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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 (Clewel 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) (Petrone 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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452

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454 **References**

455 Arnone, E., Caracciolo, D., Noto, L.V., Preti, F., Bras, R.L., 2016. Modeling the hydrological and
456 mechanical effect of roots on shallow landslides. *Water Resources Research* 52,8590–8612.

457 Aronson, J., Floret, C., Le Floc'h, E., Ovalle, C., Pontanier, R., 1993. Restoration and rehabilitation of
458 degraded ecosystems in arid and semi-arid lands. I. A view from the South. *Restoration*
459 *Ecology* 1, 8-17.

460 Barker, D.H., Watson, A.J., Sombatpanit, S., Northcutt, B., Magliano, A.R., (Eds). 2004. Ground and
461 water bioengineering for erosion control and slope stabilization. Science Publishers Inc,
462 Enfield, NH.

463 Barré, J.B.B., Bourrier, F., Bertrand, D., Thévenon, M.F., Rey, F., 2017. Assessment of the level of decay
464 of small-diameter silver fir logs degraded in natural conditions in the French Northern Alps
465 using two different methods. *Ecological engineering* 109, 240-248.

466 Bast, A., Wilcke, W., Graf, F., Lüscher, P., Gärtner, H., 2016. Does mycorrhizal inoculation improve plant
467 survival, aggregate stability, and fine root development on a coarse-grained soil in an alpine
468 eco-engineering field experiment? *Journal of Geophysical Research Biogeosciences* 121,
469 2158–2171.

470 Bifulco, C., Pereira, A., Ferreira, V., Mota, A., Martins, L., Rego, F., 2015. Renewing dangerous highway
471 slopes in Portugal. *Ingenieurbiologie* 3, 43-50.

472 Bischetti, G.B., Chiaradia, E.A, D'Agostino V., Simonato, T., 2010. Quantifying the effect of brush
473 layering on slope stability. *Ecological Engineering* 36, 258-264.

474 Bischetti, G.B., Di Fi Dio, M., Florineth, F. 2014. On the origin of soil bioengineering. *Landscape*
475 *Research*,1-13.

- 476 Bochet, E., Garcia-Fayos, P., Poesen, J., 2009. Topographic thresholds for plant colonization on semi-
477 arid eroded slopes. *Earth Surface Processes and Landforms* 34, 1758-1771.
- 478 Bogaard, T.A., Greco, R., 2015. *Landslide hydrology: from hydrology to pore pressure*. Wiley
479 *Interdisciplinary Reviews: Water* 3, 439-459.
- 480 Borselli, L., Cassi, P., Torri, D., 2008. Prolegomena to sediment and flow connectivity in the landscape:
481 A GIS and field numerical assessment. *Catena* 75, 268–277.
- 482 Bresci, F., Preti, F., 2010. A historical survey on the evolution of some forest watershed management
483 techniques (part II: stream channel works). *Journal of Agricultural Engineering* 1, 13-22.
- 484 Burylo, M., Dutoit, T., Rey, F., 2014. Species traits as practical tools for ecological restoration of marly
485 eroded lands. *Restoration Ecology* 22, 633-640.
- 486 Chirico, G.B., Borga, M., Tarolli, P., Rigon, R., Preti, F., 2013. Role of vegetation on slope stability under
487 transient unsaturated conditions. *Procedia Environmental Sciences* 19, 932–941.
- 488 Clemente, A.S., Moedas, A.R., Oliveira, G., Martins-Loução, M.A., Correia, O., 2016. Effect of
489 hydroseeding components on the germination of Mediterranean native plant species.
490 *Journal of Arid Environments* 125, 68-72.
- 491 Clewell, A.F., Aronson J., 2013. *Ecological restoration: principles, values, and structure of an emerging*
492 *profession*. Society for Ecological Restoration, 336 p.
- 493 De Baets, S., Poesen, J., Reubens, B., Muys, B., De Baerdemaeker, J. & Meersmans, J., 2009.
494 *Methodological framework to select plant species for controlling rill and gully erosion:*
495 *application to a Mediterranean ecosystem*. *Earth Surface Processes and Landforms* 34, 1374-
496 1392.

