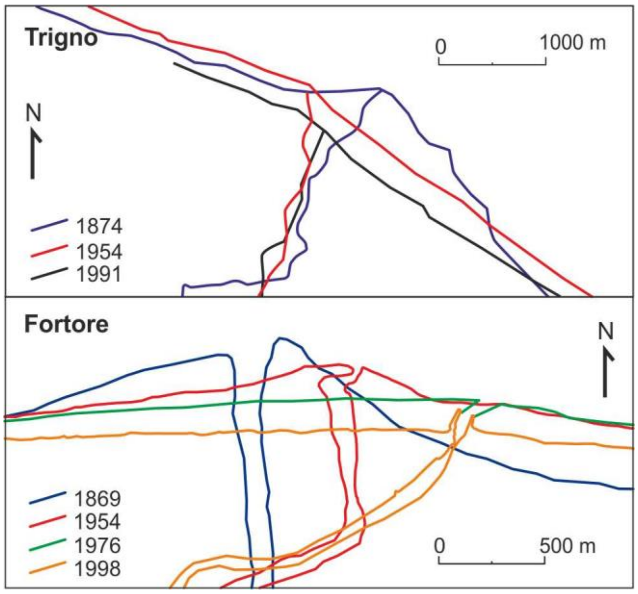

Trigno
0
1000 m
N
1874
1954
1991
Fortore
N
1869
1954
1976
1998
0
500 m

Table 1

Literature overview on morphological channel changes and related controlling factors over the last century in Italian rivers

River / ID Fig.1	Period	Channel adjustments	Main Controlling Factors	Effects of Land use changes at catchment and / or reach scale	Reference
Po	Pleistoc. - present	Narrowing	Climatic fluctuations during the Late Pleistocene. Increasing anthropogenic activities, during the Holocene	-	Marchetti, 2002
Ahr/Aurino (1)	1820-2011	1820 - 2003: Narrowing up to 65% Incision 2-4m After restoration in 2003: widening and aggradation	Climatic changes: end Little Ice Age; 1960s - 1980s: gravel mining 1970s: dam and check dam construction 2003: restoration interventions	Qualitative analysis of forest decrease at catchment scale (1850s-1940s)	Campana et al., 2014
Adige/Etsch (2)	1803-1917	Narrowing up to 87%; Incision; Patter simplification	Channelization	-	Scorpio et al., 2018a Scorpio et al., 2018b
Mareta (3)	1805-2017	1850 - 1870s: stability 1870s - 1917: narrowing 1917 -1945: widening 1945- 1954: stability 1954- 1990s: Intense narrowing 1990s- 2009: stability 2009-2011: widening 2011 - 2017: narrowing	1850- 1917: end Little Ice Age; levees construction; corridor management 1917 - 1945: flood events 1945- 1990s: gravel mining; check dam construction 2009: river restoration operation	-	Scorpio et al., in progress
Rivers in South Tyrol region (4)	1850s-1954	1850-1917: narrowing, pattern shifting from multithread/transitional to single-thread. 1917-1950: narrowing, stability or slight tendency toward widening	1850–1917: retreat of glaciers and decrease in sediment supply. 1917–1950: steady glacial cover or glacier advance determining unvaried channel widths or some widening.	Modification of forest cover at catchment scale between 1850 and 1976. Forest cover quite stable: average increase = 6% ; maximum increase = 16%.	Marchese et al., 2017
Brenta (5)	1805-2011	19th century - 1990s: narrowing (-54% ; - 62%) 1990s –2003: widening (20%) Incision: 5m in the braided reach; up to 7-8m in single-thread reach	Degradation: Dam operation and gravel mining Recovery: suspension of gravel mining	Qualitative information on intense reforestation since the 1950s	Rinaldi et al., 2005 Surian and Cisotto, 2007 Surian et al., 2009a Surian et al., 2009b Moretto et al., 2014
Piave (6)	1805-2006	1900s- 1960s (Phase 1): narrowing 1970s-1990s (Phase 2): narrowing and incision up to 2m 1990s- 2006 (Phase 3): widening and possible aggradation	19th century: deforestation; end Little Ice Age; Phase1: land use variation at catchment scale; groynes built in the 1940s; dams during 1930s-1950s Phase 2: gravel mining Phase 3: large flood events	Analysis of forests cover at catchment scale. Forest reached minimum extent between the 18th and the 19th century. Reforestation on hillslopes: since World War I and especially after the 1950s. * Analysis of vegetation cover type evolution and structure in the river corridor of studied sub-reaches	Surian et al., 1999 Surian et al., 2009a Surian et al., 2009b *** Comiti et al., 2011** *** Picco et al., 2017**
Cellina (7)	1805 - 2002	19th century - 1970s: stability 1970s- 1990s: narrowing (-54%) Since 2000s: widening (+ 5%)	Dam operation and gravel mining (since 1970s) Widening: after large floods	-	Surian et al., 2009a Surian et al., 2009b
Tagliamento (8)	1805-2012	1805- 1890s (Phase 1): stability/slight narrowing 1890s -1950s (Phase 1): narrowing (- 33%) 1950s-1990s (Phase 2): narrowing (- 56%) 1990s-2012 (Phase 3): widening and slight aggradation (0.2 m) Incision 0.5-3m (especially phase 2)	Phase 1: groynes, afforestation Phase 2: gravel mining; bank protections Phase 3: decrease of mining activity and bank protection	Modification at catchment scale over the last 180 years. Increase of forest cover from 21% in 1828 to 72% in 2006. * In the corridor area vegetation is mapped in 3 categories: herbaceous vegetation and low shrubs/trees; high shrubs and trees of low-medium height and tall trees	Rinaldi et al., 2005 Surian et al., 2009a Surian et al., 2009b Ziliani and Surian, 2012 *** Surian et al., 2015**
Torre 9)	1805-2000s	19th century - 2000s: Narrowing (-76%) ; incision (- 3m)	1920s - 1930s: torrent control works 1950s - 1970s: gravel mining	-	Surian et al., 2009a Surian et al., 2009b
Main rivers in Piemonte region	Last decades	Narrowing -50%; Incision exceeding 1m	-	-	Bizzi et al., 2018

