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## Soil and water bioengineering: Practice and research needs for reconciling natural hazard control and ecological restoration

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## **Soil and water bioengineering: practice and research needs for reconciling natural hazard control and ecological restoration**

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43

44 **Abstract**

45 Soil and water bioengineering is a technology that encourages scientists and practitioners to combine  
46 their knowledge and skills in the management of ecosystems with a common goal to maximize benefits  
47 to both man and the natural environment. It involves techniques that use plants as living building  
48 materials, for: (i) natural hazard control (e.g., soil erosion, torrential floods and landslides) and  
49 (ii) ecological restoration or nature-based re-introduction of species on degraded lands, river  
50 embankments, and disturbed environments. For a bioengineering project to be successful, engineers  
51 are required to highlight all the potential benefits and ecosystem services by documenting the  
52 technical, ecological, economic and social values. The novel approaches used by bioengineers raise  
53 questions for researchers and necessitate innovation from practitioners to design bioengineering  
54 concepts and techniques. Our objective in this paper, therefore, is to highlight the practice and research  
55 needs in soil and water bioengineering for reconciling natural hazard control and ecological restoration.  
56 Firstly, we review the definition and development of bioengineering technology, while stressing issues  
57 concerning the design, implementation, and monitoring of bioengineering actions. Secondly, we  
58 highlight the need to reconcile natural hazard control and ecological restoration by posing novel  
59 practice and research questions.

60

61 **Keywords**

62 Benefits; Biodiversity; Ecological engineering; Ecosystem services; Erosion; Vegetation

## 63 **1. Development and issues in soil and water bioengineering**

### 64 **1.1. Definition, applications and benefits of soil and water bioengineering**

65 Soil and water bioengineering combines the implementation of techniques using plants as living  
66 building materials, through knowledge of their mechanical and/or biological properties (Figure 1)  
67 (Barker et al., 2004; Stokes et al. 2004). Bioengineering is a well-recognized component of ecological  
68 engineering, itself defined as “the design of sustainable systems, consistent with ecological principles,  
69 which integrate human society with its natural environment for the benefit of both” (Mitsch and  
70 Jørgensen, 2003; Mitsch, 2012). Bioengineering is used to: (i) control natural hazards (e.g., Norris et  
71 al., 2008; Dhital et al., 2013), (ii) restore or reintroduce plant and animal species onto degraded lands  
72 and disturbed environments (e.g., Li et al., 2006; Rauch et al., 2014), and (iii) increase soil, air and  
73 water quality (e.g., Pretty et al., 2003; Woolsey et al., 2007).

74 Natural hazards such as soil erosion, torrential floods, and landslides, are phenomena that have  
75 severe consequences globally (Poesen et al., 2003; Smith and Katz, 2013; Poesen, 2017). The use of  
76 vegetation for protecting against natural hazards and attaining economic and/or social goals is typical  
77 of traditional forest and hydraulic engineering programs in Europe, such as the ‘Restauration des  
78 terrains en montagne’ (RTM) in France (Vallauri et al., 2002), ‘Wildbach und Lawinen Verbauung’  
79 (WLV) in Germany and Austria, or ‘Sistemazioni Idraulico-Forestali’ (SIF) in Italy (Bresci and Preti,  
80 2010; Bischetti et al., 2014). Today, the control of these types of hazards using herbaceous and woody  
81 vegetation through bioengineering remains a major challenge in areas where technical,  
82 socioeconomic, and ecological issues are confounding factors that can hinder success (Phillips et al.,  
83 2013; Dhital and Tang, 2015). Bioengineering in areas that are difficult to access, e.g. torrential  
84 catchments, riverbanks and lakes, as well as on disturbed lands, such as agricultural zones, road and  
85 rail embankments, ski slopes, mines, quarries and in urban areas (Lin et al., 2006), requires  
86 understanding of the interdependency of hydrological, ecological, and biophysical processes

87 underway at the site. Bioengineering solutions should provide a combination of the benefits of  
88 immediate hazard control, comprising techniques such as (Figure 1): (i) brush layers (that provide  
89 deep-seated protection), (ii) drain fascines or live pole drains (which drain excess water to allow  
90 vegetation establishment), (iii) vegetated crib walls (that immediately protect stream banks), (iv)  
91 brush mattresses (providing roughness from establishment against flow), and the long-term  
92 stabilization due to plant reinforcement effects. As with any stabilization technique, there is a stress  
93 (or load) transfer between the soil and the structure, but, in contrast to other solutions, this initial  
94 response is modified by the evolving role of the living material used in the bioengineering structure  
95 (Preti and Giadrossich, 2009; Graf and Frei, 2013; Yildiz et al., 2015, 2018; Tardio and Mickovski,  
96 2016). This latter feature must be reflected in the bioengineering work design methodologies.

