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RECENT CHANNEL ADJUSTMENTS AND RIPARIAN VEGETATION RESPONSE: SOME EXAMPLES FROM MOLISE (ITALY)

ABSTRACT: AUCELLI P.P.C., FORTINI P., ROSSKOPF C.M., SCORPIO V. & VISCOSI V., *Recent channel adjustments and riparian vegetation response: some examples from Molise (Italy)*. (IT ISSN 0391-9838, 2011).

An integrated geomorphological and ecological approach was adopted to investigate the relation between recent channel adjustments and riparian vegetation evolution by performing a large-scale multi-temporal analysis of channel and land cover features and a study of the present-day floristic setting along the three major river systems present in Molise (Southern Italy), the Volturno, Biferno and Trigno. Our results highlight the major channel adjustments that occurred between 1954 and 2009 consisting in progressive morphological changes, extreme channel narrowing (between 84% and 97%) and moderate to very intense channel incision (between 2 and 10.5 m). These channel adjustments led to the progressive stabilization of most of the formerly active channel systems and were accompanied by substantial changes in the riparian vegetation which now appears largely, but not completely, in equilibrium with the present river dynamics. Major differences may be noted between the studied river reaches in relation to their state of naturalness, floristic richness and differentiation in vegetation types, which appear particularly controlled by the amount of channel incision and human disturbance. Our findings underline the importance of fluvial dynamics and trends in controlling the development and structure of riparian vegetation and the connected ecological status of river systems.

KEY WORDS: Fluvial morphology, GIS analysis, Recent channel adjustments, Riparian vegetation, Floristic evolution, Molise, Italy.

RIASSUNTO: AUCELLI P.P.C., FORTINI P., ROSSKOPF C.M., SCORPIO V. & VISCOSI V., *Recenti variazioni plano-altimetriche dei corsi d'acqua e risposta della vegetazione ripariale: esempi dal Molise (Italia)*. (IT ISSN 0391-9838, 2011).

Nel presente lavoro è stato adottato un approccio di studio integrato geomorfologico-ecologico per indagare sulla relazione tra la recente evoluzione dei corsi d'acqua e quella della vegetazione ripariale, scegliendo come area di studio alcuni tratti rappresentativi dei maggiori corsi d'acqua molisani, i fiumi Volturno, Biferno e Trigno. Tale approccio si è basato sull'analisi multi-temporale di ortofoto e foto aeree di varia data in ambiente ArcGIS riguardo l'evoluzione morfologica dei tratti fluviali prescelti e le connesse variazioni della copertura del suolo, e sullo studio integrato di tali tratti in rapporto agli attuali assetti morfologici e floristici della vegetazione ripariale. L'analisi eseguita ha consentito di evidenziare, oltre ai cambiamenti progressivi della morfologia d'alveo (da *braided* a rettilineo), restringimenti degli alvei molto consistenti (tra l'84% ed il 97%), e abbassamenti degli alvei da moderati fino a molto intensi (tra 2,0 e 10,5 m). Tali modificazioni sono state accompagnate da cambiamenti altrettanto consistenti della vegetazione ripariale che si è progressivamente adattata ai cambiamenti morfologici. Lo studio ha messo in evidenza importanti differenze tra i tratti fluviali studiati in rapporto al loro grado di naturalità, alla ricchezza floristica e alla differenziazione in tipi vegetazionali, che appaiono negativamente condizionate dall'entità di approfondimento degli alvei e del disturbo antropico. I risultati riportati nel presente lavoro sottolineano l'importanza che l'evoluzione dei corsi d'acqua e la dinamica fluviale hanno nel condizionare lo sviluppo e la struttura della vegetazione ripariale e lo stato ecologico del sistema fluviale.

TERMINI CHIAVE: Morfologia fluviale, Analisi GIS, Variazioni plano-altimetriche recenti, Vegetazione ripariale, Evoluzione floristica, Molise, Italia.

INTRODUCTION

River systems are characterized by a significant diversity of physical conditions which allows the development of rich biological communities, and are able to adapt rapidly, thanks to their high dynamics, to environmental, especially climatic, and human-induced influences. Consequently, environmental influences on river systems are easily reflected in channel adjustments and consequent changes in the riparian vegetation which are indicative of the state of equilibrium and naturalness of the river system.

The Natura 2000 network, which is the centrepiece of EU nature and biodiversity policy, identifies river systems as sites of high ecological value. Indeed, the importance of

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rivers as ecological corridors and migration pathways is well known (Naiman & *alii*, 1993; Tabacchi & *alii*, 1998; Tockner & Ward, 1999; Van der Nat & *alii*, 2003) and the prevention of the deterioration of aquatic ecosystems and the preservation of biotic diversity represents a primary goal of the Water Framework Directive 2000/60/EC (European Commission, 2000; Hooke, 2007; Nardini & *alii*, 2008; Van Looy & *alii*, 2008; Mouton & *alii*, 2009). Moreover, the presence of riparian vegetation along river channels plays an important role in mitigating stream bank erosion (Aberney & Rutherfurd, 1999; Ciutti, 2003) and in limiting potential damage due to flooding (see for example Anderson & *alii*, 2006 and references herein), respectively.

Riparian zones support differentiated ecosystems and habitats whose natural evolution is primarily controlled by hydro-morphological conditions and fluvial geomorphic processes (Heller & *alii*, 1995; Hupp & Osterkamp, 1996; Bendix & Hupp, 2000; Tockner & *alii*, 2000; Van der Nat & *alii*, 2003; Hupp & Rinaldi, 2007; Larsen & *alii*, 2007) and secondarily by the local phytoclimate (Sansoni, 2003). Riparian zones are characterized by high physical heterogeneity and sharp environmental gradients which determine the structure of riparian plant communities (Hughes, 1997) and thus play a fundamental role in the maintenance of regional biodiversity (Naiman & *alii*, 1993; Ward & Tockner, 2001; Ward & *alii*, 2001; Kern & *alii*, 2002; Larsen & *alii*, 2007).

Riparian ecosystems typically comprise a chain of primary forest communities forming an edaphic climax (Pedrotti & Gafta, 1996). Within the central sector of Italy, from Tuscany to the region of Basilicata, riparian vegetation forms a typical sequence of edapho-hygrophilous forest communities, represented by small willow communities growing on stream banks and floodplains, followed by woodland dominated by *Salix alba* and/or *Alnus glutinosa*, then by *Populus nigra* woodland and, finally, by woodland formed by *Ulmus, Fraxinus* and *Quercus* species (Pedrotti & Gafta, 1996; Blasi, 2010). Unfortunately, complete riparian sequences are only sporadically present and riparian ecosystems are frequently disturbed and fragmented by widespread human interventions affecting valley floors and especially river channels (see for example Marston & *alii*, 1995; Johnson, 2002; Mingione & *alii*, 2004; Aguiar & Ferreira, 2005; Kondolf & *alii*, 2007; Larsen & *alii*, 2007). Besides direct interventions on river systems such as gravel extraction, construction of dams, weirs and embankments, changing land use practices can also significantly contribute to changes in sediment rates and thus favour river entrenchment, as illustrated for example by Marston & *alii* (1995) and by Kondolf & *alii* (2007) respectively for the Ain and the Eygues rivers in France.

Specific investigations on the relations between fluvial morphology, channel adjustments and riparian vegetation are the focus of an increasing number of recent studies on a European and world-wide scale (Marston & *alii*, 1995; Hupp & Osterkamp, 1996; Johnson, 1997; Kondolf & *alii*, 2007; Van Looy & *alii*, 2008; Gonzalez & *alii*, 2010 and references herein). Italy has also been the subject of numerous studies, albeit limited to its central and northern parts (see for example Gurnell & *alii*, 2001; Hupp & Rinaldi, 2007; Bertoldi & *alii*, 2009 and relative references; Surian & *alii*, 2009b, 2009c; Comiti & *alii*, 2011).