Orco (10)	1881-2000s	1881- 1950s (Phase 1): narrowing (-33%) 1950s- 1990s (Phase 2): narrowing (-44%) 1990s-2000s (Phase 3): widening (+133%) Incision, especially 1961-1975 (1-2 m on average; 3-4 m max)	Phase 1: management of corridors; use of secondary channels for irrigation; construction of road infrastructures. Phase 2: gravel mining; channel works Phase 3: large floods	-	Pellegrini et al., 2008 Turitto et al., 2008 Surian et al., 2009a
Stura di Lanzo (11)	1881-2000s	1881- 1950s (Phase 1): slight narrowing (-36%) 1950s-1990s (Phase 2): narrowing (-68%) 1990s - 2000s (Phase 3): widening (+98%) 1936-1975: incision 2-5m	Phase 1: management of corridors; use of secondary channels for irrigation; construction of road infrastructures. Phase 2: gravel mining; channel works Phase 3: large floods	-	Pellegrini et al., 2008 Surian et al., 2009a
Scrivia (12)	1878-2017	1878 - 1950s (Phase 1): avulsions, lateral migration 1950s -1990s (Phase 2): narrowing or channel banks stability 1990s - 2016 (Phase 3): slight widening, reactivation of bank-erosion processes.	Phase 1: river corridor management; natural processes; groynes construction and partial bank-stabilization in the last part of the first period. Phase 2: sediment mining and channelization Phase 3: floods	* In the historical migration zone, analysis of land use modification between 1954 to 2017, mapping of: active channel, semi-natural areas (woodlands, shrubs, herbaceous vegetation), agricultural and artificial areas.	Mandarino et al., 2019a *** Mandarino et al., 2019b**
Trebbia (13)	1880-2014	1880-1954 (Phase 1): narrowing (-19%) 1954-2000s (Phase 2): narrowing (-58%) and incision (1-2m) 2000s-2014 (Phase 3): partial recovery of channel morphology; widening (+15%)	Phase 1: land use changes at the catchment scale, bank protection; artificial levees; end Little Ice age Phase 2: sediment mining Phase 3: reduction in sediment removal	Modification of land cover at catchment scale (between 1885 and 2006). Increase of forest cover from 22% to 51%; decrease of meadow from 59% to 6%.	Pellegrini et al., 2008 Surian et al., 2009a Bollati et al., 2014
Taro (14)	1828-2011	Channel narrowing up to -75%; incision; decrease of braiding (- 43%), increase in channel length (13%) and sinuosity (29%); while in the last years morphological stability with possible slight narrowing.	Construction of 10 bridges and bank protections. Subtraction of riverbed areas for agricultural and industrial purposes. 1950s - 1980s: gravel mining	Before 1828: deforestation and agriculture expansion.	Clerici et al., 2015
Rivers in Toscany	1954 - 1998	Average narrowing 50%; maximum narrowing (-75%) Incision between 2 and 9m (especially between 1945 -1980)	19th century - 20th century: reforestation at catchment scale 1950s - 1998: sediment mining; dam construction	Reforestation of large upland areas favored by a series of land management laws, for stabilization of slopes, and by the construction of a large number of weirs along mountain streams (more than 2700 weirs were built in the Arno River basin).	Rinaldi, 2003
Vara (15)	1877-2006	1877-1950s/1971 (Phase 1): narrowing (-62% - 68%) 1950s/1971- 1995 (Phase 2): narrowing (-32%-38%) 1995 - 2006 (Phase 3): widening (+2; +7%) Incision between 2 and 4 m	Phase 1: construction of check-dams along tributaries, and construction of groynes Phase 2: sediment mining Phase 3: intense floods	-	Rinaldi et al., 2005 Rinaldi et al., 2008 Rinaldi et al., 2009 Surian et al., 2009a
Magra (16)	1877-2010	1877- 1937 (Phase 1): narrowing 1937-1954 (Phase 1): widening (+5%; +10%) 1954 - 1995 (Phase 2): narrowing (-53%; - 58%) 1999- 2010 (Phase 3): widening (+2; +13%) Incision between 5 and 8m	Phase 1: construction of check-dams along tributaries, and construction of groynes (widening between 1937 and 1954 related to some large floods). Phase 2: sediment mining Phase 3: intense floods	*Analysis of the current vegetation and analysis of effects on channels dynamic of land cover changes in the historical corridor. Trends of 6 classes: active channel, pioneer vegetation, shrub, woodland, meadow and arable land, and human activity.	Rinaldi et al., 2008 Rinaldi et al., 2009 Surian et al., 2009a Nardi and Rinaldi, 2015 *** Dufour et al., 2015**
Panaro (17)	1890-2007	1890-1969 (Phase 1): narrowing (-41%; -68%) 1969- 1997/2007 (Phase 2): narrowing (-31%;-59%) 1997 - 2007 (Phase 3): narrowing/stability Incision: 4-10m	Phase 1: levees; afforestation at catchment scale; torrent control works Phase 2: check dams; sediment mining;	-	Rinaldi et al., 2008 Surian et al., 2009a
Arno (18)	1954-1980s	1844 - 1945 (Phase 1): incision between 0.5 and 2m 1945 - 1980s (Phase 2): incision between 1 and 3m.	Phase 1: land cover changes at basin scale, afforestation; construction of weirs along tributaries. Phase 2: dam construction, sediment mining	-	Rinaldi and Simon, 1998 Rinaldi et al., 2005
Cecina (19)	1883 - 2004	1883- 1994: narrowing (-81%--89%) 1994 - 2004: narrowing or stability Incision: 1-3m	-	-	Rinaldi et al., 2008 Surian et al., 2009a
Reno (20)	1860-2003	End 19th - 1950s (Phase 1): narrowing 1950s-1970s (Phase 2): narrowing; incision 1970s -2012: no evidence of relevant changes Total narrowing 75-85%	Phase 1: reforestation; check dams; reservoir construction on some tributaries. Phase 2: gravel mining; reforestation; check dams. Most of the torrent control works consist of check dams	Land use modification at catchment scale in 1830, 1959, 2000. Four classes: crops, and agricultural surface; pastures and grasslands; forested areas; urban areas	Preciso et al, 2012

