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Innovative management and multifunctional utilization of traditional coppice forests - an answer to future ecological, economic and social challenges in the European forestry sector (EuroCoppice)

STSM REPORT

STSM Reference number 29704

STSM title: "Hydraulic flow resistance and elastic behaviour of coppice in river beds"

Host Institution: Norwegian university of science and technology, NTNU NO-7491,Trondheim-Norway

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Introduction

The interaction between flow and vegetation is presently one of the most challenging aspects of civil and environmental research. In the past, vegetation was considered an unwanted source for flow resistance and, for this reason, it was often removed from watercourses to improve the conveyance capacity of streams. Due the rising environmental awareness of the society, vegetation is nowadays regarded as a means for soft engineering practices to stabilize banks and channels, improving habitat, and it is also important for providing a pleasing landscape for recreational use. Thus, the sustainable management of vegetation has great relevance for the ecology of all water systems.

However, vegetation has still significant effects on water flow: the significance of these effects depend on vegetation characteristics such as height, density, distribution, stiffness and type of vegetation. i) it decreases the water velocity and raises the water levels resulting in a reduction of the conveyance capacity which in turn has a significant effect on flood safety; ii) it triggers deposition of suspended sediments but can at the same time in- or decrease erosion dependent on local boundary conditions; and iii) it interferes with the use of streams for navigation, recreation, fishing etc.

Focusing on riparian vegetation, vegetation can also have positive effects. In fact, floodplain trees help to control the momentum exchange between the main river channel and the floodplains, and it affects the exchange processes between surface and ground water flow. For example, infiltration rates in a well-wooded buffer strip have been reported to be over 60 times greater than those sheep in grazier fields(Heede, 1990; Akora, 2003). Furthermore, vegetation helps to control excessive run-off (as can be, for example, observed from sealed surfaces) provides a barrier of high ecological value between the water (river, streams, and estuaries) and the floodplains. With regard to coppicing practice is it well known that vegetation controls excessive shading without loss of stability from root system and produces sustainable yield of timber. One of the aim of riparian coppicing is, besides flood safety, to increase the amount of light promoting the natural regrowth of bankside plants and therefore allowing the river to reform at its natural width (see Fig. 1)

Fig. 1 The structure at the Danube at Fundu Mare Island (Romania) during low flow conditions in the Danube

Fig.2 Increasing of water depth impacting vegetation in river banks

The significance of the interaction between riparian vegetation and flow for the morphodynamic development of river systems has recently been highlighted in the literature. Plants can significantly influence morphodynamic processes by colonizing inundated alluvial sediments and stabilizing sediments to build pioneer landforms (Gurnell, 2014). However, the proper understanding of the morphodynamic processes triggered by vegetation requires the understanding how vegetation alters the flow field and in turn how the flow field affects vegetation growth. The adequate determination of this interaction is problematic as the plants' hydrodynamic effects depend on their flexibility, biomechanical properties and foliage. Thus, standard approaches for the determination of hydraulic roughness by considering vegetation elements as rigid elements (typically cylinders) are not valid and novel approaches are required to consider vegetation characteristics to adequately determine their effect on the flow (Nikora 2010, Stone et. al 2011, Aberle and Jarvela, 2013, Whittaker et.al, 2013, 2015)

In this context, the practice to coppice riparian vegetation along river banks changes the tree structure (i.e., height of the plant, shape of the branches, etc.). Such changes can significantly affect the "river flow" process but also the ecological value of the vegetation. Hence such practices should be designed within a multidisciplinary approach between geomorphologists, hydraulic engineers, and ecologists, in order to improve the actual management practice of traditional coppice forests.

This STSM action approaches the outlined problem from an hydraulic point of view. It specifically addresses how coppicing affects flow resistance of riparian vegetation in order to develop an adequate tool for the engineering community not only to calculate hydraulic roughness but also to better understand the hydraulic process at the river scale. Furthermore it addresses the significance how the flexure rigidity of the plant (i.e, EI product of product of E=Young Elasticity Module and I=inertia momentum) affect the flow resistance).