97 Ecological restoration encompasses all actions for repairing degraded lands, with the aim of  
98 reestablishing both form and function to attain autonomous and stable ecosystems (Clewell and  
99 Aronson, 2013). Ecological engineering in general and bioengineering in particular, can be employed  
100 for the restoration of a degraded environment (Mitsch and Jørgensen, 2004). Actions can include: (i)  
101 rehabilitating degraded land, which requires techniques aimed at recovering the natural succession of  
102 the ecosystem, especially by installing pioneer vegetation and enhancing its development; and (ii)  
103 monitoring and maintaining the rehabilitated land, thereby guiding the natural dynamics of the  
104 degraded systems so that they recover with a structural and functional autonomy (Aronson et al.,  
105 1993). A significant advantage of bioengineering actions is the incorporation of vegetation  
106 establishment and succession processes into the design stage. Therefore, the need for further  
107 intervention or maintenance is reduced and a long-term solution is provided. Bioengineering could  
108 also make restoration faster in the sense that, if the path of plant succession is known, it is possible to  
109 establish vegetation at the most advanced stage which will be compatible with the soil and  
110 microclimatic conditions of the site. Moreover, considering the energy balance of any civil  
111 engineering construction, a benefit from using soil bioengineering techniques is that although we  
112 need energy for its construction, we "save" energy with the development of the plant biomass. Finally

113 these actions not only include ecological restoration, but also water and soil quality restoration or  
114 depollution (e.g., Wang et al., 2008).

115 Soil and water bioengineering is an emerging discipline globally, with regulatory frameworks  
116 (including the European Water Framework Directive or more recently the European Green  
117 Infrastructure Strategy) introducing the need to implement “soft” techniques for natural hazard  
118 control instead of “hard” techniques (engineered concrete and steel structures such as check dams),  
119 in the pursuit of restoring degraded environments or preventing further degradation during new  
120 construction. Prioritizing soil and water bioengineering techniques is now highly encouraged in the  
121 European Community and in many countries worldwide, often promoted through various incentives  
122 (e.g., European Commission, 2013). The International Union for the Conservation of Nature (IUCN) is  
123 proactively endorsing the use of Nature-based solutions for disaster risk reduction (EcoDRR), and  
124 includes soil bioengineering as a technique for protecting against natural hazards (Furuta et al., 2016;  
125 Renaud et al., 2016). Questioning practitioners and scientists about their experience, successes, and  
126 failures will allow a better understanding of the multiple benefits and services that natural habitats and  
127 human populations derive from bioengineering actions (Table 1).

## 128 **1.2. An interactive process between researchers and practitioners**

129 Soil and water bioengineering implies an interface between the researcher and the practitioner, i.e.  
130 between the improved knowledge base and its application (Stokes et al., 2013, 2014; Mitsch, 2014).  
131 The questions raised are increasingly complex and many practitioners are now involved in research  
132 projects, improving dialogue and mediation between different stakeholders. Bioengineering projects  
133 could also benefit from more multi- and inter-disciplinary approaches, as well as from a better  
134 understanding of practical issues experienced by practitioners (e.g., choice of materials, costs,  
135 insurance, health and safety, and management of human resources).

136 For those working in the field of bioengineering, a specific framework is required at three levels:



- 137 (i) questions: identification of the technical, socio-economic, and ecological problems, evaluated by  
138 the practitioners. Researchers and practitioners should then work together to solve specific  
139 objectives.
- 140 (ii) applied research: translation of the technical, socioeconomic, and ecological concerns into  
141 scientific questions, and increase of knowledge by observations and experiments. Soil and water  
142 bioengineering can be implemented based on relevant knowledge from several scientific  
143 domains, especially geosciences (e.g., geomorphology and soil science), ecology (e.g.,  
144 restoration ecology, landscape ecology, and plant sciences), engineering (e.g., fluvial hydraulics,  
145 civil and geotechnical engineering), sociology (e.g. community engagement and social  
146 acceptability of the methods and tools proposed; legitimate design approach), and economics  
147 (e.g. project financial management, carbon accounting) (Petroni and Preti, 2010; Stock and  
148 Burton, 2011).
- 149 (iii) management in bioengineering: as soil and water bioengineering is consistent with policies  
150 aimed at encouraging “soft” solutions, in particular by including environmental concerns into  
151 standard technical practices such as civil engineering, it is essential that current and improved  
152 knowledge is included at the work design stage. For example, features such as natural wood  
153 deterioration rates (Barré et al., 2017; Tardio and Mickovski, 2016), plant development and  
154 successional trajectories (Walker et al., 2009; Gonzalez-Ollauri and Mickovski, 2017a), must be  
155 incorporated into the routines and protocols of bioengineering projects. Research results should  
156 then be used to develop methods and tools to assist management, conceptualization and action.  
157 Adaptation of these tools needs to be performed in collaboration with practitioners, while the  
158 knowledge transfer and learning should occur in training courses at every educational level  
159 (Mitsch, 2014; Mickovski et al., 2018). The application of knowledge to real cases using newly  
160 gained expertise should be verified. Long term monitoring programs, with accurate benchmark  
161 data, are also required to compare similar case studies and establish databases on the successes

162 and failures of various techniques and plant material used (Tardío-Cerrillo and García-Rodríguez,  
163 2016; Perez et al., 2017; Tardio et al., 2017). Such considerations should improve practitioners'  
164 understanding of recent knowledge in ecology and geosciences, as well as increasing scientists'  
165 understanding of practical needs in soil and water bioengineering.