		Incision 1 and 8m	that were constructed mainly from the 1950s to the 1970s.	The reduction of sediment supply from the headwater is ascribed to: land use changes, cropland abandonment, natural and artificial reforestation, soil erosion-control measures on slopes.	
Paglia (21)	1883-2013	1883- 1954 (Phase 1): narrowing 64% 1954 - 2012 (Phase 2): narrowing 70% Incision: 5 order of terraces in the 130 years	Gravel mining	-	Colica et al., 2018
Trigno (22)	1875-2011	1875 - 1950s (Phase 1): narrowing (up to 30%) 1950s - 2007 (Phase 2): narrowing (-75%; -85%) 2007 - 2011 (Phase 3): widening (up to +15%) Incision: 3- 9m increasing downstream bridges and check dams	Phase 1: deforestation at catchment scale; end of Little Ice Age. Phase 2: gravel mining; groynes Phase 3: flood events; cessation of sediment removal	Analysis of land use changes at catchment scale in 1836/1850, 1950, 2000, 2006. Deforestation took place between 1836/1850 and 1929. Forest expansion occurred after 1929, due to natural reforestation; especially starting from the 1950s onwards reforestation due to agricultural abandonment and displacement of agricultural activities to valley bottoms and alluvial coastal plains. * In the studied reach analysis of the modification of the land use in the abandoned portion of the channel active in 1954, considering six land cover types: roads and mine sites; agricultural areas; broad-leaved forest; shrub and herbaceous vegetation; open spaces with little or no vegetation; river channels. Analysis of current floristic pattern in the recent terraces, floodplain and channel banks.	Aucelli and Rosskopf, 2000 *** Aucelli et al., 2011** Scorpio et al., 2015 Scorpio et al., 2016a
Biferno (23)		1869 - 1950s (Phase 1): widening (up +33%) 1950s - 1998 (Phase 2): narrowing (up to -96%) 1998- 2011 (Phase 3): stability Incision: 3.5m especially between 1950s and 1980s.	Phase 1: land cover modification at catchment scale; end of Little Ice Age. Phase 2: gravel mining; dam closure in 1977; bank protections Phase 3: cessation of sediment removal	Same analysis than as for the Trigno River	*** Aucelli et al., 2011** Rosskopf and Scorpio, 2013 Scorpio et al., 2015
Fortore (24)	1869-2015	1869-1950s (Phase 1): widening prevailed in the reaches upstream reaches the dam and narrowing in those downstream. 1950s - 1990s (Phase 2): narrowing of up to 81% in upstream reaches the dam and 98% in downstream reaches. Incision from 1 to 5m 2000 - 2015 (Phase 3): widening and aggradation in the reaches upstream the dam and stabilization those downstream.	Phase 1: Deforestation and climate amelioration at the end of the LIA. Phase 2: gravel mining, channel works, the closure of the Occhito dam in 1966. Phase 3**:** large flood upstream the dam	Analysis of land cover changes at catchment scale (1800s, 1954, 1992, 2012). From 1800s to 1929 deforestation. Differences in deforestation in the upstream and downstream sectors of the catchment, caused different influences on the channel trends in the upper and lower sectors of the river. From 1929 to 1990, moderate reforestation, accompanied by a decline of cropland especially between 1929 and 1971.	Scorpio and Rosskopf, 2016
Volturno (25)	1875-2011	1875 - 1950s (Phase 1): widening (up to +40%) 1950s - 1998 (Phase 2): narrowing (up to -89%) 1998- 2011 (Phase 3): stability Incision between 2 and 3m	Phase 1: land cover changes at catchment scale; torrent work; end of the LIA. Phase 2: bank protections, groynes, gravel mining. Phase 3**:** cessation of sediment removal and bank protection construction	Same analysis than as for the Trigno River	*** Aucelli et al., 2011** Scorpio et al., 2015 Scorpio et al., 2016a
Calore (26)	1954-1998	1950s - 2004: average narrowing -66%, maximum narrowing -86% Incision up to 4m Pattern morphology shifting from transitional to single-thread	Damming and channelization in the main tributaries; reduction of discharges due to water withdrawals and sediment mining from the riverbed	-	Magliulo et al.,2013 Scorpio et al., 2016a
Tammaro (27)	1870-1955	1870 - 1909: any common trends; slight prevalence of widening. Any changes in planform morphology mainly single thread. 1909 - 1955: homogeneous widening and changes from a single thread to transitional patterns	1870 - 1909: unmechanized agriculture coupled with a strong emigration which drastically decreased the population density. 1909 - 1955: climate variability, ploughing, increase of population density. Increase of mechanization techniques in agricultural practice and inducing increase of soil erosion. Human activities such as sediment mining, channelization, are not documented.	Analysis at catchment scale (Benevento province scale): In 1920s: 65 % of territory consisted of arable lands, 15 % of forests, 10 % of permanent crops (mainly olive groves and fruit trees), and 10 % of pastures and open spaces with little or no vegetation. In 1951, arable lands composed more than 73 % of the territory.	Magliulo et al, 2016
Sinni	1877-	1877 - 1950s (Phase 1): widening (+12%)	Phase 1: land cover modification at catchment scale; end	Analysis of land use changes at catchment scale in	Cencetti and Fredduzzi, 2008