STSM purpose

The principal aim of this mission was to investigate the behaviour of riparian vegetation under hydraulic loads taking recent scientific developments into account. In particular, it is addressed how the drag force exerted by submerged and foliated riparian plants changes due the plants' flexibility and hence how flow resistance of flexible plants can be taken into account when evaluating the consequences of coppicing practice. This traditional method of woodland management affects the flow resistance of exerted by vegetation by changing the shape of the plants. The report highlights the difference between hydraulic roughness of "normal" trees and coppiced ones, and how this difference influences the hydraulic system. This difference is pointed out for vegetation of different height in order to cover all the plant's coppicing phases (by immediately before coppicing up to final growth of the trunk). For this purpose, the plants' flexibility is considered by calculating the bending of the vegetation in order to better understand the reconfiguration of plants under hydrodynamic loads. The focus of the STSM-action is on the hydraulic behaviour of a typical Mediterranean riparian plant due to its common presence along river banks , i.e. *Poplus Nigra*.

State of Art and Methods

The hydraulic processes in vegetated rivers are affected by the hydraulic drag force acting on the vegetation elements which has been classically formulated according to (Douglas et al, 2005)

$$F_D = \frac{1}{2}\rho C_D A_p V^2 \tag{1}$$

where C_D is the dimensionless drag coefficient, A_p is the frontal projected area of the vegetation element, ρ is water density and V is flow velocity (Fig.3).

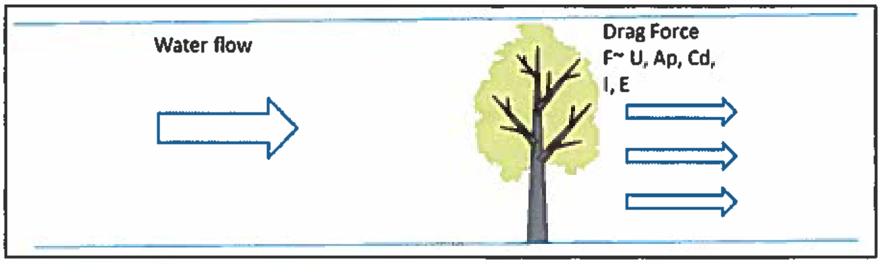
In contrast to rigid bodies, where C_D is a function of the Reynolds-number and A_p is constant for one and the same water depth, flexible plants change their shape as a function of flow attack when the resistance forces of the plant are exceeded by the hydrodynamic forces resulting in both a change in C_D and A_p. This has been expressed in the literature in form of a proportionality ($F_D \propto V^{2+\square}$; where □ denotes the Vogel-exponent), i.e. the force – velocity proportionality for flexible elements tends deviates from the quadratic relationship due to the reconfiguration of the plants shape. This hampers the calculation of the drag force for changing hydrodynamic conditions. However, a recently developed approach addressed this issue and its applicability will be testes in this study. This approach is based on the "Vegetative Cauchy number" (Luhar and Nepf, 2011; Aberle and Järvelä, 2013; Whittaker et. al, 2013, 2015) which can be considered one of the most advanced tools to predict drag force and trees bending. Reconsidering (1) as:

$$F = 0.5\rho C_{do} A_{po} Ca^{\psi/2} V^2$$

(2)

where C_{do} and A_{po} represent the drag coefficient and the project area of the plant in condition of "still air", (i.e., not loaded by hydrodynamic forces), the Vogel exponent ψ is considered as a species specific constant, and Ca is the vegetative Cauchy number defined as:

$$Ca = \left(\frac{\rho V^2 A_{po} H^2}{EI} \right) \tag{3}$$



In this new approach the ψ and *Cdo* have to be calibrated for every vegetation type. Whittaker et al. (2015) found for *Populus Nigra* species ψ= -0.8, -0.81 and C_{do} = 0.76, 1.04, respectively, for fully submerged foliated or defoliated specimen in towing tank experiments. In this action, these values are adapted and only the case of completely submerged is considered.