166 For soil and water bioengineering, all the above features are essential and, for a project to be  
167 successful, close interactions between stakeholders and bioengineers are necessary. Improved  
168 communication and interaction between the stakeholders will allow bioengineering interventions to  
169 both become more effective over time and take advantage of the accumulated experience within the  
170 sector.

171

## 172 **2. Natural hazard control and/or ecological restoration?**

173 Depending on the precise objective of a project, the choice of the bioengineering intervention and  
174 the desired long-term strategy can vary considerably. For example, soil or streambed erosion can  
175 cause different types of damage: (i) loss of topsoil, organic matter and nutrients, which lowers soil  
176 quality and hence crop yields and, in turn, threatens agricultural activities (e.g., Jin et al., 2008); it can  
177 also cause imminent risk of structural failure of roads, bridges, and railway lines (e.g. Mickovski,  
178 2014); (ii) topographic changes (terrain deformation) in the case of gully channel development,  
179 landslide triggering and suffusion risk phenomena (e.g. Poesen et al., 2003); (iii) biodiversity loss,  
180 which affects vegetation and animal habitats (Mkanda, 2002); (iv) silting of reservoirs, as a  
181 consequence of soil erosion and sediment transport, compromising the functioning of these  
182 structures (e.g. Schleiss et al., 2016) and (v) increased floods, caused by sediment deposition in river  
183 channels (e.g. Steiger et al., 2001). Strategies to control soil erosion rates will vary depending on the  
184 type of problem requiring action. For example, if reducing the sediment yield in rivers and reservoirs  
185 is the final objective, then the only intervention required is sediment control. Hence, it may be

186 possible to allow hillslope erosion to take place, but to aim at trapping and retaining sediment before  
187 it reaches the river channel (Rey, 2009). If riverbed erosion causes lateral displacement and bank  
188 failures, and impacts nearby infrastructure, the main objective is to protect facilities with highly  
189 specialized and adapted bioengineering solutions, e.g. based on geotechnical preliminary  
190 investigations during design and monitoring stage (Peklo, 2015). However, if soil and biodiversity  
191 conservation are the final objectives, then both erosion control and ecological restoration are  
192 required to prevent soil particles from being detached and removed (Petrone and Preti, 2010).

193 The current challenge when using bioengineering techniques is to define rules that satisfy a set of  
194 diverse functions and benefits, particularly those that reconcile natural hazard control and ecological  
195 restoration (Figure 2). This approach requires innovation from the practitioners, and also raises new  
196 questions for scientists, as part of an interactive process that necessitates the designing and testing of  
197 bioengineering actions that reconcile the competing demands of both natural hazard control and  
198 ecological restoration. As soil and fluvial bioengineering operates on complex systems (ecosystems)  
199 intrinsic adaptive management strategies and feedback loops are necessary to ensure that the  
200 project and the intervention is well informed.

201

### 202 **3. From practice to research needs**

203 One of the currently pressing challenges is to define bioengineering actions for a range of different  
204 situations. Although techniques are well described (e.g., Schiechl and Stern, 1996, 1997; Gray and  
205 Sotir, 1996; Zeh, 2007; Florineth, 2007; Hacker and Johanssen, 2012; EFIB, 2015), quantitative  
206 recommendations on how and which materials to use in specific situations are lacking, especially  
207 when the objective is to reconcile natural hazard mitigation and ecological restoration. To overcome  
208 this knowledge gap, scientists should heed practitioners' needs through discussions during projects,

209 conferences or training, and conduct research at different spatial scales, with specific objectives in  
210 mind (Figure 3).

### 211 **3.1. Selection of plant species**

212 Numerous studies have already dealt with the performance of specific species in protecting against  
213 different hazards (e.g. plant species potential to control gully erosion rates in a Mediterranean  
214 ecosystem; De Baets et al. 2009), in a specific climate (Gonzalez-Ollauri and Mickovski, 2016),  
215 environment or topographic location (Bochet et al. 2009). Furthermore, an open access plant species  
216 database has recently been developed by Perez et al. (2017), allowing users to access the database or  
217 add information about species suitable for controlling erosion and shallow landslides in different  
218 climates. Traditionally, a limited number of plant species has been used for this purpose, although  
219 there are countless species available that could perform equally well, many of which have not yet  
220 been tested for suitability (Preti and Petrone, 2013; Perez et al., 2017). In general, although using  
221 pioneering species in soil bioengineering projects is sometimes necessary to initiate the successional  
222 processes that will maintain vegetation on the site, native species should be preferred over exotic  
223 species and ecological succession trajectories should be included in the bioengineering intervention  
224 design (Clemente et al., 2016; Xiao et al., 2017).