497 Demenois J., Rey F., Stokes A. Carriconde F., 2017. Does arbuscular and ectomycorrhizal fungal
498 inoculation improve soil aggregate stability? A case study on three tropical species growing in
499 ultramafic Ferralsols. *Pedobiologia* 64, 8-14.

500 Dhital, Y.P., Kayastha, R.B., Shi, J., 2013. Soil bioengineering application and practices in Nepal.
501 *Environmental Management* 51, 354-364.

502 Dhital, Y.P., Tang, Q., 2015. Soil bioengineering application for flood hazard minimization in the
503 foothills of Siwaliks, Nepal. *Ecological Engineering* 74, 458-462.

504 European Commission (2013). Communication from the Commission to the European Parliament, the
505 Council, the European Economic and Social Committee and the Committee of the Regions
506 'Green Infrastructure (GI) — Enhancing Europe's Natural Capital' (COM/2013/0249 final).

507 EFIB. 2015. European guidelines for soil and water bioengineering. European Federation of Soil
508 Bioengineering.

509 EFIB. 2014. Soil and Water Bioengineering and Green infrastructure. VIIIe Congress EFIB-AEIP-APENA
510 Vitoria Gasteiz, Spain.

511 Erktan, A., Cécillon, L., Roose, E., Frascaria-Lacoste, N., Rey, F., 2013. Morphological diversity of plant
512 barriers does not increase sediment retention in eroded marly gullies under ecological
513 rehabilitation (Southern Alps, France). *Plant and soil* 370, 653-669.

514 Florineth, F., 2007. Bioengineering methods of strengthening slopes in the Alps: protection of deep
515 soil and subsoil horizons. *Environmental Planning and Management* 2, 35-45.

516 Furuta, N., Monty, F., Murti, R., 2016. Helping nature help us: transforming disaster risk reduction
517 through ecosystem management. IUCN Publication, Switzerland.

518 Gonzalez-Ollauri, A., Mickovski, S.B., 2016. Using the root spread information of pioneer plants to
519 quantify their mitigation potential against shallow landslides and erosion in temperate humid
520 climates. *Ecological Engineering* 95, 302-315.

521 Gonzalez-Ollauri, A., Mickovski, S.B., 2017a. Plant-soil reinforcement response under different soil
522 hydrological regimes. *Geoderma* 285, 141-150.

523 Gonzalez-Ollauri, A., Mickovski, S.B., 2017b. Shallow landslides as drivers for slope ecosystems
524 evolution and biophysical diversity. *Landslides* 14, 1699-1714.

525 Graf, F., Frei, M., 2013. Soil aggregate stability related to soil density, root length, and mycorrhiza using
526 site-specific *Alnus incana* and *Melanogaster variegatus* s.l. *Ecological Engineering* 57, 314-
527 323.

528 Gray, D.H., Sotir, R.B., 1996. *Biotechnical and soil bioengineering slope stabilization: a practical guide*
529 *for erosion control*. John Wiley & Sons, New York, NY.

530 Hacker, E., Johanssen, R., 2012. *Ingenieurbiologie*. Eugen Ulmer KG, Stuttgart.

531 Jin, K., Cornelis, W.M., Gabriels, D., Schiettecatte, W., De Neve, S., Lu, J., Buysse, T., Harmann, R.,
532 2008. Soil management effects on runoff and soil loss from field rainfall simulation. *Catena* 75,
533 191-199.

534 Kim, J.H., Fourcaud, T., Jourdan, C., Maeght, J.L., Mao, Z., Metayer, J., Meylan, L., Pierret, A., Rapidel,
535 B., Rouspard, O., de Rouw, A., Villatoro Sanchez, M., Wang, Y., Stokes, A., 2017. Vegetation as
536 a driver of temporal variations in slope stability: The impact of hydrological processes.
537 *Geophysical Research Letters* 44, 4897-4907.