In order to estimate the bending of the specimen, the approach suggested by Stone et al. (2011) and Stone et al. (2011) can be used which is partly based on results from Ang. Jr et al. (1993) and Chen (2010). In this approach, vegetation is considered in a simplified way as a bottom mounted cylindrical cantilever beam. In case of large deflections of the cylinder, these can be determined using the following equation (Ang. Jr et al. (1993)):

$$\frac{\frac{d^2x}{dy^2}}{\left[1+(\frac{dx}{dy})^2\right]^{\frac{3}{2}}}=\frac{M(y)}{EI} \tag{4}$$

in which *dx/dy* represents the horizontal displacement respect to beam's axis. The solution of equation (4) gives hence the elastic curve, $x = f(y)$. In case of small deflections *dx/dy* is approximately zero (its square is negligible compared to unity), and equation (4) becomes a linear differential equation. In case of large deflections, as for flexible vegetation, the denominator cannot be neglected, and the solution of equation (4) is not straightforward to obtain.

Ang. Jr.et al. (1993) applied a numerical method to solve the large deflection cantilever problem re-purposed by Chen (2010) in order to calculate horizontal displacement for cylindrical cantilevers under specified loads by the mean of an iterative procedure that determines the deflected beam length h_v and the specific shape of the bending curve. Here, this approach is used exemplarily to calculate the final height of specifically chosen specimen for four different flow velocities (V = 0.5, 1, 1.5 ,and 2 m/s).

This procedure allows to model the vertical reconfiguration of riparian trees and allows hence to gain insight how the shape of individual specimen (Height H, initial projected Area A_{po}, Inertia momentum I) affects drag forces. Thus the practice of coppicing of flexible trees can, for the first time, be evaluated with regard its effect on drag forces. Consequently, this procedure provides the basis for further investigations to evaluate in more detail changes in the velocity profile, flow resistance and turbulent flow patterns.

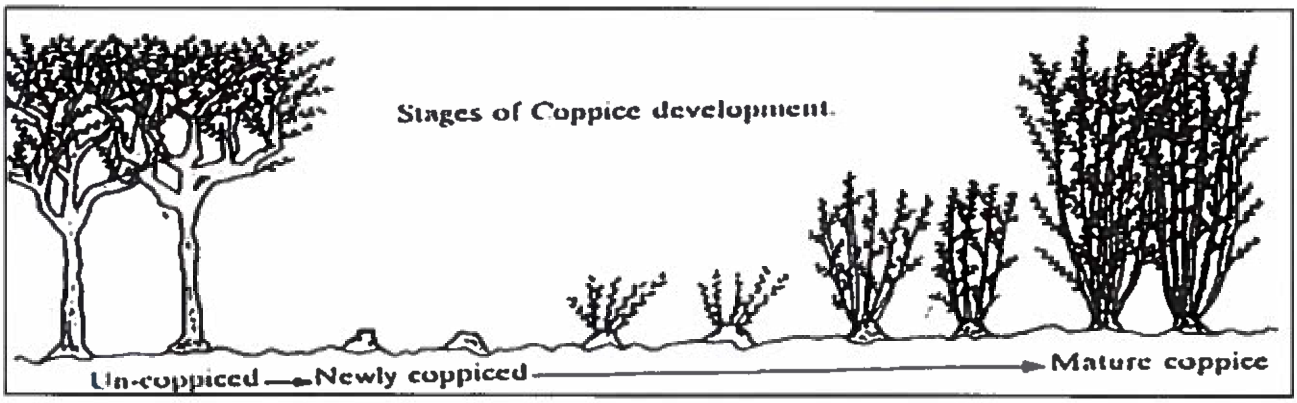


Fig.4 Coppicing phases by un-coppiced to mature coppice. The development of the plant includes a dynamic changing of its shape(courtesy of designafireplace.com)

In fact, examining the stages of the development of coppiced elements shown in Fig.4 it can be seen how the practice of coppicing changes the shape of the plant and its subsequent development. Working with Prof. Jochen Aberle at NTNU-Trondheim (staff member at the host institution for this STSM Action and one of the developers of this new approach) the applicant improved his knowledge of this new theory resulting in the development of this novel modelling strategy to evaluate the consequences of coppice management. In this action, the outlined procedure was applied to 5 specimen of *Populus Nigra* whose properties were determined on a previous study (Saulino et. al, 2015). The results of this work are discussed in the next paragraph.

