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CARBON SEQUESTRATION AND HABITAT RECONSTRUCTION ON RIVERBANK CONSOLIDATION WORKS BY MEANS OF BIOENGINEERING TECHNIQUES WITH WIRE MESH STRUCTURES*

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Abstract

Carbon sequestration, combined with an increasing attention for environment, as stated in different EU Directives (WFD, Flood Directive, Habitat directive) and EU Policies (Green Infrastructure and Biodiversity), is a leading argument for technicians involved in river management. The study's purpose was the evaluation of carbon sequestration and habitat reconstruction by means of bioengineering techniques on wire mesh hydraulic structures. A set of seven Italian case studies with different geographical and climatological locations and various construction typologies was selected for the estimation. In particular, green reinforced earths, bank protections mattresses and gabion dams and walls were analyzed. A standard field survey was conducted on every location in order to measure dendrometric parameters of arboreal and shrubby vegetation and to calculate an estimate for biomass through empirical correlation formulas; phytosociology of present vegetation was analyzed in order to characterize biodiversity and to obtain habitat reconstruction results. The total CO_2 sequestration amount was derived from fresh and dry weight calculated from biomass together with the annual CO_2 sequestration rate pro unit area. Values obtained were consistent with the estimates made for natural woodland vegetation. Higher values of the total CO_2 stored amount were found among older works, or where the study area already presented previous natural vegetation. Some of the study areas previously described are going to be investigated by the new Environmental Quality Assessment (EQA) methodology developed within the EU-project (FESR South Tyrol) WEQUAL, based on ecological indicators derived from LiDAR data, RGB and multispectral images collected by drone surveys. Biomass, canopy cover, vegetation height/distribution/continuity, river morphology and riparian zone width are examined in order to evaluate habitat sustainability, biodiversity, landscape connectivity and carbon sequestration capacity. The WEQUAL EQA aims to support technicians and administrators in

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evaluating hydraulics works impacts ex-ante and ex-post, providing an easy and time-cost-effective instrument.

Keywords: carbon sequestration, gabions, habitat reconstruction, mattresses, reinforced earth

1. Introduction

Riparian vegetation plays a major role in defining river ecological functionality and environmental quality. This awareness, as stated in different European and national directives and laws, enhance the importance of evaluating environmental impacts of river training works. Riparian vegetation growth, its carbon sequestration capability, and habitat reconstruction on hydraulic works are useful elements to assess the ecological value of each technical solution and can be used as easy understandable indicators by technicians – hydraulic engineers, ecologists, landscape architects- and administrators involved in river management. The paper's aim is to illustrate carbon sequestration, seen as proxy of vegetation resilience, and habitat reconstruction capability by means of bioengineering techniques combining wire mesh products with plantation of cuttings and native plants. The research, commissioned by the company Maccaferri, has been conducted on fourteen different wire mesh structures along riverbanks, streets and mining slopes (Sauli, 2014). The analyzed works have different ages and are set in various climatological locations in Northern and Central Italy. In this paper, it will be discussed the results of vegetation development related to hydraulic works. Some of these will be used as calibration sites for the new Environmental Quality Assessment (EQA) methodology, developed within the EU-project (FESR South-Tyrol) WEQUAL - WEb service centre for a QUALity multidimensional design and tele-operated monitoring of Green Infrastructures - with the purpose of supporting designers, administrators and other stakeholders in evaluating hydraulics works impacts in an easy and cost effective way. The EQA is based on ecological indicators derived by drone collected LiDAR data, RGB and multispectral images, and on a forecasting method which relies on previously collected data. Biomass, canopy cover, vegetation height/distribution/continuity, river morphology and riparian zone width – current and potential - are examined in order to evaluate habitat sustainability, biodiversity, landscape connectivity and carbon sequestration capacity.

2. Case studies

A set of seven case studies has been selected among various double twisted wire mesh hydraulics works located at different heights and climatological Italian zones. Structures, aged between 15 and 50+ years, were constructed by means of different bioengineering techniques. In particular, vegetation growth, habitat reconstruction and carbon sequestration on green reinforced earths, bank protection green mattresses and green gabions have been analyzed in every site. Present vegetation typologies have been identified through phytosociological surveys. The major features of the seven case studies are presented in Table 1.