Our study focuses on recent channel adjustments that have affected the three major river systems in Molise, a region in southern Italy. The overall aim was to gather data on the specific environmental contexts in question, and determine how fluvial dynamics and channel adjustments have affected riparian vegetation dynamics and its evolution.

Indeed, these river systems have suffered (Aucelli & Rosskopf, 2000; Faillace, 2004; Mingione & *alii*, 2004; Aucelli & *alii*, 2009), like many other rivers in Italy (Surian & *alii*, 1999; Rinaldi, 2003; Surian & Rinaldi, 2003; Hupp & Rinaldi, 2007; Surian & Cisotto, 2007; Rinaldi & *alii*, 2008; Surian & Rinaldi, 2008; Surian & *alii*, 2008; Surian & *alii*, 2009b, 2009c; Comiti & *alii*, 2011), major recent channel adjustments including pattern changes, channel and floodplain narrowing and channel lowering, which are thought to be largely induced by human interventions on river systems that have contributed considerably to altering the original flow and sediment regimes.

STUDY SITES

This study examines the three major river systems in the southern Italian region of Molise, namely the Volturno, Biferno and Trigno rivers (fig. 1). These are perennial streams with alternating low-flow and high-flow conditions, dominating in spring-summer and autumn-winter, respectively. Along each of them a reach was selected where a large-scale, integrated analysis on geomorphic and vegetation features could be carried out. Reach selection was based on a preliminary small-scale analysis of these streams concerning channel mobility and recent channel adjustments, in order to accurately represent a larger,

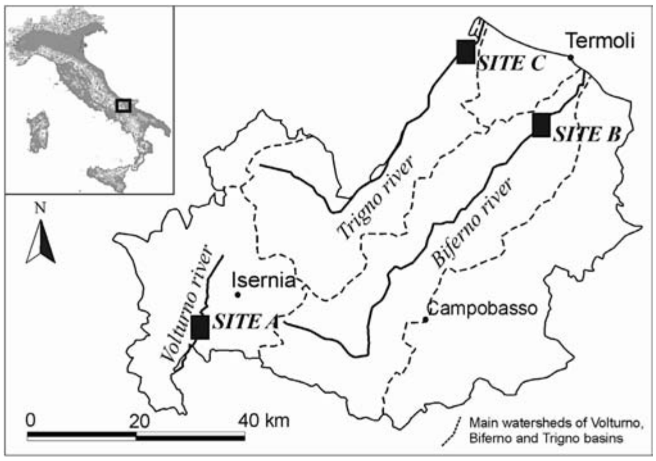


FIG. 1 - Location of the study area (Molise region) and the examined river reaches (sites A, B and C).

stream-specific environmental context. None of these streams is in a state of complete naturalness: all have been affected in recent times by various human interventions, such as gravel extraction, water withdrawal and the construction of dams and weirs (Aucelli & Rosskopf, 2000; Faillace, 2004; Aucelli & *alii*, 2009), that have significantly helped to alter sediment and flow discharges, especially peak flow discharges. In the cases of the Volturno and Trigno, a small flood moderation reservoir and various water withdrawal points, respectively, are located upstream of the selected study sites; the Biferno site is located downstream of a dam that captures the water supply of ca. 70% of the catchment.

The Volturno river originates at about 500 m a.s.l. and flows into the Tyrrhenian Sea. It has a catchment area of about 5550 km^2 and a total length of about 176 km. Its upper course is partially underlain by Tertiary flysch successions and is strongly controlled by extensive Pleistocene tectonics which has generated a large depression coinciding with the upper Volturno valley (Brancaccio & *alii*, 1997). The upper Volturno valley has a temperate-warm humid climate with warm summers which corresponds to the Köppen climate class *Cfb* with mean annual rainfall and temperatures reaching about 1300 mm and 15° C, respectively (Aucelli & *alii*, 2007). The selected river reach (site A, fig. 1) has a length of ca. 2.2 km, an average width of ca. 1.5 km and is located between 231 m and 214 m a.s.l. It accurately represents the fluvial morphology that typifies the upper Volturno valley.

The Biferno and Trigno rivers (fig. 1) have a catchment area of about 1300 and 1200 km^2 and a total length of 100 and 120 km, respectively. They cross transversally the Molise sector of the Apennine chain before reaching the Adriatic Sea. Their medium and upper valley sectors are underlain by limestones, marly limestones and clays and by siliciclastic flysch deposits. Valley incisions are typically V-shaped and characterized by generally very narrow valley bottoms occupied by largely confined channel systems, and are thus affected by strongly interacting slope and river processes (Aucelli & *alii*, 2000). Within the lower sectors, instead, valley floors progressively widen and are of alluvial origin, with a typical flat morphology and mobile stream channels. The headwater portions of the Biferno and Trigno river have a temperate-warm humid climate (*Cfb*), while in the medium and lower valley sectors there is a largely predominant temperate-warm humid climate with very hot summers, classified climatically as *Cfa* (Aucelli & *alii*, 2007). In the lower sectors, mean annual temperatures and precipitation are about 15-16° C and 500-600 mm, respectively, and summers are very dry.

The reaches selected along the Trigno and Biferno rivers (sites B and C, respectively, fig. 1) are located within the lower, alluvial valley sectors and accurately represent the fluvial dynamics and the environmental contexts that typify these sectors. Site B lies between 36 m and 18 m a.s.l. and reaches a length of ca. 4.7 km and an average width of 1.7 km. Site C has a length of ca. 2 km and an average width of 3 km, and is located between 28 and 14 m a.s.l.

METHODS

In our study we used an interdisciplinary approach, based on a multi-temporal, integrated geomorphological and vegetation analysis. To investigate the recent evolution of sites A, B and C in relation both to geomorphic features and land cover, multi-temporal analyses were performed in ArcGIS on: the topographic map at a scale of 1:5,000 (CTR Molise), certified by the Molise regional authority; medium-scale orthophotographs dating to 1998, 2004 and 2007, certified by the Molise regional authority; medium-scale aerial photographs dating to 1954, 1977 and 1986, respectively, first scanned with a resolution of 800 dpi and then rectified. For their rectification, instead of DGPS ground control points, we used a number of control points selected from the CTR map of Molise, clearly visible also on the aerial photos (i.e. crossings, constructions, etc.).

First, the fluvial geomorphic features of the bottomlands (*sensu* Hupp & Ostercamp, 1996) in different years were distinguished and mapped for each selected site. The qualitative data were integrated with quantitative data on channel planform and changes in time.

Channel pattern, braiding and sinuosity indices were determined according to Surian & *alii* (2009a). In particular, the braiding index was calculated by summing the number of channels crossed by each single cross-section (using the same sections considered for calculating channel widths) and dividing the obtained sum by the number of considered cross-sections. The sinuousity index, instead, was determined by dividing the reach length at the channel midline by the straight line length between the reach endpoints.

Minimum, maximum and average widths of the active channels were determined using the georeferenced aerial photos and the certified orthophotos of various dates taken during low flow conditions (dry season). During the digital mapping of channel features two sources of potential error were considered which stem from the rectification of the aerial photos and the editing itself (Gurnell, 1997; Winterbottom, 2000; Hughes & *alii*, 2006; Comiti & *alii*, 2011). In the specific case, the digitalization error (which is due to the map scale and the pixel dimensions of the aerial photos) is estimated at ca. 2.5 m for the 1:5,000 scale map, 1.5 m for the aerial photos from 1954 and 0.6 m for those of 1977 and 1986. The error related to the process of rectification, which stems from co-registration and rectification, corresponds to a resultant RMSE value of 7.0 m for the 1954 aerial photos and to an RMSE of ca. 5 m for those dating to 1977 and 1986.