Results

In this paragraph we examine the elastic behaviour of 5 sampling of a typical Mediterranean riparian plant, *Populus Nigra* which is common in rivers in Southern of Italy. As indicated above, the biomechanical properties were collected from adult trees in natural stands along the *Badolato* stream in Cilento (Campania Region, Southern Italy).

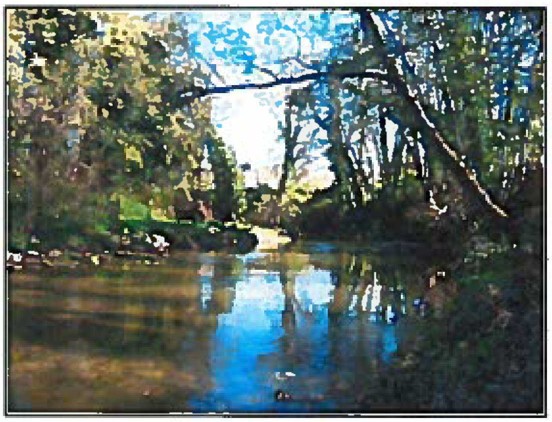


Fig.5 Badolato Stream

Plant samples collected on old *P.nigra* tree stands are grown under short-rotation plantation for bio-energy production. Usually, these plantations are characterized by single stems and coppice rotation shorter than 5 years. Tab.1 shows the biomechanical properties determined by(Saulino et. al, 2015). (…) of the specimen chosen for this study. The diameter of the plants was measured at the middle of the trunk and it is worth mentioning that there were no significant differences in diameter values in the different sections of the trunk. In order to test the approach specifically with regard to coppicing, five samples with the same E elasticity module were chosen which are characterized by different diameters, height, and initial projected areas.

Sampling	D(cm)	E(Mpa)	I(m^4)	H(m)	Apo(m^2)
1	0.5	8.72E09	1.32E-11	0.97	0.062
2	1.075	8.72E09	2.96E-10	1.71	0.12
3	1.5	8.72E09	1.32E-09	2.24	0.16
4	2.03	8.72E09	3.95E-09	2.73	0.20
5	2.51	8.72E09	9.33E-09	3.28	0.25

Tab.1 Populus Nigra biomechanical properties.

The drag forces exerted by these trees, calculated using equations (2) and (3), are shown in Figure 6. The deflected height of the trees h_v was subsequently determined using equation (4) with the resukts shown in Figure 7.