225 When choosing which species to use on a site, and considering ecological restoration principles, the  
226 local and regional environmental conditions need to be considered carefully, so that an optimal and  
227 sustainable system is created (Mickovski and van Beek, 2006). For the successful creation of a  
228 bioengineering system, the initial phase is of major importance. For the last 30 years, practitioners  
229 and scientists have been studying the installation phase, by e.g. examining the relationship between  
230 the richness of pioneer species and soil aggregate stability (Pohl et al., 2012), or the efficacy of using  
231 mycorrhizal inoculations to improve plant growth and soil structure on eroded soil (Powell, 1980;  
232 Yildiz et al., 2015; Bast et al., 2016; Demenois et al., 2017). These studies concluded that the key to

233 fully understanding ecological processes at eroded sites requires similar long-term experiments in the  
234 field.

235 Species adapted for hazard protection are not necessarily those used for ecological restoration. One  
236 of the most difficult questions a manager can ask is: is it better to use only one or a few species that  
237 can efficiently mitigate a specific hazard, or should a diverse range of species, sometimes less  
238 efficient, be used? Promoting species diversity is generally recommended in ecological restoration  
239 projects, but could an increased diversity result in less effective hazard control? Investigating this  
240 problem, Erktan et al. (2013) showed that a morphological diversity of plant species used in  
241 vegetation barriers did not increase sediment retention in eroded marly gully floors in the French  
242 Southern Alps, compared to monospecific barriers (Figure 4). Such a consideration of plant  
243 biodiversity is a critical issue, as it generally corresponds to a more ecologically stable system (Preti  
244 and Petrone, 2013). A stable and healthy planting system would be less vulnerable to abiotic (e.g.,  
245 flooding, storms, snow loading and landslides) and biotic stress (e.g., pathogens and grazing). A  
246 diversity of plant species would also enable a manager to “cover all options”; for example in the case  
247 of a particular species becoming susceptible to abiotic/biotic factors, the loss of one species would be  
248 less likely to compromise the aims of the project. Referring to the study of Erktan et al. (2013), Rey  
249 and Labonne (2015) suggested using only one species to build brush layers and mats in eroded gully  
250 floors, but to use different species between structures along the gully floor, thus reconciling natural  
251 hazard mitigation with improved biodiversity.

### 252 **3.2. Selection of bioengineering structures**

253 The choice of the appropriate structure to use in a bioengineering project largely depends on the  
254 objective. When considering natural hazard control, the first principle to follow is to use structures  
255 and plants that have sufficient mechanical resistance to withstand gravitational or hydrological forces  
256 linked to the hazard process. Firstly, although technical drawings describing structures and their  
257 mechanical resistance exist in guidelines, we do not necessarily know their origins and performance

258 or reliability for the myriad of field situations likely to be encountered (Schaff et al., 2013). With the  
259 exception of gravitational structures (e.g. crib walls and fascines), whose design procedures are well  
260 established, and apart from a few cases (e.g. brushlayers and riverbank protection, Bischetti et al.,  
261 2010), most bioengineering techniques have not yet been sufficiently studied. At the individual plant  
262 scale, it is not well known to which topographic (e.g. Bochet et al. 2009, Nadal Romero et al., 2014)  
263 and hydrological forces plants resist before failing, and which plant traits are important for  
264 mechanical resistance (Burylo et al., 2014), therefore this topic needs significantly more attention  
265 from the scientific community. Questions also remain concerning the types of hazard and their  
266 different return periods depending on geographic situation and climate, especially under extreme  
267 climates such as in tropical countries. This knowledge gap calls for large-scale experiments taking into  
268 consideration all the variables and elements to which the structures are subjected (Schwarz et al.,  
269 2012). Secondly, it should be kept in mind that certain plant species or conditions may destabilize a  
270 structure. For example, along river embankments, vegetated crib walls (Figure 1D) can act as a slope  
271 buttress or slope break when placed on an eroding embankment to mitigate gully erosion processes  
272 (Florineth, 2007). Vegetated crib walls help protect the shoreline and promote revegetation because  
273 plants are incorporated within the structure and root growth stabilizes soil (Stangl, 2007). Although  
274 some long-term observations have demonstrated that root development and tree stem growth did  
275 not adversely affect the structure of vegetated crib walls (K. Peklo, unpublished data), practitioners  
276 may hesitate to choose this type of structure because of the way that vegetation interacts with the  
277 structure over time.

278 There is a need to assess more precisely the interrelationships between inert and living materials in  
279 bioengineering structures. Questions remain, in particular with regard to wooden structures, where  
280 wood decay has to be assessed over time, as vegetation grows and develops around the structure  
281 (Barré et al., 2017). Although the role of plants in stabilizing slopes over the long-term is crucial, the  
282 growth dynamics of plants used in bioengineering structures are basically unknown and more  
283 research is needed to address this gap. Questions particularly arise with regard to the desirable

284 biodegradation of wooden structures. When inert structures are used to enhance vegetation  
285 development, for example certain small-scale wooden structures, their initial rigidity has to allow the  
286 triggering of new natural processes such as an improved resilience, an improved ecological  
287 functioning, and vegetation succession processes, before these inert structures disappear (Stokes et  
288 al., 2014). The initial rigidity achieved by means of the inert elements used in the bioengineering  
289 intervention must exist long enough so that plants are capable of developing their reinforcing effect.  
290 This evolution must be reflected well at the design stage related to a predefined construction aim.  
291 Deterioration models of the material used in the work (such as wood) must also be included in the  
292 design (Tardio and Mickovski, 2016). All these considerations call for research to evaluate the level  
293 and speed of decay of wooden structures, as well as the dynamics of vegetation within  
294 bioengineering structures, in relation to the development and diversification of vegetation and to the  
295 desired stage of natural hazard mitigation (Barré et al., 2017).

