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Review Article

Use of Vegetation as Biomaterial for Controlling Measures of Human Impact on the Environment

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In a context of a climate change, bioengineering techniques and biomaterials are needed to reduce the human impact on the environment. Thus, in recent years, living materials have been used in environmental engineering applications. In the present paper, attention is restricted to the vegetation, and a brief review on its use as biomaterial in engineering control techniques is presented. The core of this review is a comprehensive overview of two important techniques using vegetation as living material for measures limiting the human impact both in extra-urban and in urban sites. In particular, the use of vegetation both as living material for soil erosion protection and river's bank stabilization in extra-urban areas and as a part of green roofs or walls added to buildings in urban areas is presented. Considerations about the advantages and disadvantages of these techniques conclude this review.

1. Introduction

Environmental engineering is the branch of engineering identifying technical solutions to protect the environment and/or to control environmental hazards.

It is generally accepted that climate change is one of the biggest problems of our times. Climate change determines warmer temperatures altering the hydrologic cycle and changing the amount, timing, and intensity of precipitations [1]. This leads to a more frequent high-intensity rainfall events and consequent inundation phenomena both in urban and extra-urban areas. Recent literature (see as an example [2, 3]) exalts the role of the anthropogenic actions, such as the gases emissions, the fossil fuel use, and the fertilization, in the global mean temperature changes.

The use of biomaterials in bioengineering techniques, also in combination with traditional hydraulic or geotechnical engineering practices, would allow us to have an "environmentally friendly" measure to control the risks related to the extreme events and to mitigate considerably their effects. Furthermore, the application of such a kind of measure would allow us to reduce the worst effects of the anthropogenic actions with low overall costs.

In recent years, much more attention has been devoted to vegetation as living material in the ambit of bioengineering measures. Such "environmentally friendly" material was used especially in the United States since the first decades of the 20th century; recently, and the interest on its use in environmental engineering has strongly increased also in Europe [4].

As literature (see as an example [5]) shows, climate is one of the controlling factors of the evolution and distribution of the vegetation species. Thus, a limitation in the use of vegetation is related to the fact that its characteristics are closely correlated to the climate so that rapid climate changes could lead to remarkable changes in the vegetation behavior, contributing to modify its protecting function.

In the present work, measures in environmental engineering using vegetation as living material are considered, and the emphasis is on two techniques adopted for limiting the human impact in extra-urban and in urban sites. Considerations about the advantages and disadvantages of these techniques conclude this review.

2. Vegetation as Biomaterial in Environmental Engineering

2.1. Vegetation and Measures for Protection and Erosion Control. In extra-urban areas, vegetation is generally used as living material for protection and stabilization actions in bioengineering techniques. In particular, vegetation and derived materials are used in controlling measures of soil erosion and of river's bank stability [6]. Soil erosion processes can severely damage the infrastructures and the environment. In fact, heavy rainfall can determine strong soil erosion either producing hyperconcentrated flows or determining localized erosion around structures or producing river's bank failure and inundation phenomena.

Thus, especially in recent years, researchers have devoted much attention to the identification of mutual interactions between riparian vegetation and rivers' morphodynamics (among others [7–12]). Riparian zones are transitional areas between water and land, and the vegetation in riparian zones (see Figure 1) is a key element exerting both an active role and a passive role on channel's morphodynamics.

In fact, on one hand, vegetation traps, reinforces, and aggrades landforms and the exposure of the trees to the hydrological processes; on the other hand, vegetation provides additional stability of deposited sediments due to the root systems [11]. According to Güneralp and Rhoads [8], as Figure 1 shows, different types of plants, which range from macrophytes to riparian trees, could control river morphology and the interaction between vegetation and fluvial morphology.

From a hydraulic point of view, vegetation is a source of flow resistance because it increases the bed roughness, decreasing bed shear stress and reducing the flow conveyance capacity [13–16]. As consequence, vegetation protects the bank and the bed creating feedbacks to sediment deposition [17] and reducing the soil erosion due to the reduction of the bed shear stress [18]. It should be noted that the quantification of the dissipative effects due to the presence of the vegetated elements depends on plants' shape, size, arrangement, and concentration [16].