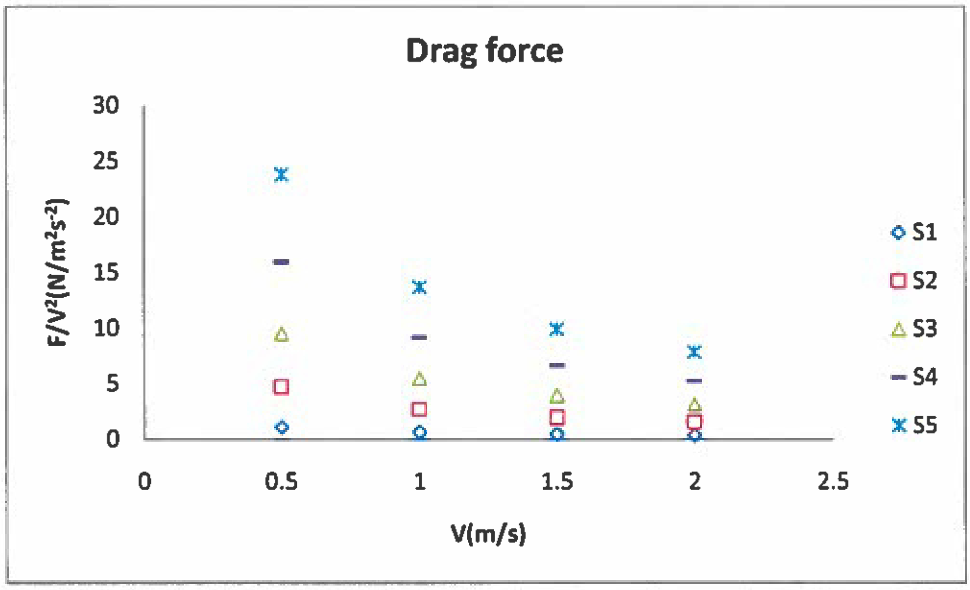


Fig.6 Speed specific drag variations of *Populus nigra* 's five sampling (S1 up to S5)

Figure 6 shows the ratio of the drag force and the squared flow velocity (F/V^2) as a function of the flow velocity which corresponds to the

$$\frac{F}{V^2} = 0.5 \rho C_{do} A_{po} Ca^{\psi/2} \tag{5}$$

This ratio characterises indirectly the reconfiguration of the flexible plant for different velocities. According to the figure, the F/V^2- V relationship becomes nearly linear and is significantly different from the more squared relationship for rigid bodies and underlines hence once more the importance of the "Cauchy number" approach in order take flexibility into account. Moreover, the drag force is larger for plants with higher diameter and larger area (see values in Table 1) as expected. Thus, this result shows that it is important to take flexibility into account and that the simulation of vegetation as "rigid cylinders", as still often done in literature and hydraulic models, can result in significant errors. In order to connect this result with coppice management, the elastic behaviour of the specimen was determined as outlined above. The corresponding results, expressed in terms of the height ratio (deflected height of vegetation h_v to height H in still air) are shown, in Figure 7 as a function of flow velocity.

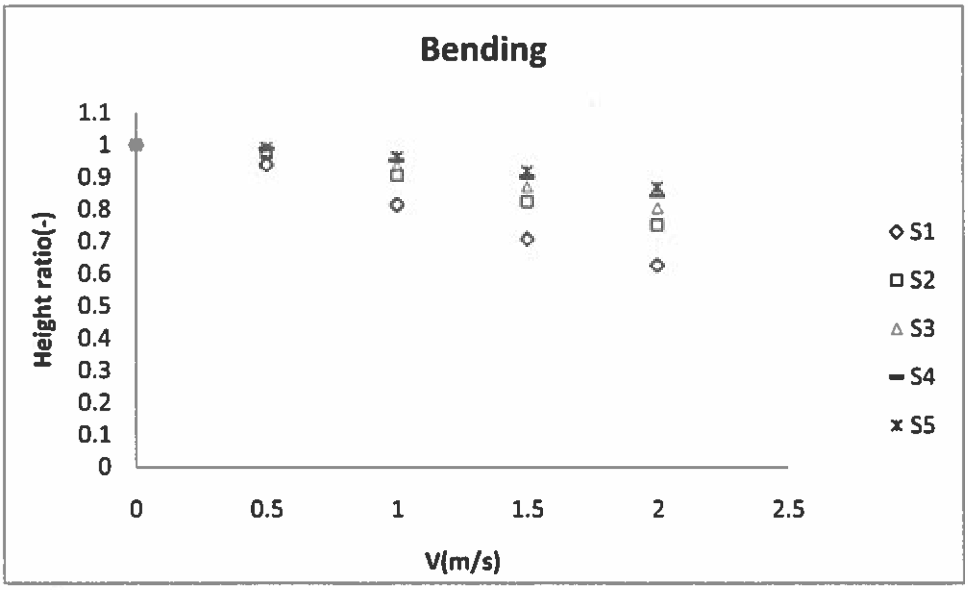


Fig.6 Speed specific drag variations of *Populus nigra* 's five sampling (S1 up to S5)