296 Finally, a maintenance schedule of the living material used in bioengineering structures may be  
297 required. These maintenance tasks are usually needed to avoid vegetation becoming too heavy,  
298 resulting in the overturning of the bioengineering structure. On riverbanks, this maintenance should  
299 also aim at keeping vegetation flexible enough to avoid excessive hydraulic resistance, which can  
300 cause an increase of water levels, and to reduce stem and branch breakage, which produce debris  
301 obstructing bridges and narrow sections of the river (EFIB, 2015).

### 302 **3.3. Design of bioengineering structures**

303 To improve the adoption of bioengineering methods by a wider community, new tools (e.g. soil-  
304 vegetation interaction models, technological frameworks, enhanced methodological approaches and  
305 guidelines) must be developed for use in the design of bioengineering structures. In particular, it is  
306 necessary to know how to use living plants to attain the expected objectives, and to predict the  
307 spatial-temporal development of the installed bioengineering structure, while considering the climate  
308 and ecological conditions of the site. During the pre-design phase, the designer must be able to

309 decide if the bioengineering techniques are feasible or must be used in combination with other  
310 conventional techniques (so called 'mixed' techniques), in order to improve the resistance of the  
311 structure and resilience of the system. Finally, a global, long-term vision of the project at all spatial  
312 scales, from local to catchment, is needed.

313 Improved knowledge is required to design bioengineering structures and optimize their performance  
314 in terms of hazard mitigation while enhancing plant diversity. For example, where is it most effective  
315 to install a structure at a site? How many plants or cuttings should be used within a structure?  
316 Particular attention should be paid to improving our understanding of the efficiency of different plant  
317 species and their traits, depending on the final goal of the intervention (Burylo et al., 2014). To design  
318 technical solutions, the bioengineer can sometimes use physical scale models. This approach is often  
319 not feasible, as plant effects on e.g. slope stability or erosion control and the impact of vegetation on  
320 discharge capacity cannot be downscaled appropriately at reasonable laboratory scales such as 1:30  
321 to 1:40 (Wilson et al., 2006). Prototype scale (1:1) tests remain a viable solution for scientists and  
322 practitioners, but are often not feasible because of time, space, and cost (Schwarz et al., 2012).  
323 Therefore, most engineers use readily available numerical geotechnical models that include the  
324 effects of vegetation. Different types of models have been implemented over the years to predict  
325 landslide risk (see Stokes et al., 2014; Gonzalez-Ollauri and Mickovski, 2017b), many of which  
326 calculate a global Factor of Safety (FoS) at the slope level, but are not suitable for calculating the  
327 efficacy of individual bioengineering structures. Several uncertainties exist in model parameters,  
328 which can be overcome by using a probabilistic approach to e.g. synchronize the mechanical behavior  
329 of roots and soil throughout the development of the shear surface (Tardio and Mickovski, 2015).  
330 Further information on the hydrological effects of root water uptake is also required, particularly for  
331 herbs, shrubs and trees (Chirico et al., 2013; Tron et al., 2014; Arnone et al., 2016; Kim et al., 2017).  
332 Upscaling to the catchment level is still a significant challenge, partially because of a lack of suitable  
333 data to either parameterize or validate models, but also because of a lack of understanding of  
334 biophysical processes at different scales. However, Rossi et al. (2017) demonstrate that the physical



335 landslide model LAPSUS\_LS is suitable for calculating the effects of vegetation on slope stability at the  
336 catchment level. Nevertheless, parallel studies should investigate how soil hydrological and physical  
337 processes at the slope level are altered over a larger scale and vice versa (Bogaard and Greco, 2015).

#### 338 **3.4. Reconciling qualitative experience and quantitative engineering**

339 Statutory constraints related to building structures used for natural hazard control require quantitative  
340 engineering methodology, whereas bioengineering often, but not always, comprises more qualitative  
341 experience. Thus there is a need to develop research that will reconcile these qualitative and  
342 quantitative issues for natural hazard control, but also for ecosystem restoration. Methods for  
343 identifying precise performance thresholds for bioengineering installations at local scales could be very  
344 helpful. Questions to ask include: (i) is a stepwise strategy necessary and therefore an initial plant  
345 protection plan needed? (ii) what is the most efficient spatial distribution of bioengineering structures  
346 and plants for hazard control with regard to the physical forces to which they are subjected? (iii) what is  
347 the necessary, but adequate, rate of vegetation cover to control a given natural hazard, while  
348 considering also ecological processes at this spatial level? Answers to these questions are strongly  
349 related to the objectives, which will be different in the case of natural hazard mitigation or ecological  
350 restoration. A need also expressed by practitioners is to define appropriate indicators that allow  
351 managers to determine the thresholds of efficiency when reconciling natural hazard control and  
352 ecological restoration. Finally, the need for case study analysis in terms of bioengineering work  
353 performance has been suggested as a useful tool for proposing improvements at the design,  
354 construction, and monitoring stages.