3. Materials and method

In order to determine the carbon sequestration and habitat reconstruction capability on double twisted wire mesh works, field analysis have been conducted on every study-site location. Through dendrometric surveys, humidity rate of single sample determination and phytosociological identification, it has been possible to obtain an estimate of biomass volume and, as a consequence, carbon sequestration of on-site grown vegetation. For every study site a vegetated sample area (SA) has been defined (Table 1), marked and localized via GPS; location and survey characteristics (id location, place, date, surveyor, GPS coordinates, works typology and structure age) have been collected and a field-form has been filled.

Table 1. Case studies description

Site (n.,name, province)	***Bioengineering technique with wire mesh structures***	***Works description***	***Fitogeographic features***	***Year***	***sample area SA[m²]***
1a -Fella river (UD)	Green reinforced earth	Reinforced concrete channeling dismantling; realisation of river bank protections using combined bio-engineering techniques – green reinforced earths and mattresses with willow cuttings; bed river morphologic rearrangement	Decidous termophilic and mesophilic forests (*Ostrya caroinifolia, Fraxinus ornus, Carpinus Betulus*) River vegetation typically composed by *Salix eleagnos*, *Pinus sylvestris* and *Alnus incana*	1999	3
1b - Fella river (UD)	Bank protection green mattresses				6
2 - Rivoli Bianchi (UD)	Green gabion dam	Double twisted wire mesh gabion dam with cuttings is the most important work; a green reinforced earth and a mattress are also present.	Decidous termophilic (*Ostrya caroinifolia, Fraxinus ornus, Carpinus Betulus*), mesophilic forests (*Fagus sylvatica; acer pseudoplatanus*) and pinewoods (*Pinus nigra*). River vegetation typically composed by*Salix eleagnos, Pinus sylvestris* and *Alnus incana*	1999	6
3 -Rio Valleluce (FR)	Green gabion walls	Double twisted wire mesh gabion walls with rooting of different willow cuttings (*Salix Alba, Salix eleagnos, Salix purpurea*)	Heterogeneous forests: hophornbeem, oak forests and holm oak woods on carbonate substrates; turkey-oak woods and chestnut groves are present where water availability is higher	2000	360
4 - Rio Mutino (FR)	Green gabion walls	Double twisted wire mesh gabion walls with willow cuttings	Mixed woods with dominance of *Fraxinus ornus* and *Ostrya Carpinifolia*, *Quercus cerris* or termophillic oak woods (*Quercus pubescens*)	1999	35
5 - Arno River (AR)	Gabion walls	Gabion walls; riverbank consolidation,	Thermophillic decidous broadleaves forest, where *Quercus*	1955	600

		height=2 m, length=200 m ca	*pubescens* dominates		
6 - Alento River (PE)	Green mattresses; riverbed protection with gabions	Riverbank protection with mattresses; rooting of willow cuttings; riverbed protection with gabions. Hydraulic work total length: ca 200 m	Quercus pubescens woods; pensinular hygrophilous riparial vegetation	1984	1160
7 - Foro river (PE)	Bank protection green mattresses; riverbed protection with green gabions	Riverbank protection with mattresses; rooting of willow cuttings; riverbed protection with gabions. Hydraulic work total length: ca 200 m	Quercus pubescens woods; pensinular hygrophilous riparial vegetation	1982 1983	400

Present vegetation on SA has been identified through phytosociological survey (Braun-Blanquet, 1928, 1964), in order to obtain the maximum possible level of recognition, distinguishing variety or subspecies and to find both coverage and abundance according to the levels proposed by (Braun-Blanquet, 1928) and (Pignatti, 1982) for every recognized group. The following dendrometric parameters have been collected: trees and shrubs individuals number count; shoots count for every single plant; average height for every surveyed specie measured with hypsometer and through direct sampling on individuals which had been cut for being weighted; single specie shrub-like diameter (maximum diameter and its orthogonal) measured with caliber 10 cm over the ground; single arboreal specie diameter (maximum diameter and its orthogonal) measured with a measuring tape 1.3 m ca over the ground. Some samples of willows (*Salix eleagnos*) have been collected for humidity level analysis. All samples, 10 cm long and with diameter between 2 and 4.5 cm, have been conserved in PVC sealed bags in order to maintain their original humidity and sent to a specialized laboratory (Fantoni S.p.A.), where dry weight has been determined trough a controlled drying process.

Collected dendrometric measures have been used to calculate volume and weight for vegetation on every SA; volume estimation has been calculated with the Dendrometric Tables published by the region Emilia-Romagna (Servizio Paesaggio, 2000). Trunk volume [dm^3] is related to trunk diameter at breast height d [cm] and tree height h [m] through the quadratic formula reported in Eq. (1).

$$V = b_o + b_1(d^2 h) + b_2 d \qquad (1)$$

where: b_0, b_1 and b_2 are numeric coefficients estimated trough regression analysis for different species, as reported in Table 2.