(28)	2006	1950s - 1998 (Phase 2): narrowing (-58%; -79%) 1998 - 2006 (Phase 3): narrowing (-60%; -87%) Incision -2; -4.5 m increasing downstream check-dams and dams	of Little Ice Age. Phase 2: gravel mining; dam closure and check dam construction Phase 3: sediment deficit downstream dams and check dams	between 1850 and 2006. Deforestation took place between 1850 and 1929, while forest expansion occurred starting from1929.	Scorpio et al. 2015
Crati (29)	1877-2012	1877- 1950s (Phase 1): narrowing 1950s - 2006 (Phase 2): narrowing (-78%; -87%) 2006 - 2012 (Phase 3): widening Incision -3m	Phase 1: deforestation at catchment scale; end of Little Ice Age; channel works Phase 2: bank protections; gravel mining Phase 3: flood event	-	Scorpio et al. 2015
Fiumara Sant´Agata (30)	1955-2012	Narrowing 48% Incision between 1.3 m and 2.1 m; aggradation upstream check dams	Land cover changes; check dams construction	Land-use modification at catchment scale between 1955 and 2012. Forested areas, shrublands and agricultural areas increased by 43%, 25% and 12.5%, respectively. Open spaces areas and pasture lands decreased by 70% and 84%.	Fortugno et al., 2017

Numbers in the "river/ ID Fig.1" column, refer to rivers represented in Fig. 1. The asterisk symbol (*), in the column "Effects of Land use changes at catchment and /or reach scale", and bolded references indicates papers that analyzed land cover vegetation changes in the river corridor in relation with channel adjustments.