355 One further crucial issue determining the success of a bioengineering project is to know if bioengineers  
356 can have the financial freedom to create the "best" solution to each problem (EFIB, 2014). For example,  
357 for a project in which ecological restoration is required and when significant financial means can be  
358 used to implement optimal actions, such actions are able to achieve effective restoration, and enable  
359 the damaged ecosystem to recover its original condition. But when constraints are imposed in

360 budgeting and financing bioengineering projects, such as in underdeveloped countries, it is necessary to  
361 minimize interventions. In this later case, complete 'restoration' is not economically possible. Therefore,  
362 recovering the ecosystem to a state before degradation is not the final objective, but reaching a specific  
363 ecosystem objective in line with the current technical, socio-economic and ecological problems, such as  
364 controlling a specific natural hazard, becomes the main aim (Rey, 2009). This situation also calls for  
365 reconciling possible qualitative issues linked to the definition of precise objectives of a bioengineering  
366 project, and quantitative engineering, corresponding to the design of the bioengineering structures and  
367 the related financial means.

### 368 **3.5. Defining actions at the catchment and landscape scales**

369 Soil and water bioengineering techniques are usually targeted to discrete locations, whereas their  
370 design often needs to be considered at the catchment and landscape scales (Bifulco et al., 2015). The  
371 variables with the greatest influence on a bioengineering structure's final design are usually  
372 structural, hydraulic or related to plant characteristics, especially when natural hazard mitigation is  
373 the main objective. Using bioengineering for natural hazard mitigation at the catchment scale,  
374 especially with regard to water and sediment transport, implies taking into account the connectivity  
375 between slopes and the river or gully channel, and between upstream and downstream parts of the  
376 catchment. For example with respect to flood reduction, a key objective can be to reduce runoff and  
377 particularly to interrupt the fine sediment connectivity between various parts of the catchment (e.g.  
378 Verstraeten et al., 2006; Borselli et al. 2008; Rey and Burylo, 2014; Mekonnen et al. 2015). The spatial  
379 distribution of control measures such as planted areas also needs to be considered at the wider  
380 catchment scale, as does the climatic regime. In some cases it will be possible to provide a level of  
381 control for more frequent climatic events that generate sediment. Nevertheless, designing structures  
382 or bioengineering solutions to deal with extreme, infrequent or high magnitude events remains  
383 problematic.

384 The need to define strategies for bioengineering at the catchment and landscape scales is well  
385 illustrated in the framework of Green infrastructure (GI), interconnected networks of natural or semi-  
386 natural sites able to provide environmental, social, and economic benefits to human populations  
387 (known as ecosystem services). Soil bioengineering can play a fundamental role in creating networks  
388 because their capability is to bridge natural and man-made environments. It allows the restoration of  
389 ecosystems and is an effective tool in the implementation of GI (EFIB, 2014). Although GI is included  
390 in several EU and International Agencies programs and policies (e.g. EU 2020 Biodiversity Strategy,  
391 Natura 2000, UNEP-DHI 2014 Green Infrastructure Guide for Water Management), the use of soil  
392 bioengineering techniques is generally implicit. The success in implementing a GI strategy strongly  
393 depends on the achievements of bioengineers. Soil bioengineering techniques, by including  
394 vegetation as an intrinsic component of installations, are able to provide several functions, such as  
395 slope and riverbank stabilization and protection from soil erosion, as well as habitat for animals,  
396 microclimate regulation and recreational use (Table 1, Stokes et al., 2014). Therefore, design of  
397 bioengineering structures can be thought for allowing them to provide both slope stabilization and  
398 ecological restoration (Figure 5).

399 The Blue infrastructures (BI) framework is also a good illustration of the complex questions facing  
400 bioengineers. Worldwide, two contrary eco-geomorphological management practices co-exist for  
401 rivers. In some catchments, aggradation of the river channel occurs, a phenomenon caused by  
402 excessive fine sediment in the river. Habitats for fish reproduction may be damaged, flood risks  
403 increase, and hydroelectric reservoirs can fill with sediment (Rey, 2009). In contrast, other catchments  
404 suffer from a lack of bed load in the river. As a consequence, groundwater levels can decrease and  
405 river beds incise, causing damage such as bridge destabilization (Liébault et al., 2005). Vegetation  
406 cover in the surrounding landscape is an important factor controlling the erosion responsible for  
407 sediment yield in rivers. In case of bedload excess, eroding slopes and riverbanks are controlled  
408 through bioengineering measures and revegetation efforts, considered as restoration actions on  
409 degraded land (e.g., Vallauri et al., 2002). Conversely, where a deficit of bedload exists, slope erosion

410 can be reactivated by destroying the vegetation on highly erodible soils. Sometimes, both situations  
411 co-exist within the river's catchment, but generally in different parts and at different times, as stated  
412 by Liébault et al. (2005) who recorded both aggradation followed by degradation in the same  
413 catchment pre-reforestation and post-reforestation. Thus the influence of vegetation on a river's  
414 sediment production, especially in mountainous areas, is often difficult to understand.