Shrubs grown on bioengineering work structures do not generally fit limits on trunk diameter and tree height reported in Table 2, as they normally show a reduced cormometric growth and trunk diameter in general inferior to 5 cm. For this reason, their volume estimation has been done through the generic function (Eq. 2).

$$v = \frac{\frac{\pi}{4}\left(\frac{d}{100}\right)^2}{2} \cdot 10001 \qquad (2)$$

Table 2. Volume estimate equations for different vegetal species – among other broadleaved trees maples, elms, ashes, willows and poplars are considered

Specie	*d min [cm]*	*d max [cm]*	*h min [m]*	*h max [m]*	*Volume estimation function*
Spruce	8	55	6	30	$2.7043 + 0.0361 d^2 h$
Pine	5	45	6	24	$4.3739 + 3.6956 * 10^{-2} * d^2 h$
Hornbeam	5	40	4	20	$-2.1632 + 3.1843 * 10^{-2} * d^2 h + 0.9844 d$
Chestnut	5	55	4	22	$2.7549 + 3.5766 * 10^{-2} * d^2 h$
Turkey oak	5	60	4	24	$4.0462 + 3.3584 * 10^{-2} * d^2 h$
Beech	5	50	4	28	$2.7296 + 3.4917 * 10^{-2} * d^2 h$
Downy oak	5	50	4	24	$4.0929 + 3.4862 * 10^{-2} * d^2 h$
Other broadleaved trees	5	55	6	30	$-1.0733 + 3.2504 * 10^{-2} * d^2 h + 0.5807 d$

For each individual, estimated volume has been used to calculate fresh and dry weight according to specific weights derived from literature and from humidity level estimation done on willow samples. Carbon sequestration for tree and shrub stands on every SA has been calculated taking into account dry weight for each individual and Eq. (3):

$$1g \text{ dry plant tissue} = 0.42gC = 1.54gCO_2 \qquad (3)$$

The total amount of sequestrated CO_2 in every SA has been divided by the work age in order to obtain the yearly carbon sequestration rate expressed in ton ha^{-1} yr^{-1}. An estimate for carbon sequestration by root systems and soil has been conducted as well. Carbon sequestration estimate in root systems has been done considering the shoot/root growth ratio. It has been demonstrated (Brouwer, 1963) that this value depends on plant age and can be heavily modified by different factors, such as defoliation. Nevertheless, for our study aims, constant values (Pearsall, 1927) for deciduous trees, as reported by (Klepper, 1991) can be assumed. Carbon sequestration on technogenic soils has been derived from values obtained by Coehlo et al. (Carbon sequestration in Slopes Revegetated with Bioengineering Techniques, 2010) on road embankments after 10 years, where graminaceous and fabaceous seeds were used.

A simplified ecological index has been calculated for every site, taking into account riparian zone width, transversal and longitudinal continuity, arboreal and shrubby coverage (APAT, 2007), in order to classify ecological level reached by vegetation communities grown on wire mesh structures.

4. Results and discussion

4.1. Carbon sequestration

Carbon sequestration values for every SA are presented in Table 3. Carbon sequestration low value calculated for SA 3 is due to very permeable soil and to southern exposure, which determines xerophilous conditions, and as a consequence, lower arboreal and shrubby coverage. The very high value observed for SA 6 can be explained as a result of the previous presence of vegetation on the surveyed area. Average carbon sequestration rate, calculated with exception of SA3 and SA6 (which can be reasonably considered as outliers), is 6.93 ton $CO_2 ha^{-1} yr^{-1}$. This rate is comparable to the average values for high forest and coppice proposed by (Manes, 1993), which are respectively 6.47 ton $CO_2 ha^{-1} yr^{-1}$ and 6.35 ton $CO_2 ha^{-1} yr^{-1}$.

Carbon sequestration of vegetation grown on wire mesh structures can be considered as an important environmental feature of these bioengineering works. Carbon sequestration annual rates calculated for the different double twisted wire mesh products are shown in Table 4. The results are obtained by considering all the study cases taken into consideration in the research.