538 Li, X., Zhang, L., Zhang, Z., 2006. Soil bioengineering and the ecological restoration of riverbanks at
539 the Airport Town, Shanghai, China. *Ecological Engineering* 26, 304-314.

540 Liébault, F., Gomez, B., Page, M., Marden, M., Peacock, D., Richard, D. and Trotter, C. M., 2005. Land-
541 use change, sediment production and channel response in upland regions. *River Research*
542 *and Applications* 21, 739–756.

543 Lin, W.T., Lin, C.Y., Chou, W.C., 2006. Assessment of vegetation recovery and soil erosion at landslides
544 caused by a catastrophic earthquake: A case study in Central Taiwan. *Ecological Engineering*
545 28, 79-89.

546 Mekonnen, M., Keesstra, S., Stroosnijder, L., Baartman, J., Maroulis, J., 2015. Soil conservation
547 through sediment trapping: a review. *Land Degradation and Development* 26, 544-556.

548 Mickovski, S.B. 2014. Resilient design of landslip prevention measures: a case study. *Proceedings of*
549 *the ICE - Forensic Engineering* 168, 96-106.

550 Mickovski, S.B., Van Beek, L.P.H., 2006. A decision support system for the evaluation of eco-
551 engineering strategies for slope protection. *Geotechnical and Geological Engineering* 24, 483-
552 498.

553 Mickovski, S.B., Tardio Cerrillo, G., Sangalli, P., Perez, J., Thomson, C.S., Gallagher, C., 2018.
554 Development of Eco-Engineering Sector Specific Routines and Curricula for the
555 Mediterranean Region. In: Kallel A., Ksibi M., Ben Dhia H., Khélifi N. (eds) *Recent Advances in*
556 *Environmental Science from the Euro-Mediterranean and Surrounding Regions. EMCEI 2017.*
557 *Advances in Science, Technology & Innovation (IEREK Interdisciplinary Series for Sustainable*
558 *Development)*. Springer, Cham. pp 937-939.

559 Mitsch, W.J., 2012. What is ecological engineering? *Ecological Engineering* 45, 5-12.

560 Mitsch, W.J., 2014. When will ecologists learn engineering and engineers learn ecology? *Ecological*
561 *Engineering* 65, 9-14.

562 Mitsch, W.J., Jørgensen, S.E., 2003. Ecological engineering: a field whose time has come. Ecological
563 Engineering 20, 363-377.

564 Mitsch, W.J., Jørgensen S.E., 2004. Ecological engineering and ecosystem restoration, John Wiley &
565 Sons.

566 Mkanda, F.X., 2002. Contribution by farmers' survival strategies to soil erosion in the Linthipe River
567 Catchment: Implications for biodiversity conservation in Lake Malawi/Nyasa. Biodiversity and
568 Conservation 11, 1327-1359.

569 Nadal-Romero, E., Petrlíc, K., Verachtert, E., Bochet, E., Poesen, J., 2014. Effects of slope angle and
570 aspect on plant cover and species richness in a humid Mediterranean badland. Earth Surface
571 Processes and Landforms 39, 1705–1716.

572 Norris, J.E., Stokes, A., Mickovski, S.B., Cammeraat, E., van Beek, R., Nicoll, B.C., Achim, A., (Eds).
573 2008. Slope stability and erosion control: ecotechnological solutions. Springer, Dordrecht, The
574 Netherlands.

575 Peklo, K., 2015. L'apport d'un programme de modélisation hydrodynamique bidimensionnel au travail
576 de l'ingénieur. Ingenieurbiologie 3, 13-17.

577 Perez J., Condes Salazaar R., Stokes A., 2017. An open access database of plant species useful for
578 controlling soil erosion and substrate mass movement. Ecological Engineering 99, 530-534.

579 Petrone, A., Preti, F., 2010. Soil bioengineering for risk mitigation and environmental restoration in a
580 humid tropical area. Hydrology and Earth System Sciences 14, 239-250.