415 Another situation showing the difficulty in reconciling natural hazard mitigation and ecological  
416 restoration is the management of dams on rivers. These structures often have a role in managing  
417 floods and many have been constructed over a century ago in different countries (e.g, Vallauri et al.,  
418 2002 on French experience). However, today these structures are blamed for representing obstacles  
419 to aquatic fauna, and programs for removing them are developed, calling into question the impact of  
420 this kind of action on the river's stability. One solution consists in replacing dams with rough rock  
421 ramps with integrated fishway (Figure 6). All these examples call for more discussion between  
422 scientists and practitioners, as well as a better assessment of current knowledge. There is an urgent  
423 need to consider new research strategies and to determine whether ecological restoration actions  
424 should be carried out on areas where natural hazards occur, with different ecological and socio-  
425 economic issues calling for different solutions in the management of these hazards.

#### 426 **4. Conclusion**

427 In the sections above, we highlighted the practice and research needs in soil and water bioengineering  
428 through a critical review of the definition and development of bioengineering technology, while  
429 stressing the issues about the design, implementation, and monitoring of bioengineering actions. Based  
430 on the critical analysis presented above, we conclude that there is a need to reconcile natural hazard  
431 control and ecological restoration by posing new applied research questions aimed at meeting this  
432 purpose. More importantly, there is a need to define sound techniques that reconcile natural hazard  
433 control and ecological restoration. The key considerations helping succeeding bioengineering actions in

434 the future can be summarized as: (i) considering a multidisciplinary approach for soil and water  
435 bioengineering projects, (ii) establishing practical guidelines and tools for designing bioengineering  
436 structures, (iii) implementing monitoring stages in bioengineering projects, (iv) transmitting  
437 knowledge and know-how on soil and water bioengineering, (v) analyzing existing bioengineering  
438 works in terms of their performance, successes and failures, and (vi) continuing to identify the needs  
439 of the bioengineering professional sector.

440

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687 **Table 1: Illustration of some ecosystem services provided by grass buffer strips, grassed waterways,**  
688 **and small flood retention ponds (bioengineering techniques) installed to reduce soil erosion rates**  
689 **by water and muddy floods in the loess belt of Belgium (based on Vandaele (2010) and various**  
690 **unpublished data).**

691

692 \* **Maintenance and improvement of soil ecosystem services:** e.g. food, fiber, fuel and other biomass  
693 production; environmental interactions such as water filtering, carbon storage (e.g., due to the  
694 change of cropland to grassland) and nutrient cycling (e.g. N and P), transformation of substances,  
695 biological habitat for soil micro-organisms, fauna and gene pool; archive of our past (artefacts and  
696 indicators of environmental change).

697 \* **Maintenance and improvement of hydrological systems:** e.g. on site water infiltration, retention  
698 and storage, flow energy dissipation, off site flood control through reduced peak flow discharge and  
699 reduced sediment overloads.

700 \* **Increase of biodiversity:** e.g. vegetation (such as properly managed species-rich grasses, herbs and  
701 multiple cover crops), providing food and habitats for spiders, insects (e.g. bees, ground beetles,  
702 Ichneumonidae, ladybirds that are important for pollination and pest control), birds (such as skylarks,  
703 partridges and birds of prey), mammals as well as amphibians (in ecologically designed flood  
704 retention pools).

705 \* **Increase of ecological connectivity** facilitating circulation of fauna in landscapes dominated by  
706 crops. Creation of ecological corridors for various kinds of animals, including potentially slow moving  
707 earth or water-bound species. Increase of genetic exchanges between distant populations of the  
708 same species.

709 \* **Adsorption of pollutants** transported by runoff and wind (dust), hence cleaner surface water,  
710 groundwater and air

711 \* **Reduction of negative off-site effects** such as sediment deposits on cropland, infrastructure and  
712 private property, psychological stress to inhabitants that were frequently affected by muddy floods.

713 \* **Enhanced quality of landscapes** predominantly consisting of cropland through the installation of  
714 green corridors (grass buffer strips, grassed waterways and cover crops) and blue measures (such as  
715 flood retention ponds), which lead to an improved recreational attractiveness.

716

717 **Figure 1.** Examples of bioengineering structures and installations worldwide. A. Palissades (France)  
 718 (photo: F. Rey); B. Grass buffer strips (Belgium) (photo: J. Poesen); C. Green steel structure and log  
 719 branch/dormant cuttings after completion (France) (photo: K. Peklo); D. Prefabricated wooden  
 720 structure (Italy) (photo: F. Preti); E. Modified brush layers (Canada) (photo: D. Polster); F. Sowings  
 721 with straw mats and vegetated bench (Portugal) (photo C. Bifulco); G. Mixed check dam (Canary  
 722 Islands) (photo: G. Tardio); H. Planting with willow cuttings and coconut tissue (Switzerland)  
 723 G. De Cesare); I. Brushlayer, straw and wattle (Canada) (photo: P. Raymond); J. Vegetated crib wall  
 724 (Austria) (photo: H.P. Rauch); K. Hydroseeding (Scotland) (photo: S. Mickovski); L. River modeling  
 725 (Austria) (photo: F. Florineth).