The widths of active channels were determined by measuring the shortest distance between channel margins at equally spaced cross-sections (Winterbottom, 2000; Rinaldi, 2008; Richardson & Fuller, 2010). Cross-sections were spaced, taking into account the channel widths, at 300, 50 and 20 m intervals for aerial photos from 1954, 1986 and 1997-2004, respectively. Channel widths in 2007 were directly determined on the basis of DGPS data acquired during the topographic surveys carried out within each reach in 2009 (see below).

Rates of channel incision were estimated by determining the differences in height of similar geomorphic surfaces of different age (such as those between floodplain surfaces active in 1954 and 1986, respectively) using the data extracted from topographic maps and those acquired during the DGPS surveys (see below). The estimated amounts of channel incision were defined, according to Rinaldi (2008), as limited (0.5-1 m), moderate (1-2 m), intense (2-4 m) and very intense (> 4 m).

Secondly, by analyzing land cover changes in the areas occupied by the active channel systems in 1954 we were able to identify and separately map, with reference to the CORINE land cover project (APAT, 2000), the following six land cover types: *roads and mine sites* (categories 1.2.2. and 1.3.1., grouped together); *agricultural areas* (categories 2.1. and 2.2,); *broad-leaved forest* (category 3.1.1.); *shrub and herbaceous vegetation* (categories 3.2.1. and 3.2.3.); *open spaces with little or no vegetation* (categories 3.3.2. and 3.3.3.); *river channels* (category 5.1.1.).

To investigate the present-day morphologic setting of sites A, B and C, a large-scale geomorphologic field survey was performed from 2008 to 2009. In particular, the last field surveys in February 2009 and autumn-winter 2009-2010 allowed us to evaluate the effects of intense and/or prolonged rainfalls on water levels and confirm the limits of flood plain areas as determined on the basis of previous field surveys and aerial photos dating to 2007.

These geomorphological surveys were integrated by detailed topographic DGPS surveys carried out along various transects normal to the river channels, using a Trimble R6 GPS system which allowed vertical and horizontal measurement errors to be limited within 3 cm and 2 cm, respectively. The location of transects was determined by taking into account the local morphological pattern, the possibility of access and the state of naturalness (avoiding areas where there was evident human disturbance). Topographic data collected along these transects were used to reconstruct seven cross-sectional views of the investigated bottomlands to be investigated in relation to their present-day geomorphic and vegetation features.

To characterize the current floristic pattern and establish its relationships with the present-day small-scale geomorphic/topographic features, floristic-phytosociological (Braun-Blanquet, 1964) and physiognomical relevés were performed along the constructed cross-profiles. Through a cover-abundance value, phytosociological relevés allowed all the species occurring in the sampling plot area to be detected and indexed, while physiognomical surveys were used to list the guide species of the three present-day vegetation layers: trees, shrubs and herbs. In all, 126 plant species were sampled and identified according to Conti & *alii* (2005). For the life forms reference was made to Tutin & *alii* (1964-1980). Statistical analyses were carried out on the data matrix, allowing a quantitative matrix of 81 species and 33 samples to be obtained. By means of multivariate statistical methods (Podani 1994) a principal coordinate analysis (PCoA) and a cluster analysis were carried out to define groups of samples identifiable as vegetation types, by grouping more than one plant community. Statistical analyses were computed on the transformed matrix with Br.-Bl. index values converted following Westhoff & Van Der Maarel (1973). Finally, for each stream reach and vegetation type the floristic richness was calculated.

RESULTS

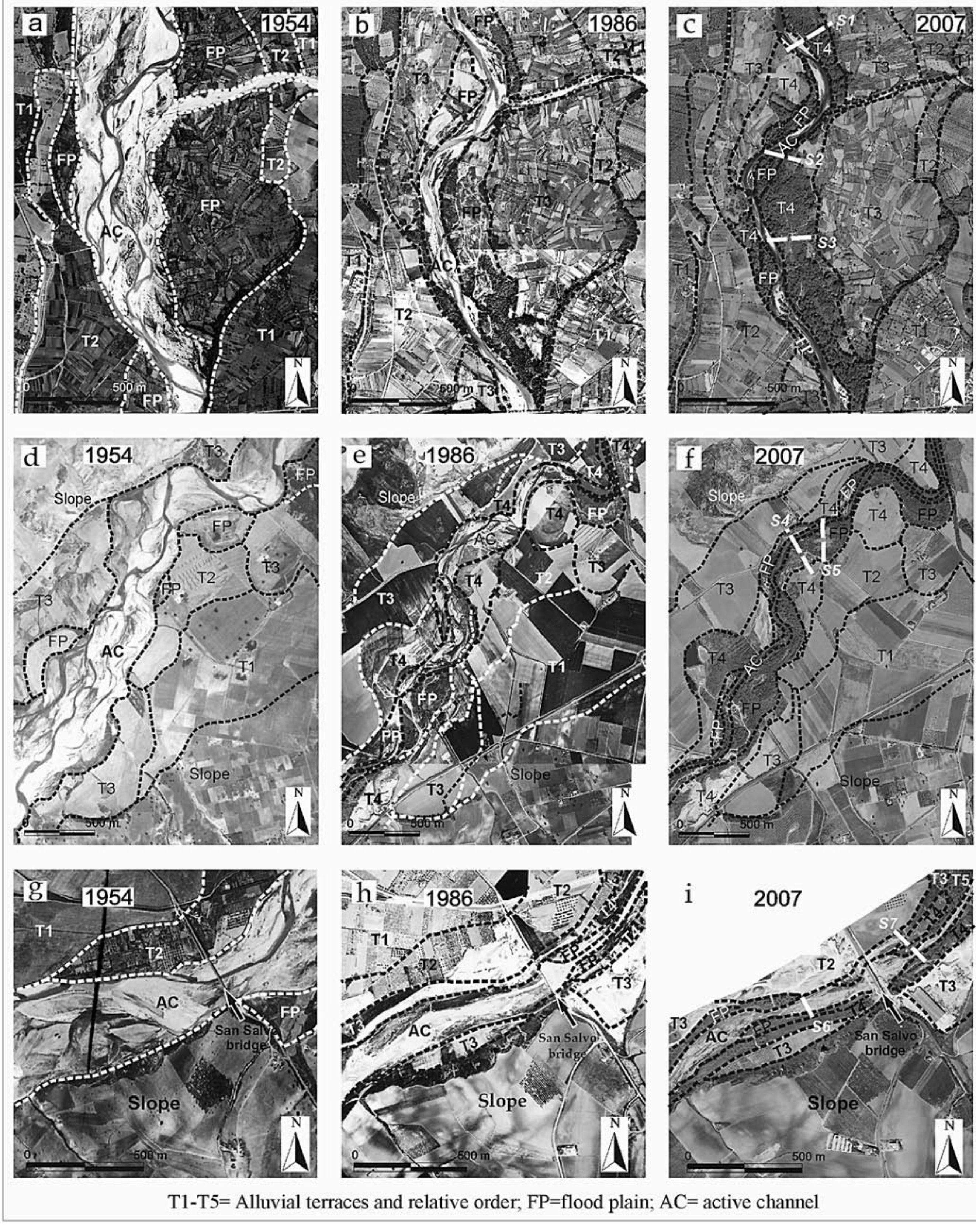
Planform changes

As illustrated in figure 2 and table 1, considerable channel adjustments occurred from 1954 to 2007 within each site. In 1954 (figs. 2a, 2d and 2g), all the studied reaches typically have a braided pattern (braiding indexes 1.71-3.13) and active channel systems with average widths of more than 340 m (tab. 1).