On the construction point of view, the protective techniques in riparian zones could consist either of distributed single roots of plants (which are called as point-by-point systems) or of rows of roots of plants (which are called as linear systems) or of covering-mattress of plants (which are called as covering systems). Covering-mattresses of plants are also realized as measures against soil erosion processes. These measures consist either of flexible mattress or of wool geotextiles [19] with inseminated vegetation [20]. The plants grown on the wool geotextiles (Figure 2(a)) determine a mattress covered with the mixture of grasses and various herbaceous plants. Recently, simple mattress of inseminated herbaceous plants with deep roots has been realized [21].

To protect the vegetated river's bank, the so-called "crib walls" (see Figure 2(b)) are often used. They are realized with reticular systems of compartments realized either of wood or of prefabricated concrete and filled with vegetation (Figure 2(b)). In this case, vegetation especially allows

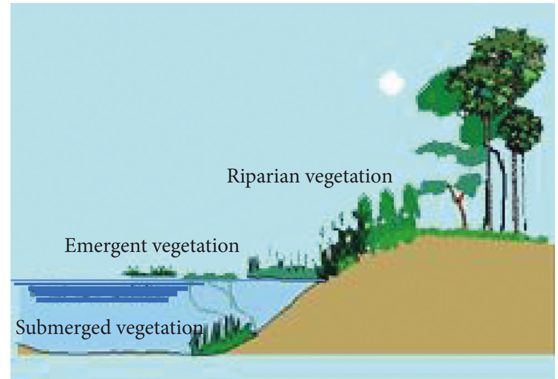


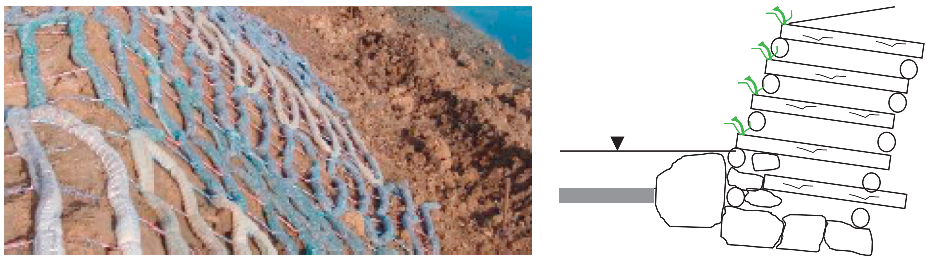
Figure 1: Example of riparian zone and vegetation.

reinforcing of the bank through its root system. In order to guarantee the good performance of such a measure, an efficient and periodical maintenance has to be performed because of the potential transport of sediment by the flow which could determine the emptying of the compartments especially before that the vegetation is fully developed.

It should be noted that the vegetation patterns are strongly controlled by flood disturbance which determines either its mechanical damage or the transport of seeds or the deposition of sediments. Thus, flood disturbance strongly influences the type of vegetation that establishes (among others [12, 22]). As consequence, vegetation composition and growth can vary greatly depending on the tolerances of the vegetation species. Furthermore, the vegetation distribution could also change in time and in space depending on the combination of factors affecting the settling and growth of the vegetated elements.

2.1.1. Functions and Advantages. In the aforementioned techniques, vegetation exerts a fundamental role performing both a hydrological-hydraulic function and an environmental function and a mechanical function, as schematized in Table 1. From Table 1, it can be summarized that on a hydrological-hydraulic point of view, vegetation allows to intercept raindrops, thus protecting the soil from erosion caused by rain splash. Furthermore, the roots of vegetation absorb the water surface limiting the soil saturation and the slope failure and reducing the flow velocity by increasing surface roughness; on an environmental point of view, vegetation allows the absorption of CO_2 depending on the soil characteristics and the temperature; on the mechanical point of view, the vegetation and its roots improve the stabilization of the bed material, thus increasing the soil strength and protecting the surface from water infiltration.