For $V = 0$, the height ratio is obviously equal to 1 but reduces then subsequently with increasing velocity.. For the lower velocities used in this approach of 0.5 and 1 m/s, there is a slight difference in the height ratio between the specimen. In general, the ratio corresponds to 90-97% at $V =$ 1m/s; only S1 is characterised by a lower height ratio (i.e. more significant bending) of 80% by this few resistance due to its little diameter D and I. With increasing velocity, the difference between the specimen becomes more important due to the less resistance in bending exerted by more flexible plant, i.e. less EI flexure rigidity. For $V =$ 1.5m/s, the height ratio of specimen S1corresponds to 0.71, S2 to 0.82, S3 to 0.86, S4 to 0.89, S5 to 0.91 At the highest velocity of $V =$ 2m/s, the height ratio is 0.62 for S1 whilst, S2 to 0.74, S3 to 0.80, S4 to 0.82 and for the bigger Sample S5 is 0.86. According to this results it can be definitely stated that for low values of diameter (up to D = 1.5cm) a single plant bends significantly (up to 62% of the initial Height) while more mature trees D > 1.5cm bend less. In the next paragraph we discuss how this result could affect the management of coppice forests.

Discussion

According to our considerations, the shape of a flexible plant in still air which is exposed to water flow affects flow resistance which in turn depends on the plants deformation due to water flow.This has to be considered when evaluating coppicing within a multidisciplinary approach (by hydraulic engineers, geologist, geomorphologist, ecologists, etc.) considering the importance of the plant flexibility and its biomechanical properties.

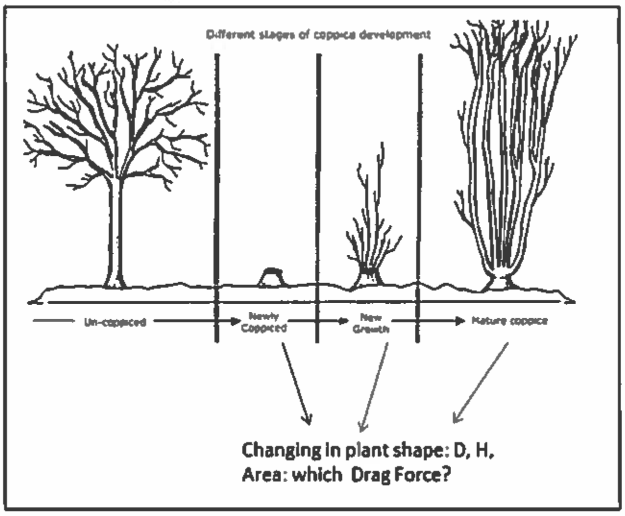


Fig. 8 Plant reconfiguration in coppice development

In fact the shape of a coppiced plant undergoes important changes during its regrowth, and the suggested approach provides a tool of how these changes can be effectively measured by an hydraulic point of view. The flexibility is captured by the "Vegetative Cauchy Number" which can be considered as one of the most appropriate and actual tools to predict plant elastic behaviour. For example, the obtained results show that it becomes possible to determine the limit of cutting so that the plant assumes a flexible behaviour. In the application of the proposed methodology it was shown that velocity values up to 1.5 m/s, a 2-2.5cm diameter plant can be considered to have a "rigid" behaviour. Thus the presented methodology could be applied to specimen on floodplains to optimise the coppicing strategy.

Recommendations

This approach evaluated the elastic behaviour of riparian trees and its hydraulic connections to coppice management in case of submerged conditions and for same E Young Module of Elasticity. In order to improve this result, further research goals have to consider "complete" cases such as: emergent/submerged conditions, different biomechanical properties, density of vegetation, different species in the same reach.

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Host confirmation of the STSM ACTION:

I, Jochen Aberle, as the inviting professor of Vittorio Pasquino in this STSM 29704, confirm that the applicant observed the workplan and reached the aim of the mission during the period 5.10.2015-30/11/2015.

SIGNATURE

Vittorio Pasquino

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Professor J. Aberle confirming applicant carried out STMS

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