In 1986, large portions of these channel systems were transformed into floodplain areas, while a smaller part, together with the 1954 floodplain areas, became terraces (figs. 2b, 2e and 2h). The channels had already been severely narrowed and reduced to about one third or less of their original average width (tab. 1). They are chiefly single-threaded and typically characterised by bare to vegetated, alternating lateral and isolated central bars. The Volturno and Biferno sites are characterized by a transitional pattern (wandering *sensu* Hupp & Rinaldi, 2007), while the Trigno site already exhibits a sinuous pattern. The adjustments in question also had major effects on the total floodplain area which

TABLE 1 - Synthesis of morphological and morphometric parameters characterising the studied river reaches. Legend: P = pattern; b = braided; t = transitional; s = sinuous; st = straight; W_{av}, W_{mx} and W_{mn} = average, maximum and minimum channel width (in m); N = channel narrowing (in %); SI = sinuosity index; BI = braiding index

	P	W_{av}	W_{mx}	W_{mn}	N	SI	BI
Volturno							
1954	b	376	539	186	–	1.02	3.13
1986	t	106	174	38	72	1.13	1.63
1992	s	73	122	31	80	1.13	1.15
1997	s	67	164	25	82	1.15	1.15
2005	s	52	157	28	86	1.16	1.11
2007	s	57	92	27	85	1.18	1.11
Biferno							
1954	b	378	721	172	–	1.12	2.30
1977	t	122	316	15	68	1.24	1.46
1986	t	99	304	16	73	1.26	1.31
1992	t	78	252	18	79	1.24	1.48
1997	s	27	85	8	93	1.30	1.43
2004	s	13	22	7	97	1.30	1.17
2007	s	13	22	7	97	1.30	1.17
Trigno							
1954	b	344	429	181	–	1.06	1.71
1986	s	118	191	73	66	1.04	1.11
1992	st	72	129	27	79	1.03	1.15
1997	st	47	102	12	86	1.01	1.07
2004	st	63	93	28	82	1.02	1
2007	st	55	113	20	84	1.02	1



T1-T5= Alluvial terraces and relative order; FP=flood plain; AC= active channel

FIG. 2 - Main fluvial features of sites A, B and C in 1954 (A, D, G), 1986 (B, E, H) and 2007 (C, F, I) and location of cross-sections S1-S7. The Volturno flow-direction is N-S; the Trigno and Biferno flow-direction is SW-NE.

experienced a severe reduction in this period. Data calculated for the Biferno river show that the percent of channel narrowing in 1977 was only slightly lower the one calculated for 1986 (68% and 73%, respectively, tab. 1), and that at least in site B the transition from a braided to wandering pattern occurred in only approximately 20 years (1954-1977).

From 1986 to 1997 the channel narrowing rates were still relative high, causing average channel widths to decrease in only about ten years to about a quarter (Biferno) and a half (Volturno and Trigno) of their 1986 widths. Hence, in 1997 the surveyed channel systems have significantly reduced average widths of 27 m to 67 m and are characterised by a sinuous or straight pattern (Biferno and Volturno sites and Trigno site, respectively, tab. 1). In the cases of the Volturno and Trigno, such pattern changes had already occurred between 1986 and 1992. By contrast, along the Biferno site such changes occurred between 1992 and 1997 (tab. 1).

From 1997 to 2007 the studied stream reaches preserved their pattern, but suffered further modest channel narrowing (figs. 2c, 2f and 2i) which reached in 2007 a total of 85%, 97% and 84% within sites A, B and C, respectively (tab. 1). The acquired data show that channel narrowing was progressive in time for the Volturno and Biferno rivers, while the Trigno River was affected by a very recent trend inversion as its channel slightly widened between 1997 and 2007 (from 47 m to 55 m on average, tab. 1). Our data suggest that this hint of trend inversion is most likely related to an important but isolated flood event that occurred on 24-26 January 2003 in the lower Molise region (Aucelli & *alii*, 2004), causing high flow and sediment discharges, diffuse channel bank erosion and extensive flooding along the lower course of the Trigno river.

Channel incision

The previously described planform changes were accompanied by various rates of channel incision, amply evidenced by the presence of various orders of alluvial terraces and floodplain areas that developed from 1954 onwards at the expense of the active channel systems and floodplains.

The Volturno reach (site A) was affected by a total moderate incision of 2.0 m: from 1954 to 1986 limited channel lowering occurred (0.5 m) which transformed the extensive floodplain and part of the active channel (FP and AC, respectively, fig. 2a) into a third-order terrace (T3, fig. 2b). From 1986 to 2007, moderate channel lowering of ca. 1.5 m generated a fourth-order terrace (T4, fig. 2c).

Within the Biferno reach (site B) intense channel incision of ca. 3.5 m occurred: from 1954 to 1986 channel narrowing was accompanied by intense channel lowering of about 2.0-2.5 m that transformed the floodplain and part of the active channel into a fourth-order terrace (T4, fig. 2e). From 1986 to 2007, channel lowering was limited, reaching a maximum of 1.0 m, and led to the stabilisation of the formerly produced terraced surfaces and the transformation of part of the active channel into flood plain.

The Trigno reach (site C) was affected by overall intense-to-very-intense channel incision between 3 m and 10.5 m. Upstream of the San Salvo bridge, the channel lowered by ca. 1.5 m during both the periods 1954-1986 and 1986-2007, causing the formation first of a third-order terrace (T3 in fig. 2h) and then of a fourth-order terrace (T4 in fig. 2i). Downstream of the bridge, channel lowering was much greater: from 1954 to 1986, it reached ca. 6.0 m and was accompanied by the formation of two new terrace orders (T3 and T4, fig. 2h); then, from 1986 to 2007, further very intense channel lowering of ca. 4.5 m occurred which led to the formation of the fifth-order terrace (T5, fig. 2i). The significant differences in channel lowering rates between the two stream portions show that the bridge structure significantly limited river incision upstream. Indeed, since the collapse of the bridge during the flood event in January 2003 (Aucelli & *alii*, 2004), the upstream located portion has experienced progressive channel incision, now directly affecting the clayey bedrock.

Land cover evolution

The river adjustments occurring in the studied reaches during the last 55 years have been accompanied by major land cover changes which have affected the active channel systems as summarized in table 2. The ascertained relationships between land cover changes, channel narrowing and channel incision are summarized in figure 3.

In 1954, the best represented vegetation cover types are *open spaces with little or no vegetation* (hereinafter *open spaces*), referring above all to channel bars, and *shrub and/or herbaceous vegetation*, that reach altogether between ca. 67% and 72% of the total land cover in the studied sites.

From 1954 to 1986, major channel narrowing caused a first, severe reduction in these land cover categories, which in 1986 accounted for only between ca. 20% and 31% of the total land cover (tab. 2), accompanied by a considerable expansion of *agricultural areas* (from ca. 0.4-2.8% to

TABLE 2 - Land cover types (in %) present within sites A, B and C in different years

	VOLTURNO - SITE A				BIFERNO - SITE B					TRIGNO - SITE C			
LAND COVER (%)	**1954**	**1986**	**1997**	**2007**	**1954**	**1977**	**1986**	**1997**	**2007**	**1954**	**1986**	**1997**	**2007**
broad-leaved forest	9.44	31.62	41.65	48.71	16.23	17.72	25.27	29.18	32.22	13.18	10.81	16.16	14.73
shrub and/or herbaceous vegetation	25.22	11.70	11.48	6.98	31.34	23.10	15.89	28.21	24.19	36.95	18.09	28.69	31.91
river channels	17.29	9.03	4.94	7.23	14.88	6.98	4.22	3.24	1.78	12.91	9.49	5.69	3.14
open spaces	45.21	13.82	7.05	3.48	36.08	11.95	3.94	0.71	3.66	35.35	12.61	8.48	7.37
roads and mine sites	–	3.00	0.69	0.28	–	3.73	8.38	3.16	4.35	1.21	21.69	22.92	25.00
agricultural areas	2.84	30.82	34.19	33.32	1.47	36.52	42.30	35.50	33.79	0.40	27.22	18.06	17.85