Table 2

Main physiographic characteristics of the studied rivers

Main characteristics	Sesia	Stura di Lanzo	Sura de Monte	Borbera	Nure	Volturno	Trigno	Fortore
Location	Western Alps	Western Alps	Western Alps	Northern Apennines	Northern Apennines	Southern Apennines	Sothern Apennines	Southern Apennines
Drainage area (km^2)	3038	928	1472	212	430	5550	1200	1614
Max/ Min basin elevation (m)	4464 / 96	3676 / 205	3268 / 194	1711 / 43	1773 / x	2175/ 0	1735/ 0	1128 / 0
Main substrate rocks	Met and Int	Met	Met and Sed	Sed	Sed	Sed	Sed	Sed
Channel length (km)	140	80	115	38	75	175	85	110
Mean annual precipitation (mm)	1013	792	704	556	1150	1300	550	700
Mean annual discharge (m^3/s)	70	26	47	6.4	15	82.1	12.6	13.5

Legend for main substrate rocks codes: metamorphic (Met); intrusive igneous (Int); sedimentary (Sed)

Table 3

Morphological characteristics of the selected 22 reaches

	Reach	River	Length (km)	Max elevation (m)	Min elevation (m)	Slope m/m	Pattern / average width (m) in 1954	Pattern / average width (m) in 2010s
Alps	Ses1	Sesia	5	259	235	0.005	W / 308	SAB / 167
	SLn1	Stura di Lanzo	7	417	346	0.010	W / 224	W / 104
	SDm1	Stura di Demonte	6.4	358	348	0.002	B / 282	W / 175
Northern Apennines	Bor1	Borbera	6.4	319	248	0.011	B / 238	B / 196
	Lar1	Lardana	1.6	540	498	0.025	W / 62	W / 54
	Lav1	Lavaiana	2.3	547	498	0.021	B / 129	B / 86
	Nur1	Nure	2.4	536	467	0.028	W / 127	W / 131
	Nur3	Nure	2.8	473	446	0.010	B / 156	W / 134
	Nur5	Nure	4.9	420	373	0.010	W / 135	W / 139
	Nur6	Nure	2.3	373	349	0.010	B / 182	W / 151
	Nur10	Nure	3.9	187	155	0.008	B / 454	B / 235
Southern Apennines	Vol2	Volturno	6.2	200	175	0.004	B / 325	SAB / 35
	Vol4	Volturno	4.3	154	138	0.004	B / 366	SAB / 25
	Vol5	Volturno	3.7	138	130	0.002	SAB / 248	S / 27
	Tr5	Trigno	4.3	178	142	0.008	B / 353	W / 114
	Tr6	Trigno	2.5	142	117	0.010	B / 415	W / 108
	Tr8	Trigno	2.8	105	86	0.007	B/ 268	SAB / 90
	Tr9	Trigno	5.4	86	54	0.006	B / 372	SAB / 105
	For1	Fortore	1.1	390	377	0.012	B / 204	SAB / 66
	For2	Fortore	2.4	377	353	0.010	B / 243	W / 90
	For3	Fortore	2.3	353	333	0.009	B / 220	SAB / 67
	For4	Fortore	3.1	333	308	0.008	B / 188	SAB / 85

Legend for pattern codes: braided (B); wandering (W); sinuous with alternate bars (SAB); sinuous (S).

Table 4

Human impacts and period of construction/activity in the selected catchments (upstream the studied reaches) and reaches.