Table 3. Carbon sequestration rates for analyzed case studies

SA	**Wire mesh structure tipology**	**Carbon sequestration rate - vegetation [tonCO_2ha^{-1}yr^{-1}]**	**Carbon sequestration rate - root system [tonCO_2ha^{-1}yr^{-1}]**	**Carbon sequestration rate - soil [tonCO_2ha^{-1}yr^{-1}]**	**Carbon sequestration rate - total [tonCO_2ha^{-1}yr^{-1}]**
1a	Green reinforced earth	7.48	2.26	7.85	17.59
1b	Bank protection green mattresses	4.91	1.48	7.85	14.24
2	Green gabion dam	2.62	0.79	7.85	11.26
3	Green gabion walls	7.57	2.29	7.85	17.71
4	Green gabion walls	7.11	2.15	7.85	17.11
5	Gabion walls	7.58	2.29	7.85	17.72
6	Bank protection green mattresses and green gabions wall	12.24	3.69	7.85	23.78
7	Bank protection green mattresses and green gabions wall	6.95	2.10	7.85	16.90

Table 4. Carbon sequestration for different wire mesh structures

Product	***Carbon sequestration rates***			
	Stand vegetation [ton CO_2ha^{-1}]	***Root system [ton CO_2ha^{-1}]***	***Soil [ton CO_2ha^{-1}]***	***Total [ton CO_2ha^{-1}]***
Green reinforced earth Terramesh	97.30	29.34	78.50	205.14
Green mattresses	95.10	29.34	78.50	202.94
Green gabions	216.9	65.45	78.50	360.85

4.2. Habitat reconstruction

Table 5 presents a short description of ecological survey results. Developed vegetation after a considerable amount of years demonstrated, in most cases, satisfying ecological levels and a remarkable habitat reconstruction capability.

Table 5. Estimated ecological level

Place	***Bioengineering technique with wire mesh structures***	***Vegetation (P = Planted S = Spontaneous growth)***	***Structure age (years)***	***Estimated ecological level (0÷5)***	***Vegetation present on site***
1a -Fella river (UD)	Green reinforced earth	P	18	5	Coetanous willows (*Salix eleagno, S. alba, S. purpurea*)
1b - Fella river (UD)	Bank protection green mattresses	P	18	5	Willows (*Salix eleagno*, *Salix purpurea*)
2 - Rivoli Bianchi (UD)	Green gabion dam	P	18	2	Coetanoeous willows (*Salix eleagnos* and *Salix purpurea*)
3 -Rio Valleluce (FR)	Green gabion walls	P	17	2	Monospeficic composition (*Salix alba* with *S. Purpurea*); sparse undergrowth with Hedera and Rubus.
4 - Rio Mutino (FR)	Green gabion walls	P	18	3	Multiplane vegetation dominated by uneven aged willows (Salix alba, Salix purpurea)
5 - Arno River (AR)	Gabion walls	S	62	3	Multiplane vegetation with uneven aged individuals dominated by *Salix alba*.
6 - Alento River (PE)	Bank protection green mattresses and green gabion wall	P	33	4	Multiplane vegetation with uneven aged individuals dominated by *Salix alba* and *Populus alba*.
7 - Foro river (PE)	Bank protection green mattresses and green gabion wall	S	34	4	Multiplane vegetation with uneven aged individuals , dominated by *Salix alba* and *Populus alba*

High ecological levels have been reached on the following rivers:

a) Fella river, which was initially characterized by a high number of native species (over 200), presents after 18 years a dense shrubs coverage, mostly composed by four willows species;

b) Alento river and Foro river, where multiplane vegetation with uneven aged individuals is present.

Satisfying levels have been reached on SA 3 and SA 5; only SA 2 shows a lower level due to gravel substrate with very high permeability.