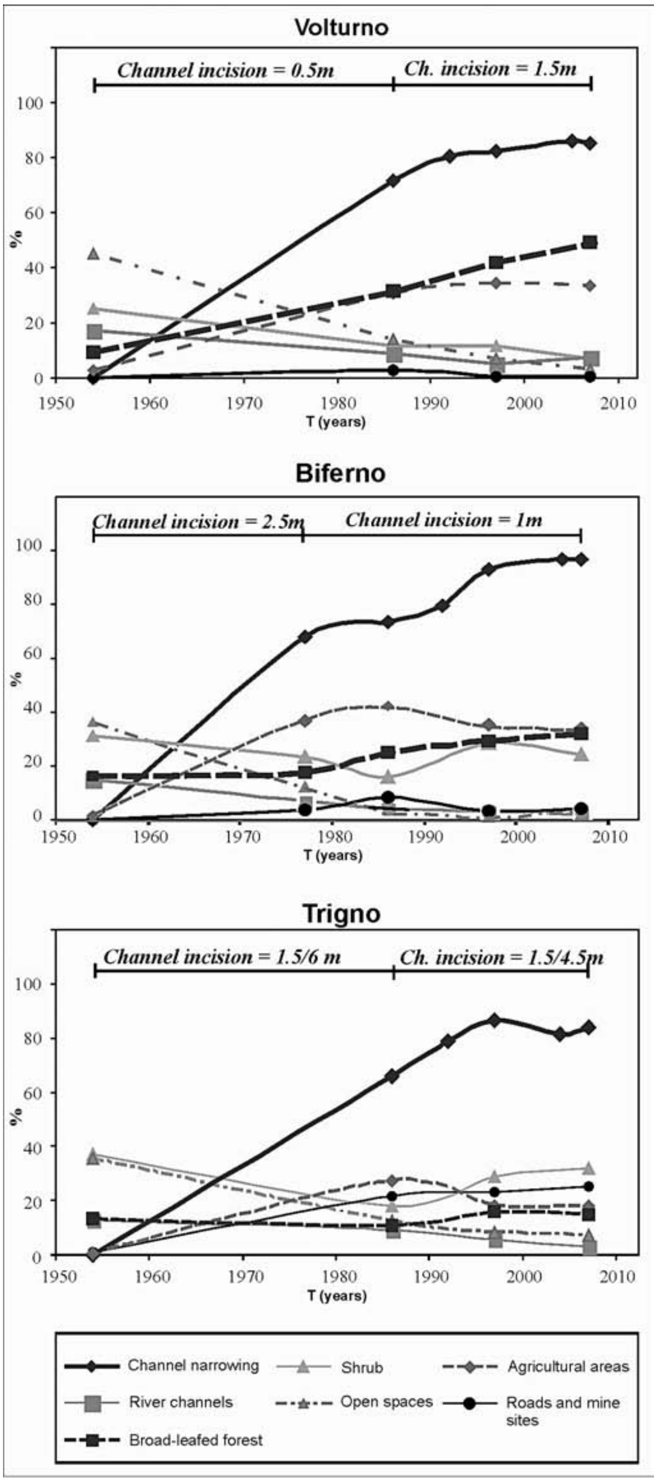


FIG. 3 - Comparison between channel narrowing and land cover changes (in percent) from 1954 to 2007, and estimated rates of channel incision from 1954 to 1986 and from 1986 to 2007, respectively.

27.2-42.3 %). According to evidence from the Biferno site, the most substantial part of these land cover changes had already occurred in 1977. More specific trends are shown by the Volturno and Trigno sites which experienced in this period a strong expansion of *broad-leaved forest* and of *roads and mine sites*, respectively.

From 1986 to 1997, further substantial channel narrowing and the partial abandonment of *agricultural areas* within the Biferno and Trigno sites were accompanied by a strong expansion of *shrub and/or herbaceous vegetation* and hence of related grazing practices which are currently very widespread as well, as shown by the present-day vegetation pattern. In the same period, the Volturno reach maintained conditions of greater stability, even if *broad-leaved forest* and *agricultural areas* increased further.

From 1997 to 2007, vegetation changes were relatively modest. Due to these further changes, in 2007 *open spaces* decreased to very modest percentages (between ca. 3.5 % and 7.4 %) and the most commonly occurring land cover within the Volturno and Biferno sites consisted of *broad-leaved forest* and *agricultural areas*, while *shrub and/or herbaceous vegetation* together with *roads and mine areas* clearly dominate along the Trigno reach. These data show that, over time, land cover changes in the Trigno study area are closely linked to human interventions on the fluvial system, in particular increasing gravel extraction. The reduction of *agricultural areas* from 1986 onwards allowed *shrub and/or herbaceous vegetation* to expand greatly and is associated to, and most probably caused by, very intense channel incision (ca. 4.5 m). By contrast, as shown by the Biferno and Volturno sites, expansion and persistence of *broad-leaved forest* and *agricultural areas* is associated to lower total rates of incision (≤1.5 m).

Present vegetation pattern

The principal coordinate analysis (PCoA) diagram (fig. 4a) shows the distribution of the 33 samples in the multivariate space where 40.74 % of the total variance is expressed by the two main axes of the diagram. Four main groups were identified according to their physiognomical features. The first axis separates the woody vegetation type (W) from herbaceous vegetation (G). The second axis separates the woody vegetation type into two subgroups: woodlands W_{SA} and W_{PN} in the lower side, and thicket and shrubland in the upper side (W_{TG}, W_{SP} and W_{SJ}). Furthermore, the second axis separates the *Arundo plinii* community (G_{AP}) from all other herbaceous communities.

The four groups of samples obtained by PCoA are confirmed by the cluster analysis dendrogram (fig. 4b). In particular, the *Arundo plinii* communities (G_{AP}), with respect to the rest of the grassland samples, form an isolated sub-cluster which is dynamically linked to the shrubland and thicket sub-clusters (W_{SJ}, W_{TG} and W_{SP}). Also the woodland communities (W_{SA} and W_{PN}) form an isolated sub-cluster, while the remaining grassland communities (G_g, G_{HI}, G_{PC}, G_{TL} G_{ER} and G_{SC}) are separated from all other sub-clusters.

Analysis of floristic richness related to grassland and woodland species shows that the Volturno reach, in relation to forest communities, exhibits significantly higher