		Catchment scale				Reach scale	
	River	Alteration of longitudinal continuity		Alteration of lateral continuity	Mining	Reach	Human impacts in the reach Period and frequency/location
		TW	D - CD	ICW	GM		
Alps	Sesia		CD			Ses1	ICW (since 1970s, 10 - 20%) GM (since 1970s, FP)
Alps	Stura di Lanzo		CD			SLn1	ICW (since mid 1970s, 14 ÷25%) GM (since mid 1970s, FP)
Alps	Stura di Demonte		CD			SDm1	ICW(mid- 1980s, 14%)
Northern Apennines	Borbera	Since 1960s	CD (1960s)	-	Mid-1980s	Bor1	CD (since late 1980s)
Northern Apennines	Nure	Since 1977	CD (Since 1977)	Mid 1800 - 1990s	1980s - 1990s	Lar1	-
						Lav1	-
						Nur1	ICW (1980s, < 5%)
						Nur3	GM (1980s - 1990s, FP)
						Nur5	ICW (since 1950s, < 5%)
						Nur6	ICW (1970s, 20%)
						Nur10	ICW (since 1950s, 20 ÷ 50%) GM (1980s - 1990s)
Southern Apennines	Volturno	1960s - 1990s	CD (1945 - 1990)	1970s - 1980s	1980s - 1990s	Vol2	ICM (1970s - 1990s, 13 ÷ 30%) GM (1980s - 1990s, FP/C)
						Vol4	ICM (since 1970s, 30%)
						Vol5	ICM (since 1970s, 37%)
Southern Apennines	Trigno	1950s - 1970s	D (1997)	1960s - 1990s	1960s - 2000s	Tr5	ICM(since mid - 1980s, 85%) GM (mid 1970s - 2000s, FP)
						Tr6	ICW (1980s, 14%)
						Tr8	ICW (1980s, 35%) GM (1980s, FP)
						Tr9	ICW (1980s, 50%) GM (1980s, FP and C)
Southern Apennines	Fortore	1950s - 1990s	CD (1970s-1990s)	1960- 1990s	1970s - 1980s	For1	GM (1980s)
						For2	ICW(1970s-1980s, 15 ÷ 30%) GM(1980s, FP/C)
						For3	ICW (mid1980s-early1990s, 60%) GM (mid- 1980s)
						For4	GM (late 1980s - 1990s)

codes: TW = Torrent control work; D = dam; CD= check dam; ICW= in-channel work (groynes, bank protection, levee); GM = gravel mining. FP = floodplain; C = channel. In column "Human impacts in the reach", the symbol % indicates the percentage of banks stabilized by bank protections.

Table 5

Characteristics of materials used for studying channel evolution and land cover changes at catchment and reach scales.

Area	River /Catchment	Year	Type	Scale	Source	Analysis
Piemonte Region - Northen Italy	Ses; StdiLan; StDem	1852	HM	1: 50,000	Piemonte Region	CW
	all reaches	1954	AP	1: 25,000	IGM	CW; RLU
	all catchments	1960	Shp	-	Piemonte Region	BLC
	StDem; Borb	1970	AP	1: 25,000	Piemonte Region	CW; RLU
	Ses	1977	AP	1: 13,000	Piemonte Region	CW; RLU
	StdiLan	1978	AP	1: 13,000	Piemonte Region	CW; RLU
	StDem; Borb	1981	AP	1: 25,000	Piemonte Region	CW
	StdiLan	1988	O	-	Ministero Ambiente	CW; RLU
	Ses; StDem; Borb	1989	O	-	Ministero Ambiente	CW; RLU
	all catchments	1990	Shp	-	Ministero Ambiente	BLC
	all reaches	1996	O	-	Ministero Ambiente	CW; RLU
	Borb	2006	O	-	Piemonte Region	CW
	Ses; StdiLan	2007	O	-	Piemonte Region	CW
	StdiLan; StDem; Borb	2010	O	-	Piemonte Region	CW
	all catchments	2012	Shp	-	Min. Ambiente	BLC
	StDem; Borb	2015	O	-	Google Earth	CW; RLU
	Ses	2016	O	-	Google Earth	CW; RLU
	StdiLan	2018	O	-	Google Earth	CW; RLU
Nure catchement Inclusing Lardana and Lavaiana rivers	Nure catchment	1853	Shp	-	Emilia Romagna Region	BLC
	Nure (from r6 to r11)	1877	HM	1: 50,000	IGM	CW
	Nure catchment	1929	C	-	ISTAT	BLC
	all reaches	1954	AP	1: 25,000	IGM	CW; RLU
	all reaches	1970	AP	1: 28,000	IGM	CW; RLU
	Nure catchment	1976	Shp	-	Emilia Romagna Region	BLC
	all reaches	1988	O	-	Ministero Ambiente	CW; RLU
	Nure catchment	1990	Shp	-	Ministero Ambiente	BLC
	all reaches	1998	O	-	Ministero Ambiente	CW; RLU
	Nure catchment	1990	Shp	-	Ministero Ambiente	BLC
	all reaches	2011	O	-	Emilia Romagna Region	CW; RLU
	Nure catchment	2012	Shp	-	Ministero Ambiente	BLC
	all reaches	2015	O	-	Google Earth	CW
Southern Italy	all reaches	1836	L	-	Di Martino, 1996	BLC
	Fort	1870	HM	1: 50,000	IGM	CW
	Trig	1878	HM	1: 50,000	IGM	CW
	Vol	1885	HM	1: 50,000	IGM	CW
	Vol	1909	HM	1: 50,000	IGM	CW
	All catchments	1929	C	-	ISTAT	BLC
	Vol	1942-46	HM	1: 25,000	IGM	CW
	Vol; Trig; Fort	1954	AP	1: 34,000	IGM	CW; RLU; BLC
	All catchments	1970	C	-	ISTAT	BLC
	Vol; Trig	1975	AP	1: 15,000	IGM	CW; RLU
	Fort	1976	AP	-	IGM	CW; RLU
	Vol; Trig	1981	AP	1: 31,000	IGM	CW; RLU
	Fort	1984	Shp	-	Campania Region	BLC
	Fort	1986	AP	1: 31,000	IGM	CW; RLU
	Vol; Trig	1988	O	-	Ministero Ambiente	CW
	Fort	1989	O	-	Ministero Ambiente	CW; RLU
	all reaches	1992	AP	1: 13,000	Molise Region	CW
	all reaches	1998	O	-	Ministero Ambiente	CW; RLU
	all catchments	2000	Shp	-	Ministero Ambiente	BLC
	Fort	2004	O	-	Campania Region	CW
	all reaches	2007	O	-	Molise Region	CW
	all reaches	2011	O	-	Google Earth	CW
	all catchments	2012	Shp	-	Ministero Ambiente	BLC
	Fort	2013	O	-	Google Earth	CW
	Fort	2015	O	-	Google Earth	CW; RLU
	Vol; Trig	2016	O	-	Google Earth	CW; RLU