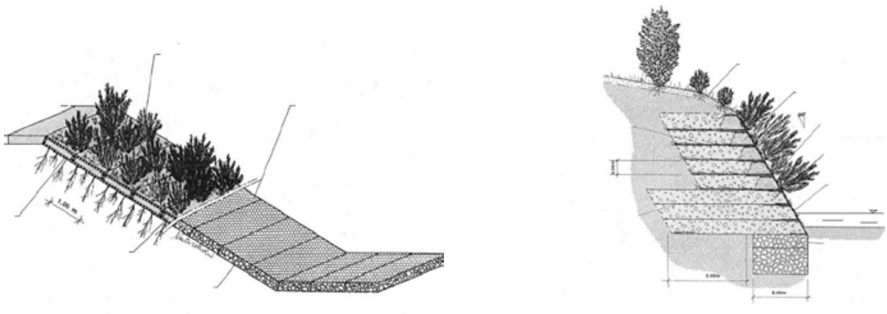
4.2. Future work

Analyses have been conducted through standard field operations by several different specialists in ecology and botany. Monitoring the environment development on river training works is useful to understand their impacts, in order to prefer, when possible, greener solutions. In order to simplify these analysis, that could be time and cost expensive, a new environment quality assessment (EQA) procedure is under elaboration within the EU project (FESR South-Tyrol) WEQUAL. The aim of the project is to develop a new evaluation methodology based on automatic elaboration of drone collected data (LiDAR, RGB and multispectral ortophotos), which allows to estimate biomass, carbon sequestration, habitat availability and ecological functionality of riparian zones ex post to river training works realization. Carbon sequestration data presented will be used to calibrate the new automatic evaluation methodology. Ex ante assessments of environmental impacts of different design alternatives are possible as well, thanks to a forecasting method based, among other, on previously collected data. Analysis on carbon sequestration capability of vegetation grown on different works typology will be used for the estimation.

Carbon sequestration capability of vegetation grown on wire mesh structure is strongly related to its resilience; these factors, together with the remarkable ecologic value of reconstructed habitat, should be taken into account during river training works design stages, in order to enhance greener and environmentally friendly solutions.

Fig. 1. Green reinforced earth Terramesh, 2000

Fig. 2. Fella river confluence with the Saisera river; bank protection mattresses are visible, 2000



(a) (b)

Fig. 3. Fella river works project; bank protection green mattresses and green reinforced earth combined with willow cuttings

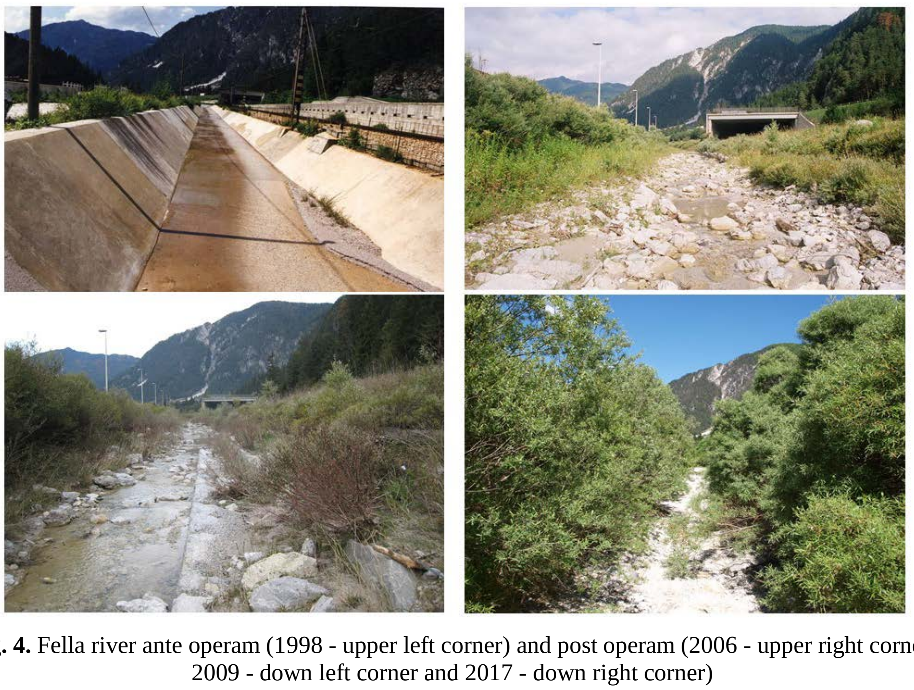


Fig. 4. Fella river ante operam (1998 - upper left corner) and post operam (2006 - upper right corner, 2009 - down left corner and 2017 - down right corner)

5. Conclusions

Our research on hydraulic works demonstrated that carbon sequestration of vegetation, grown both spontaneous and planted, on wire mesh structures (gabions, mattresses and reinforced earth) has comparable values to the high forest and coppice ones. The ecological levels reached are remarkable, demonstrating the high resilience of vegetation on wire mesh structures and, as a consequence, the environmental value of this kind of bioengineering techniques.

The analyzed study cases will be used for calibrating the currently under development WEQUAL methodology, which aims to elaborate an innovative and user-friendly method that allows cost-effective environmental quality assessment on rivers and green infrastructures. The collected data and the results derived from this analysis will be used within the WEQUAL methodology also as database in a forecasting method. This will help river training works designers in assessing environmental impacts of their solutions and selecting the design alternative which reaches the best habitat implementation and biodiversity reconstruction.

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