2.2. Vegetation and Measures to Limit the Worst Human-Induced Effects. Adding a green roof or a green wall (see Figure 3) to a building represents, especially in recent years, an "environmentally friendly" measure to limit the anthropogenic actions in urban areas. The green wall can be defined as a technological system used as a solution, even



(a) (b)

Figure 2: (a) Example of wool geotextiles. (b) Example of woods crib walls.

Table 1: Functions of vegetation in environmental engineering measures.

Function	Typology	Description
Hydrological-hydraulic	Interception	The vegetation intercepts raindrops and reduces their size and strength, thus protecting the soil from erosion caused by rain splash
	Restraint	The dense network of roots restrains bed material
	Absorption	Roots absorb water surface and underground water, thus reducing the saturation level of soil and the risk of slope failure
	Infiltration	Plants help to maintain soil porosity and permeability, increasing retention and delaying the runoff
	Evapotranspiration	Vegetation transpires water absorbed through the roots and allows it to evaporate into the air
	Surface runoff reduction	Stems and roots can reduce the velocity of surface runoff by increasing surface roughness
	Reducing flowing by stems	A portion of rainwater is intercepted by vegetation so that rainwater is stored in the stems
Environmental	Absorption	It allows the absorption of CO_2 depending on the soil fertility, type of soil, exposure, temperature trend, and the plant species
Mechanical	Catching	The loose soil materials, which roll down a slope because of gravity and erosion, are caught by planting the stems and roots
	Armouring	Vegetation can trap high-size sediments
	Reinforcing	The shear strength of the soil can be increased by planting vegetation depending on the nature of its roots
	Supporting and anchoring	Large and mature plants can stabilize layers with a tendency to slip over each other
	Draining	Surface water drains away more easily in areas with dense rooted vegetation

Figure 3: Example of green walls.

partial, of a generic building construction with the aim of guaranteeing several benefits for life [23].

In Europe, the use of green technology began since the 1960s. Promoters of this system were the countries of central and northern Europe: Switzerland, Austria, Finland, Norway, and Germany.

According to Abram [24], the "green roof" can be defined as a technological system realized on top of a building. Such a technological system consists of different stratifications attached to the thermal insulation element (if existing) and forming a unique system. In particular, as Figure 4 shows, this system consists of four types of layers: the vegetation layer, the protection (filtering and draining)

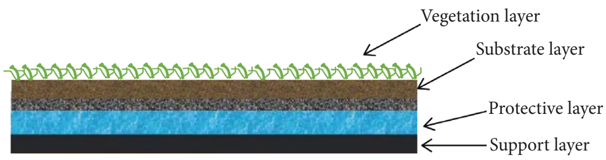


Figure 4: Scheme of the green roof system.

layers, and the supporting layer. The vegetation layer is the most essential part of the green roof. Generally, herbaceous vegetation, more precisely grass that it is very variable in quantity and grows over time, is used. The nutrition of vegetation is from the so-called growth substrate layer which could be mixed with compost and plays an important role in managing water. The protection layer could be composed of two plastic materials [25]: the first one prevents roots penetration into the support and could be made of high-density polyethylene; the second one is a layer of drainage and filtration consisting generally of polystyrene. The support layer supports all the above mentioned different layers of the green roof and could be made of wood.

Although each installation presents similar constructive characteristics, its performance could vary by region, climate, building, design, and green wall type [26]. In particular, some main elements should be considered in order to guarantee the good performance of the green roofs: (a) the roots system must not compromise the integrity and functionality of the underlying layers and in particular of the thermal insulation element; (b) it is necessary to protect the underlying waterproofing of the roof from damage and mechanical stresses caused by the weight of the overlying layers; and (c) it is necessary to guarantee the drainage and the presence of air.