Codes for reaches: Ses = Sesia; StdiLan= Stura di Lanzo; StDem = Stura di Demonte; Borb = Borbera; Vol = Volturno; Trig = Trigno; Fort = Fortore. Codes for Type: HM= historical maps; AP= aerial photographs; O = orthophotos; C = census data; L= literature data; Shp = shapfile. Codes for Analysis: CW = channel width; BLC = basin scale land cover; RLU = reach scale land use in the 22 selected reaches.

IGM: Istituto geografico Militare

Table 6

Rates of average annual channel width variation expressed in m y^{-1}.

		Annual channel width variation (m y^{-1})			
	Reach	**1954 - 1970s**	**1970s -1980s**	**1980s - 1990s**	**1990s -2010s**
Alps	Ses1	-2.0	-1.1	**-3.2**	-2.3
	SLn1	**-4.1**	-2.7	+7.8	**-3.5**
	SDm1	-1.7	**-3.4**	**-3.5**	-0.9
Northern Apennines	Bor1	-0.9	-0.7	**-2.0**	-0.7
	Lar1	**-0.2**	**-0.2**	-0.1	-0,1
	Lav1	**-0.5**	-0.3	-0.2	-0.1
	Nur1	**-0.9**	-0.5	-0.3	+1.1
	Nur3	-0.5	**-0.8**	-0.2	+0.9
	Nur5	-0.3	**-2.0**	-0.2	-0.7
	Nur6	-0.5	**-0.8**	-0.0	-0.2
	Nur10	-1.7	**-4.0**	-0.4	-0.7
Southern Apennines	Volt2	**-4.1**	**-4.2**	-0.9	-1.4
	Volt4	**-4.0**	**-4.6**	-1.5	-0.7
	Volt5	-1.7	**-1.9**	-0.5	-0.3
	Tr5	-1.3	**-3.5**	**-4.5**	+1.1
	Tr6	**-2.3**	-0.2	-1.4	-0.3
	Tr8	-1.2	**-2.6**	-1.9	+0.9
	Tr9	-3.0	**-4.5**	**-5.0**	+1.4
	For1	-0.3	-0.2	**-0.7**	+0.3
	For2	-1.3	-0.8	**-1.5**	+1.0
	For3	**-1.5**	-0.4	-1.2	+0.3
	For4	**-0.9**	-0.3	-0.5	+0.8

Annual rates of channel width variation within the 22 studied reaches, during the four periods (1954 - 1970s; 1970s- 1980s; 1980s- 1990s; 1990s- 2010s. Negative and positive values indicate narrowing and widening, respectively Bold numbers indicate the peak period for channel narrowing. Legend of background colors: white = narrowing < -1 m y^{-1}; pink = narrowing -1÷2 m y^{-1}; narrowing > 2 m y^{-1}; green = widening. For reach Id abbreviation see Table 3.