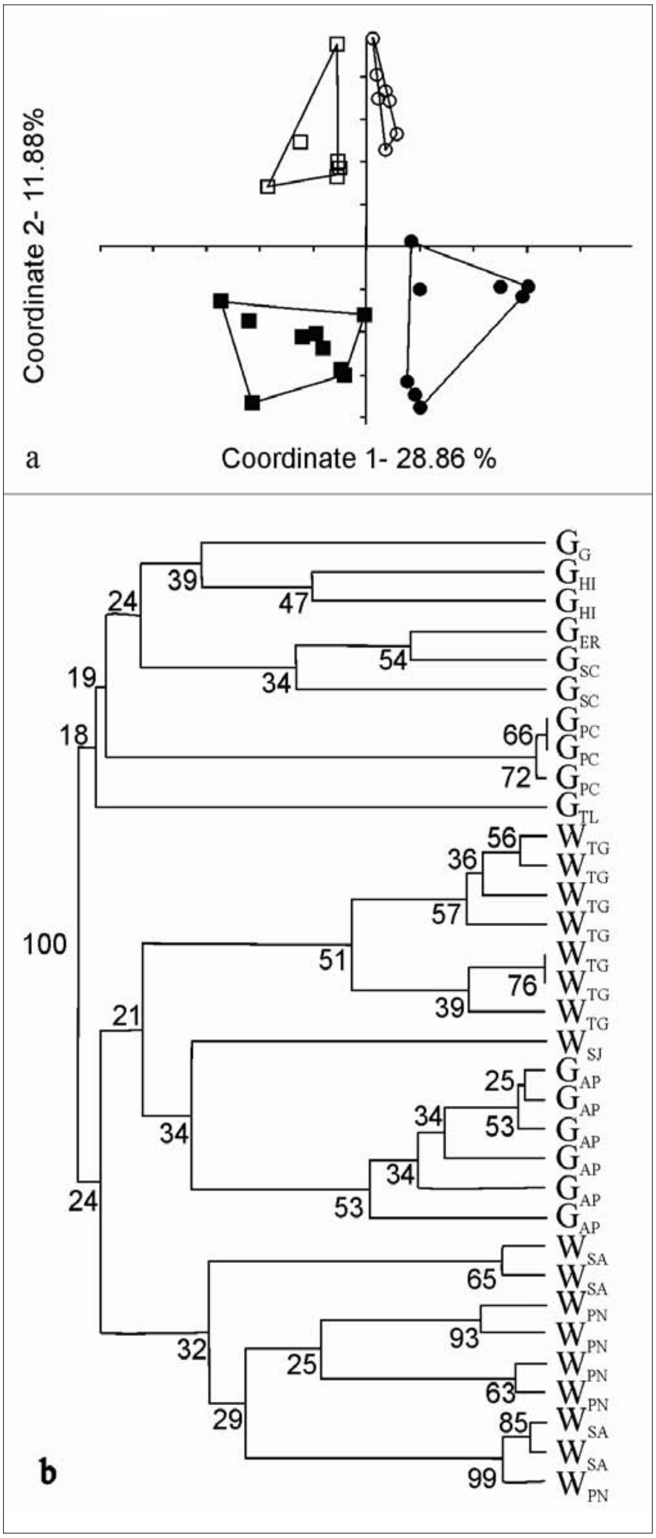


FIG. 4 - a) scatter plot showing the vegetation samples projected on PCo1 and PCo2; principal coordinate analysis (PCoA) was computed on the correlation matrix and the transformation exponent was c = 6. Woodland: ● W_{SA} and W_{PN}; ○ W_{TG}, W_{SP} and W_{SJ}. Grassland: □ grassland (G); ■ *Arundo plinii* community (G_{AP}). b) dendrogram obtained by cluster analysis computed on the correlation matrix using paired group as linkage; bootstrap was at 999 random permutations.

values than the other two reaches (fig. 5). Indeed, the Biferno reach shows little diversity of forest flora due to the presence of the exotic species *Amorpha fruticosa* that has replaced most of the herbaceous species of the woodland. The Trigno reach, instead, presents a high floristic richness of herbaceous communities which represent the predominant type of vegetation in this site.

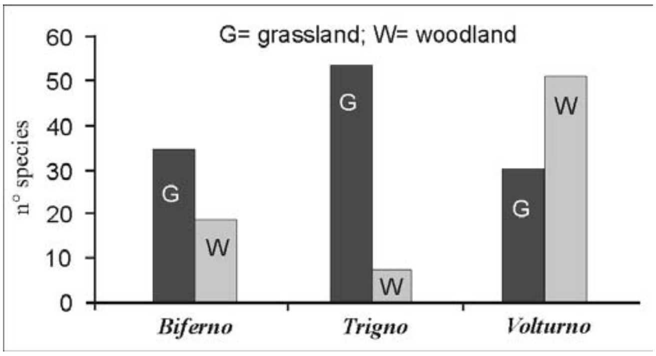


FIG. 5 - Species richness of main vegetation types recognised within the studied river reaches.

The distribution of plant communities in relation to geomorphic features

Analyzing the typology and distribution of plant communities in relation to fluvial geomorphic features along the seven constructed cross-sections (S1-S7, fig. 6, for location see fig. 2) allowed us to recognize 13 main vegetation community types (tab. 3) whose distribution appears clearly linked to morpho-topographic and hydrologic conditions.

The three sections present along the Volturno reach (S1-S3, fig. 2c) define a channel system with a longitudinal gradient of about 0.53 % which is flanked, alternatively, by the floodplain (S2, fig. 6) and the fourth-order terrace (T4, S1 and S3, fig. 6). The floodplain is located at +1.0-1.5 m above the water level established during conditions of intermediate flow discharges (hereinafter termed intermediate water level), which are relatively frequent during autumn and spring and sufficient to submerge at least partially the bars and activate the secondary channels (SC in fig. 6). Terrace T4 is located at +1.5-2.5 m above the intermediate water level (between +0.5-1.5 m above the bankfull stage), except for some low-lying zones (see S3, fig. 6) which are located within +1 m of height (slightly below the bankfull stage), but are separated from the channel and protected from flooding by higher zones.

Moving channelwards the typical vegetation sequence is represented by farmland, woodland, thicket and grassland. T3 exclusively supports farmland (S2 and S3, fig. 6), locally present also on T4 (S2, fig. 6), and typically represented by seasonal vegetable (tab. 3). The topographically higher sectors of the T4 terrace (S3, fig. 6), besides supporting woodland (W_{PN}), are dominated by shrubland and

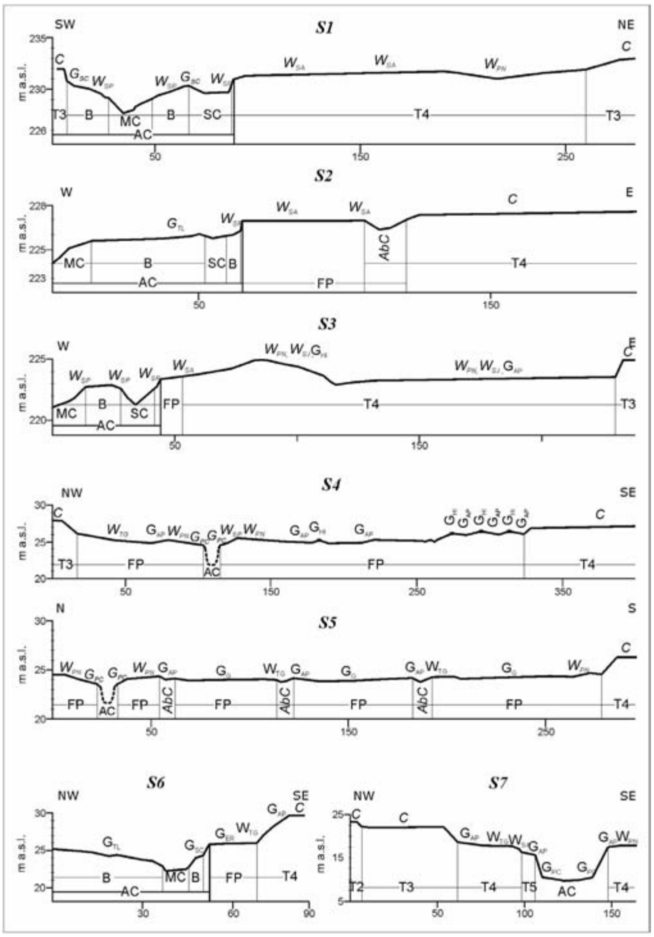


FIG. 6 - Cross-profiles (S1-S7) reconstructed within sites A, B and C. T1-T5 = alluvial terraces and relative order; FP = flood plain; AbC = abandoned channel; AC = active channel; B = bar; MC = main channel; SC = secondary channel. For the abbreviations used to indicate related plant communities see table 3.

dry grassland (W_{SJ} and G_{HI}, respectively, tab. 3), while the more external and depressed sectors (see S1 and S3, fig. 6) typically support woodland dominated by *Populus nigra* (W_{PN}), substituted channelwards by *Salix alba* and *Alnus glutinosa* communities (W_{SA}). Within the active channel, along the upper parts of the channel bank, herbaceous species (G_{SC}) develop. Surfaces and scarps of gravel bars are colonized by thicket dominated by *Salix purpurea* and *Salix eleagnos* (W_{SP}) and by helophytic grassland (G_{TL}), respectively.

The two sections S4 and S5 along the Biferno reach (fig. 2f) define an active channel system with a longitudinal gradient of about 0.43%. Only about 12 m wide, it is flanked by extensive floodplain areas bordered either by terraces T4 and T3. The floodplain areas are located at + 0.5-2.5 m above the intermediate water level (within + 2.0 m above the bankfull stage), while the T4 terrace is located at ≥ +2.5 m.