Like green roofs, the "green walls" also consist of a sequence of layers organized with a precise order in the space [27, 28]. In general, passing from the outside to the building's surface, the sequence includes four layers: the vegetated layer, the substrate layer, the technological layer, and the closure layer. The vegetated layer is composed by the plants which could be of different species although always-green species are preferably used. The substrate layer represents the layer from which the plants take nutrition. The technological layer is the layer necessary for the implementation of the green package and its functionality. Finally, the closure layer is the physical element of delimitation between the sequence and the building's surface.

It should be noted that according to the used executive procedure and the plants peculiarities, three different typologies of the green wall can be distinguished: the "green facade", the "living wall", and the "garden wall". The "green facade" represents a vegetal coating of the building's surface [29]. This typology includes a simple technological layer so that either the plants are clinging directly to the building's surface (such a practice was widely used in the past) or there are specific support elements, as the wire meshes, on which the plants cling (see Figure 5(a)). Thus, the climbing plant species are generally used for this typology. Unlike the "green facade", the "living wall" is characterized by a marked integration between the building's surface and the plants (see Figure 5(b)). In this typology, the plants are arranged directly on the closure layer [30] so that a uniform vegetal layer covering the entire building surface forms; the vegetation becomes an integrating part of the building surface itself. The "garden wall" can be considered as a subtype of the living wall [31]. The main differences with respect to the living wall are due both to the arrangements of the plant apparatus and for the material with which the substrate is made (see Figure 5(c)). In fact in the garden wall, synthetic elements are generally used for the substrate.

2.2.1. Functions and Advantages. Green roofs and walls provide many functions and offer several benefits (among others [32–35]), as schematized in Table 2. From Table 2, it can be summarized that on the aesthetic point of view, this system allows aesthetic stimulation allowing to create privacy and limiting the negative psychological effects associated with property demarcation; on the protective point of view, this system provides an additional layer of exterior insulation also limiting the thermal fluctuations; on the environmental point of view, this system allows to reduce noise, to mitigate air pollution levels by lowering extreme summer temperatures through photosynthesis. Furthermore, green walls allow both to treat water by filtering it through specific marine plants [37] and to reduce the temperature fluctuations at a wall's surface, limiting the movement of heat between building walls [38]. A recent field green wall experiment [39] has indicated a good efficiency of COD and BOD5 removal from greywater produced by an office building so that greywater reached an appropriate quality to accumulate it for its reuse for irrigation purposes [40]. This confirms that use of the green wall for greywater treatment and reuse could be a very promising additional service provided by it.

3. Discussion and Concluding Remarks

From the presented brief review of the measures for limiting the human impact in the environment, it can be concluded that in comparison with traditional engineering techniques, the use of vegetation as biomaterial presents many benefits.

In particular, from the aforementioned considerations, three general groups of benefits can be outlined: (1) technical advantages which include the protection against surface erosion, the improving of bank's stability by root reinforcement and draining of the soil, and the protection against wind; (2) environmental advantages which include the regulation of temperature and humidity close to the surface, the improving of water interception, evapotranspiration and storage, and the improving of habitat and biodiversity; and (3) aesthetic advantages which include the use of technological systems improving the aesthetic buildings' characteristics and a more appealing landscape.

An adding benefit is that related to the economic advantages. In fact, the use of vegetation in controlling measures against erosion in extra-urban sites allows the reduction of the construction and the structural maintenance costs with respect to the corresponding costs