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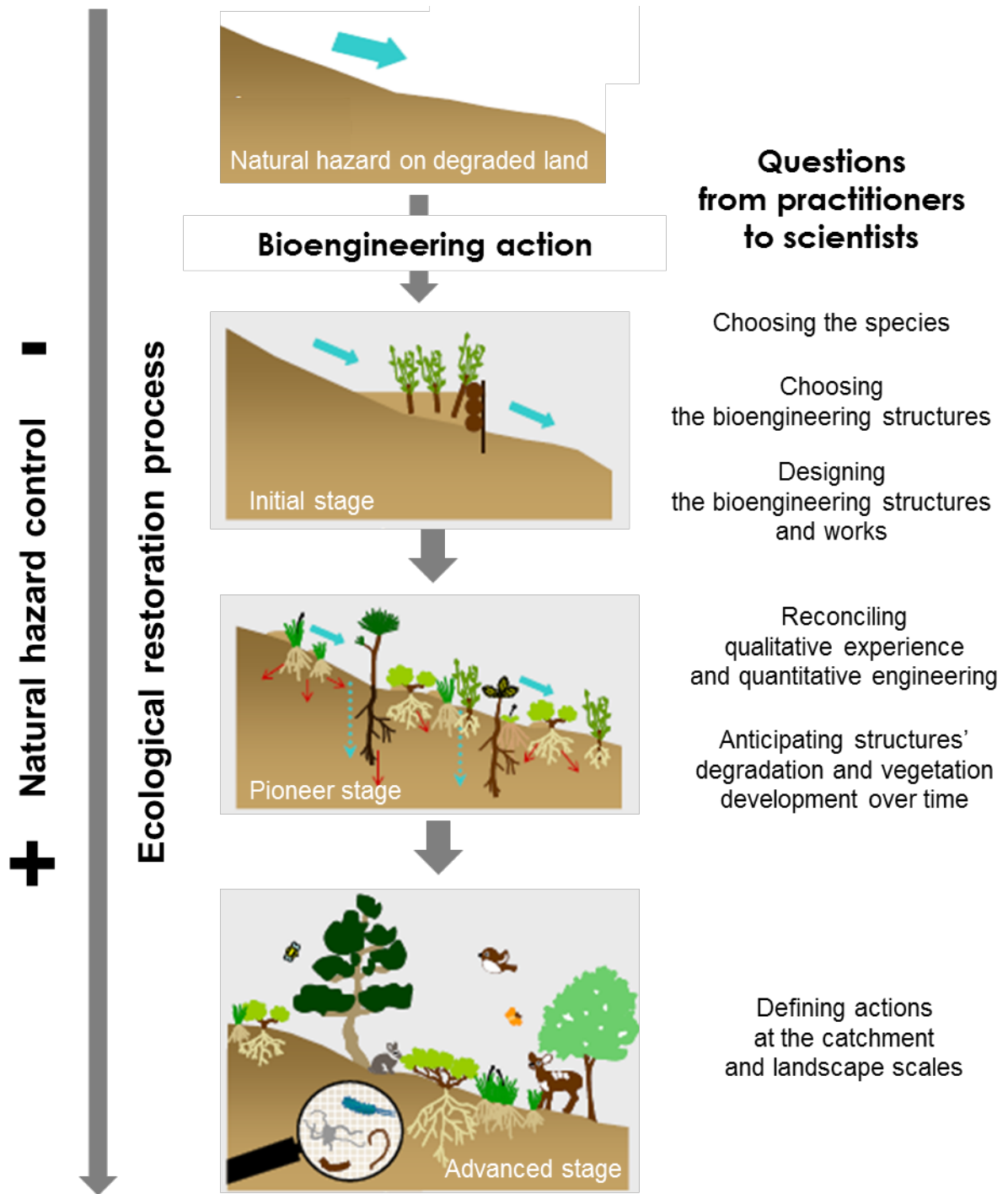
738 **Figure 2:** Which bioengineering structures to use to restore this degraded stream while protecting the  
739 railway against floods? (photo: F. Rey)



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742 **Figure 3:** Questions arising from practitioners showing how research objectives should be defined  
 743 throughout the life of a bioengineering intervention, and the consequences for the ecological  
 744 trajectory of a bioengineering structure. Such an approach would lead to improved natural hazard  
 745 control and ecological restoration of a degraded site (Burylo and Rey, unpublished)



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748 **Figure 4:** Biodiversity can have a negative effect on sediment trapping performance of vegetation  
749 barriers, as monospecific barriers involving one very performant species are more efficient than  
750 plurispecific ones including more or less efficient species (photo: F. Rey)



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754 **Figure 5:** Design of bioengineering structures along riverbanks can be thought for allowing them to  
755 provide both slope stabilization and ecological restoration (photo: K. Peklo)



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758 **Figure 6:** Rough rock ramp with integrated fishway, providing positive action for both riverbed  
759 stabilization and fish movement (photo: K. Peklo)



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