Terraces T3 and T4 support exclusively farmland. Large portions of the floodplain are covered by grazed mesophytic grassland (G_G, tab. 3) (S5, fig. 6). The topographically highest zones of the floodplain (S4, fig. 6), lying on gravel deposits, support dry grassland (G_{HI}), and include more depressed zones dominated by *Arundo plinii* grassland (G_{AP}). Along recently abandoned channels (S5, fig. 6) and in zones where gravels cropout, there is a hydrophilous thicket community formed mainly by *Tamarix africana, Salix purpurea* and *Salix triandra* community (W_{TG}). The innermost, low-lying parts of the floodplain and the upper edge of the channel banks typically support helophytic grassland vegetation dominated by *Phragmites australis* (G_{PC}).

The two sections within the Trigno reach (S6 and S7, fig. 2i) exhibit very distinct morphologic and vegetation features that accurately represent the two stream portions (hereinafter termed upper portion and lower portion, respectively) located upstream and downstream of the S. Salvo bridge, respectively, which were clearly separated until the bridge collapsed in 2003. Their intermediate water levels (24.5 m and 10.5 m a.s.l., respectively) define a very high longitudinal gradient of ca. 2.5%. In the upper portion, the active channel is chiefly limited by small discontinuous strips of floodplain and the T4 terrace, located at +1.5 m and +5 m above the intermediate water level, respectively. In the lower portion, the floodplain is completely lacking and the channel is directly confined by terraces T3 and T5. The latter is located at ca. +5.5 m above the intermediate water level, terraces T4 and T3 at ca. +6.5 m and +11.5 m, respectively.

Besides farmland (T2 and T3 and partially T4 (S6, fig. 6), the vegetation is chiefly represented by grassland communities. In the upper portion, the floodplain lies on thin sandy-gravelly deposits covering the clayey bedrock and supports pioneer hemicryptophytic vegetation (G_{ER}). Lower terraces (T4 and T5) and related scarps are, instead, dominated by mono-specific grassland dominated by *Arundo plinii* (G_{AP}) (fig. 6). In the upper portion, channel banks are sparsely covered by a mosaic of perennial and annual species forming open grassland communities (G_{SC}), while lateral, active bars support mainly helophytic grassland communities (G_{TL}). In the lower portion, the channel banks are characterised by tall helophytic grassland vegetation dominated by *Phragmites australis* (G_{PC}). Of importance is the presence on T5 (S7, fig. 6) of a small woodland community dominated by *Salix alba* (W_{SA}), which is normally typical of periodically flooded soils (tab. 3).

DISCUSSION

The major channel adjustments which we reconstructed have caused the abandonment of most of the channels active in 1954 and a severe reduction of the floodplain areas. Starting from the braided pattern which characterized in 1954 the valley sectors in which the study sites are located, there occurred a rapid transition to first transitional and then a sinuous pattern (the case of the Volturno and Biferno rivers), or directly to sinuous and then a straight pattern (Trigno River). Severe channel narrowing reduced

TABLE 3 - Physiognomical type, guide species, ecological description and abbreviation (Abb.) for plant communities present within the study sites. Hygrophytic = plants that thrive in wet or very moist ground; xerophytic = plants growing in an environment with little availability of water or moisture; mesophytic = plants growing in an environment with a moderate supply of water; helophytic = plants whose basal part is immersed in water

Physiognomic type	Guide species	Ecological description	Abb.
thicket	*Salix purpurea, Salix eleagnos, Solanum dulcamara*	phanerophytic vegetation (covering 70%) typical of channel scarps	W_{SP}
woodland	*Salix alba, Alnus glutinosa, Cucubalus baccifer, Humulus lupulus, Rubus caesius*	phanerophytic vegetation (covering 70%) typical of periodically flooded soils	W_{SA}
woodland	*Populus nigra, Salix alba, Populus alba, Cornus sanguinea, Brachypodium rupestre, Amorpha fruticosa*	phanerophytic vegetation (covering 90%) typical of surfaces with silty-sandy soils and superficial ground water tables	W_{PN}
thicket	*Tamarix africana, Salix purpurea, Populus nigra*	mixed phanerophytic vegetation (covering 70%) typical of gravel surfaces with superficial ground water level	W_{TG}
shrubland	*Spartium junceum, Emerus majus, Juniperus communis, Phyracantha coccinea*	xerophytic and mesophytic shrub (covering 80%) on terraced surfaces and dynamically not linked to hygrophytic vegetation	W_{SJ}
hemicriptophytic grassland	*Helycrisum italicum, Scabiosa columbaria, Fumana procumbens*	dry grassland (covering 50%) typical of thick gravel layers and dynamically not linked to hygrophytic vegetation	G_{HI}
pasture	*Dactylis glomerata, Foeniculum vulgare, Plantago lanceolata, Lolium perenne*	grazed mesophytic grassland (covering 100%) typical of deep silty soils	G_G
tall helophytic grassland	*Phragmites australis*	mono-specific herbaceous vegetation (covering 100%) typically located at the base of channel banks	G_{PC}
helophytic grassland	*Agrostis stolonifera, Veronica beccabunga, Scirpus holochoenus, Schoenoplectus tabernaemonti, Thypa latifolia, Persicaria hydropiper, Menta aquatica*	herbaceous vegetation (covering 80%) typical of bar surfaces	G_{TL}
tall grassland	*Arundo plinii, Dorycnium rectum, Equisteum arvense*	mono-specific herbaceous vegetation (covering 100%) typical of surfaces with silty soils	G_{AP}
hemicriptophytic grassland	*Scrophularia canina, Elymus repens, Dittrichia viscosa, Phragmites australis*	pioneer perennial grassland (covering 90%), typical of gravel layers on clayey substratum	G_{ER}
open grassland	*Dittrichia viscosa, Elymus repens, Echinochloa crus-galli, Phalarys brachystachis*	sparse mosaic of perennial and annual herbaceous species (covering 20%) typical of bar surfaces	G_{SC}
farmland	Seasonal vegetable *Solanum* sp., *Foeniculum* sp.	intensively cultivated areas typical of terraced surfaces	C

channels to between ca. 3% and 15% of their original widths, while river incision caused a moderate to very intense channel lowering of between 2 and 10.5 m.

Due to these adjustments, the riparian vegetation, thanks to specific plant-adaptive strategies (synecology), progressively developed and differentiated under the integrated control of local fluvial dynamics, related physical conditions and human interventions on the system. Diachronic analysis shows that the riparian areas underwent rapid changes and that the riparian vegetation adapted fairly rapidly, as evidenced for example by the fact that woody vegetation on bars formed within only 15-20 years. The examined river reaches largely succeeded in maintaining or generating the zonation of riparian vegetation typically found in river systems in central Italy (Pedrotti, 1996; Spada & Casella, 2007; Pirone & *alii*, 2009).

The distribution pattern of the current vegetation is related specifically to different fluvial features. In particular, cultivated areas (C, fig. 7a) are restricted to terrace surfaces which also support woodland and grassland communities. By contrast, floodplains, bars and channel banks show a more or less clear dominance of grassland communities (fig. 7a).

With reference to the distribution of individual communities (fig. 7b), our analysis showed that woodland and thicket communities W_{SA}, W_{PN} and W_{TG}, only occur on floodplains and terraces. Typical of the channel systems is the thicket community dominated by *Salix purpurea* and *Salix eleagnos* (W_{SP}), the helophytic grassland communities G_{SC} and G_{TL} that colonize bar surfaces, and the tall helophytic grassland vegetation dominated by *Phragmites australis* (G_{PC}) present along channel banks and scarps. The grassland communities G_{AP} and G_{HI} are found both on floodplains and terraced surfaces but in the opposite edaphic conditions: mesic the former, xeric the latter. These two communities are not strictly linked to the river ecosystem and frequently represent secondary substitution communities of the riparian forest as emerges from the Biferno site (sections S3 and S4, fig. 6). Here, the higher zones of the floodplain support dry grassland (G_{HI}), pioneer vegetation which easily adapts to marked conditions of soil aridity, while the more low-lying, wetter zones are dominated by *Arundo plinii* grassland (G_{AP}) or *Populus nigra* woodland (W_{PN}).