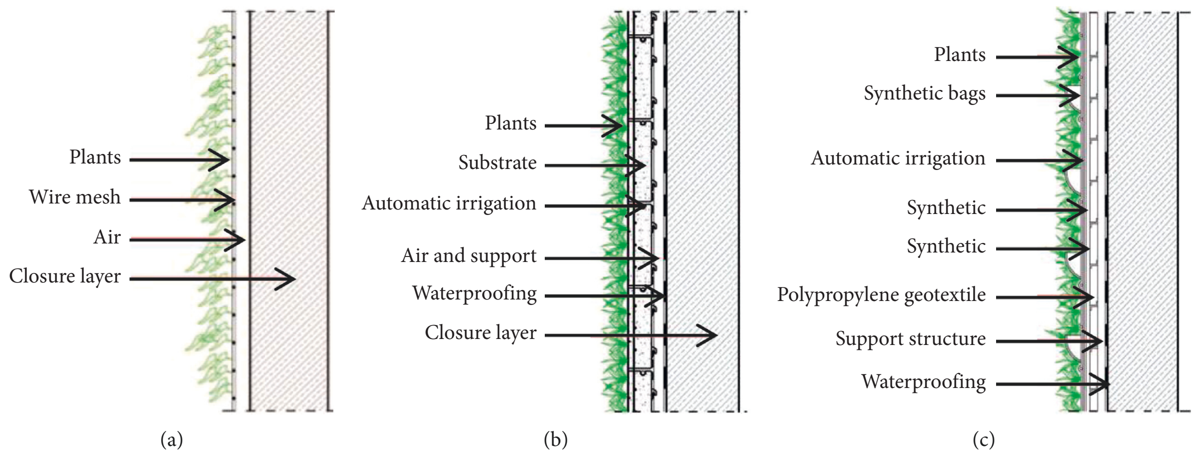


Figure 5: (a) Example scheme of the "green façade." (b) Example scheme of the "living wall." (c) Example scheme of the "garden wall."

Table 2: Functions of vegetation in green walls.

Function	Typology	Description
Aesthetic and protective function	Aesthetic improvements	Especially, green walls provide aesthetic stimulation where it would not otherwise be found. They can also serve to create privacy limiting the negative psychological effects associated with property demarcation.
	Building structure protection	Temperature fluctuations over a building's lifetime can determine damages in building facades. Green walls provide an additional layer of exterior insulation limiting thermal fluctuations. Furthermore, green walls protect exterior finishes from UV radiation and rain and decrease the effect of wind pressure [36].
Environmental	Noise reduction	The vegetated surface provided by green walls and roofs will block high-frequency sounds, and when constructed with a substrate or growing medium support, it can also block low-frequency noises.
	Increased biodiversity	Green walls can help mitigate the loss of biodiversity due to the effects of urbanization, help sustain a variety of plants, pollinators, and invertebrates, and provide habitat and nesting places for various bird species.
	On-site wastewater treatment	Several water-recycling systems can be applied to green walls. As an example, systems pump greywater through a green wall, which then passes through filters, gravel, and marine plants and treat water which is then sent to a greywater holding tank for household or irrigation use or released into the public water treatment system [37].
	Improved energy efficiency	Green walls can reduce the temperature fluctuations at a wall's surface from a range of 10–60°C to one of 5–30°C, limiting the movement of heat between building walls [38].
	Reduction of the urban heat island effect	The reintroduction of vegetation into urban environments promotes the occurrence of natural cooling processes, such as photosynthesis and evapotranspiration.
	Improved exterior air quality	Green walls mitigate air pollution levels by lowering extreme summer temperatures through photosynthesis, trapping particulate matter, and capturing gases.

necessary for a classical structural measure [40]. Furthermore, the vegetation installation contributes to create areas for agricultural and recreational use. The economic advantages in the use of green walls in urban areas are especially related to the multiple benefits which they produce [41]. A green wall can act like a cooler due to plant evapotranspiration and can reduce impact of the wind by 75% and heating demand by 25% [36].

On the other side, it should be considered that in order to guarantee the efficiency of the aforementioned measures, some important elements have to be taken into account. First of all, it is really important to select local species already adapted to the growing conditions which can resist to high frequency of occurrence of high-magnitude events. Furthermore, it should be important to select species that can be used for other purposes, for example, providing fruit or leaves that can be used for other purposes. This suggests that to analyze the effective protective action of vegetation, it is important to evaluate the durability and different aspects related to the maintenance of the planted species.

In conclusion, vegetation as biomaterial in environmental engineering could exert an important role to mitigate worst effects due to anthropogenic actions. Its use offers significant economic benefits, including a longer measure's life and an increasing biodiversity; if well designed, it can offer people also the psychological benefits of nature.

Conflicts of Interest

The author declares that they have no conflicts of interest.

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