Table 7

Land cover changes and main trends at catchments scale

River	Land use	1836	1853	1929	1954	1960	1970/ 76	1984	1990	2000	2012	Trends 1 2
Sesia	Forest	-	-	-	-	0.46	-	-	0.52	-	0.54	
	Pasture/ meadow	-	-	-	-	0.43	-	-	0.16	-	0.16	
	Ploughed land	-	-	-	-	0.01	-	-	0.00	-	0.00	
	Cultivated trees	-	-	-	-	0.01	-	-	0.04	-	0.04	
	Schrub cover	-	-	-	-	0.00	-	-	0.17	-	0.16	
Stura di Lanzo	Forest	-	-	-	-	0.18	-	-	0.33	-	0.33	
	Pasture/ meadow	-	-	-	-	0.68	-	-	0.16	-	0.21	
	Ploughed land	-	-	-	-	0.02	-	-	0.00	-	0.00	
	Cultivated trees	-	-	-	-	0.01	-	-	0.05	-	0.05	
	Schrub cover	-	-	-	-	0.00	-	-	0.14	-	0.17	
	Other	-	-	-	-	0.12	-	-	0.32	-	0.25	
Stura di Demonte	Forest	-	-	-	-	0.24	-	-	0.25	-	0.28	
	Pasture/ meadow	-	-	-	-	0.44	-	-	0.15	-	0.21	
	Ploughed land	-	-	-	-	0.22	-	-	0.13	-	0.13	
	Cultivated trees	-	-	-	-	0.01	-	-	0.09	-	0.08	
	Schrub cover	-	-	-	-	0. 00	-	-	0.14	-	0.12	
	Other	-	-	-	-	0.09	-	-	0.24	-	0.16	
Borbera	Forest	-	-	0.22	-	0.48	-	-	0.66	-	0.64	
	Pasture/ meadow	-	-	0.12	-	0.18	-	-	0.05	-	0.02	
	Ploughed land	-	-	0.19	-	0.33	-	-	0.01	-	0.01	
	Cultivated trees	-	-	0.06	-	0.00	-	-	0.21	-	0.20	
	Other	-	-	0.41	-	0.01	-	-	0.08	-	0.12	
Nure	Forest	-	0.27	0.33	-	-	0.45	-	0.51	0.53	0.52	
	Pasture/ meadow	-	0.65	0.18	-	-	0.11	-	0.08	0.08	0.09	
	Ploughed land	-	0.03	0.33	-	-	0.36	-	0.08	0.08	0.08	
	Cultivated trees	-	0.01	0.00	-	-	0.01	-	0.29	0.27	0.28	
	Other	-	0.05	0.16	-	-	0.07	-	0.03	0.03	0.04	
Volturno	Forest	0.23	-	0.18	0.26	-	0.25	-	-	0.48	0.50	
	Pasture/ meadow/Schrub	0.16	-	0.26	0.17	-	0.37	-	-	0.15	0.16	
	Ploughed land	0.56	-	0.50	0.50	-	0.23	-	-	0.06	0.07	
	Cultivated trees	0.04	-	0.05	0.05	-	0.06	-	-	0.26	0.23	
	Other	-	-	0.01	0.02	-	0.10	-	-	0.06	0.03	
Trigno	Forest	0.25	-	0.15	0.18	-	0.16	-	-	0.27	0.29	
	Pasture/ meadow	0.24	-	0.09	0.17	-	0.15	-	-	0.01	0.01	
	Ploughed land	0.46	-	0.61	0.58	-	0.35	-	-	0.20	0.30	
	Cultivated trees	0.04	-	0.05	0.05	-	0.03	-	-	0.31	0.22	
	Schrub cover	-	-	0.05	0.00	-	0.17	-	-	0.17	0.17	
	Other	-	-	0.06	0.02	-	0.14	-	-	0.04	0.02	
Fortore	Forest	-	-	0.07	-	-	0.09	0.18	-	0.14	0.15	
	Pastures/ meadow	-	-	0.05	-	-	0.09	0.02	-	0.02	0.01	
	Ploughed land	-	-	0.77	-	-	0.47	0.71	-	0.53	0.55	
	Cultivated trees	-	-	0.04	-	-	0.03	0.04	-	0.25	0.24	
	Schrub cover	-	-	0.04	-	-	0.24	0.04	-	0.05	0.04	
	Other	-	-	0.02	-	-	0.09	0.03	-.	0.01	0.02	

In the column "Trends": 1 = trends before 1960s / 1970s; 2= trend after 1960s / 1970s. Full arrows indicate clear trends; dashed arrows or lines indicate less intense or constant trends. respectively. Legend of colors: green = forest; yellow = pasture and meadow; pink = ploughed land; brown = Cultivated trees.