The observed vegetation dynamics also show distinct evolutionary trends for the three examined river reaches: the Volturno site presents the best developed zonation of ripari-

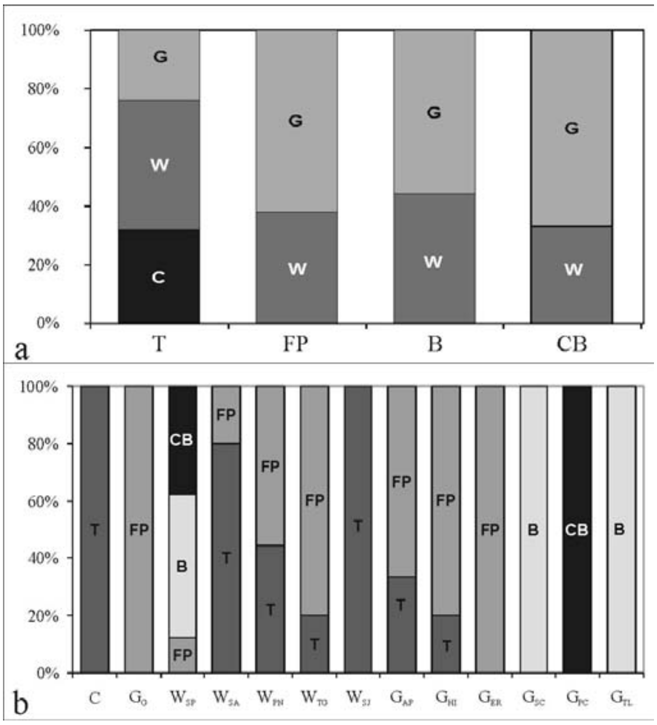


FIG. 7 - Distribution of main vegetation types (a) and plant communities (b) in relation to geomorphic features. G = grassland, W = woodland, C = cultivated area, T = terrace, FP = floodplain, B = bar, CB = channel bank. For the abbreviations used to indicate plant communities see table 3.

an vegetation and the highest floristic diversity. The zonation of riparian vegetation and, in particular, the expansion and persistence of woodland seem to be favoured by the physiographic and climatic conditions and the low human disturbance, and controlled by the smaller amount of channel incision and the consequent better hydrological connectivity between the channel and floodplain system. Nonetheless, large parts of *Salix alba* forest present on the lowest terrace (T4) show conditions of non-equilibrium with the existing hydrodynamic condition. The forest is still in a good state of preservation thanks to its resilience to disturbance, but is destined to evolve from hygrophytic to meso-hygrophytic woodland with elements such as *Populus nigra* advancing towards the river. From the floristic data reported for the middle Volturno valley (Mingione & *alii*, 2004) there emerges a high reduction and fragmentation of the present-day riparian vegetation, also rich in neophytic species, due to extensive urbanization and river regulation. The comparison of the two sectors shows that the riparian zones in the studied upper sector of the Volturno valley are much better preserved than those present in the middle one.

The Biferno and Trigno sites, more affected by river regulation, flood control works and gravel extraction than the Volturno site, have experienced a greater reduction in their floodplains and more intense channel incision which has caused *open spaces* to be more subjected to human interventions. The land cover evolution of the Trigno site, especially, appears strongly controlled by gravel extraction and very intense channel lowering. The reduction of *agricultural areas* from 1986 onwards, in particular, is most probably caused by the persistence of very intense channel incision (up to 4.5 m), allowing *shrub and/or herbaceous vegetation* to expand greatly. In the case of the Biferno site, lower overall rates of incision (< 4 m) seem to have favoured the establishment of hydro-morphological conditions that allowed the persistence of *agricultural areas*.

Accordingly, the Trigno and Biferno sites are less species-rich, and are especially poor in woody species. The rapidity of channel lowering is particularly evident in the Trigno site, where the presence of sporadic *Salix alba* on terrace T5 is interpreted as a vegetation relict of recently abandoned floodplain areas and testifies to the considerable, rapid incision that has occurred during the last twenty years alone. The instability of the channel banks is evidenced by the exclusive presence of the *Phragmites australis* community, a pioneer and very competitive species, typical of a temporarily flooded oxygen-poor habitat, which is indicative of active erosion affecting the channel banks and of consequent soil and debris accumulation greatly favouring the development of this community.

Furthermore, the great spread of human activities in the lower Trigno and Biferno valleys has caused the arrival of neophytic species as *Robinia pseudoacacia*, *Amorpha fruticosa*, *Artemisia verlotiorum* and *Arundo donax* which are common in human-impacted areas and in abandoned agricultural areas where they rapidly expand and supplant the native flora. On the contrary, these species seem to be unable to successfully invade intact native vegetation (Lohmeyer & Sukopp, 1992), thereby underlining the importance of maintaining natural conditions.

Comparing the evolutionary trends reconstructed for the Volturno, Trigno and Biferno rivers with those of other Italian rivers, our study agrees with the findings obtained for the Tuscan rivers (Hupp & Rinaldi, 2007), showing that the pattern of riparian vegetation even along human-altered streams are indicative of present and ongoing fluvial forms and processes, while reflecting stages of channel evolution and related rates of channel incision and narrowing. In the specific case of the Volturno site, the current riparian vegetation features show that, thanks to moderate channel incision, a relative good level of hydrological connectivity between the channel and floodplain system is preserved.

The present-day morpho-dynamic contexts of the examined river sections suggest that they are unlikely to change significantly in the short term if human activities persist along them, especially in relation to a possible inversion of their recent evolutionary trends.

CONCLUSIONS

The present study is the first to illustrate for southern Italy the relation between the recent evolution of once braided river systems and that of associated riparian zones and vegetation features. It highlights in particular:

- a direct rapid link between the rate of channel incision, the related lowering of the water table and the distribution of riparian vegetation communities, according to the findings obtained on Tuscan rivers (Hupp & Rinaldi, 2007). Both the strong reduction of floodplain areas and the progressively decreasing availability of groundwater have severely limited the potential transverse expansion of the riparian woodland of *Salix alba* and *Alnus glutinosa* which is considered the most important element in river corridors at the ecosystem level;
- no major, albeit temporary, inversion of the observed evolutionary trend (i.e. channel widening and/or aggradation) could be highlighted; especially in the cases of the Biferno and Trigno rivers, such a trend inversion, taking present-day human impact into account, is prevented by the persistence of such conditions affecting the river systems;
- in the lower sectors of the Biferno and Trigno, due to the intense-to-very-intense channel lowering they have experienced, there is relative low mobility of the channel system and scarce hydrological connectivity between the channel and the adjacent, strongly reduced floodplain areas. River restoration goals must therefore take careful account of current hydrological conditions which are closely controlled by permanent flow regulation interventions (damming and relevant permanent water withdrawals, respectively), largely preventing flow and flood pulse events (Tockner & *alii*, 2000) which are fundamental for the ecological integrity of the river-floodplain system (Heller & *alii*, 1995).
- riparian forests with a high degree of naturalness are reduced to a few edges which are best preserved along the Volturno river and represent a reference model of great importance for large temperate rivers in central-southern Italy both from a scientific and ecological point of view. The preservation and monitoring of such riparian systems, supported by the establishment of protected areas preventing further human activity and hence favouring the maintenance of naturalness, would be advisable, also in order to collect useful data for the purposes of environmental restoration and sustainable river management.

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