581 Phillips, C.J., Rey, F., Marden, M., Liébault, F., 2013. Revegetation of degraded steplands in France
582 and New Zealand: a comparison of geomorphic and policy responses. New Zealand Journal of
583 Forestry Science 43, 14.

- 584 Poesen, J. 2017. Soil erosion in the Anthropocene: research needs. *Earth Surface Processes and*
585 *Landforms* 43, 64-84.
- 586 Poesen, J., Nachtergaele, J., Verstraeten G., Valentin, C., 2003. Gully erosion and environmental
587 change: Importance and research needs. *Catena* 50, 91-133.
- 588 Pohl, M., Graf F., Buttler A., Rixen C., 2012. The relationship between plant species richness and soil
589 aggregate stability can depend on disturbance. *Plant and Soil* 355, 87-102.
- 590 Powell, C.L.L., 1980. Mycorrhizal infectivity of eroded soils. *Soil Biology and Biochemistry* 12, 247-250.
- 591 Preti, F., Giadrossich, F., 2009. Root reinforcement and slope bioengineering stabilization by Spanish
592 Broom (*Spartium junceum* L.). *Hydrology and Earth System Sciences* 13, 1713-1726.
- 593 Preti, F., Petrone, A., 2013. Soil bioengineering for watershed management and disaster mitigation in
594 Ecuador: a short-term species suitability test. *iForest* 6, 95-99.
- 595 Pretty, J.L. Harrison, S.S.C., Shepherd, D.J., Smith, C., Hildrew, A.G., Hey, R.D., 2003. River
596 rehabilitation and fish populations: assessing the benefit of instream structures. *Journal of*
597 *Applied Ecology* 40, 251-265.
- 598 Rauch, H.P., Sutili, F.J., Hörbinger, S., 2014. Installation of a riparian forest by means of soil bio
599 engineering techniques—Monitoring results from a river restoration work in Southern Brazil.
600 *Open Journal of Forestry* 4, 161-169.
- 601 Renaud, F.G., Sudmeier-Rieux, K., Estrella, M., Nehren, U. (Eds.) 2016. *Ecosystem-Based Disaster Risk*
602 *Reduction and Adaptation in Practice. Advances in Natural and Technological Hazards*
603 *Research. Springer.*

604 Rey, F., 2009. A strategy for fine sediment retention with bioengineering works in eroded marly
605 catchments in a mountainous Mediterranean climate (Southern Alps, France). *Land*
606 *Degradation and Development* 20, 210-216.

607 Rey, F., Burylo, M., 2014. Can bioengineering structures made of willow cuttings trap sediment in
608 eroded marly gullies in a mountainous and Mediterranean climate (Southern Alps, France)?
609 *Geomorphology* 204, 564-572.

610 Rey, F., Labonne, S., 2015. Resprout and survival of willow (*Salix*) cuttings in marly gullies in a
611 mountainous Mediterranean climate: a real size experiment in the Francon catchment
612 (Southern Alps, France). *Environmental Management* 56, 971-983.

613 Rossi, L.M.W., Rapidel, B., Roupsard, O., Villatoro, M., Mao, Z., Nespoulous, J., Perez, J., Metselaar, K.,
614 Schoorl, J.M., Claessens, L., Stokes, A., 2017. Sensitivity of the landslide model LAPSUS_LS to
615 vegetation and soil parameters. *Ecological Engineering* 109, 249-255.

616 Schaff, S.D., Pezeshki, S.R., Shields F.D., 2013. Effects of soil conditions on survival and growth of black
617 willow cuttings. *Environmental Management* 31, 748-763.

618 Schiechl, H.M., Stern, R., 1996. *Ground bioengineering techniques for slope protection and erosion*
619 *control*. Blackwell Science, Oxford, UK, 146 p.

620 Schiechl, H.M., Stern R., 1997. *Water bioengineering techniques for watercourse bank and shoreline*
621 *protection*. Blackwell Science, Oxford, UK, 186 p.

622 Schleiss, A. J., Franca, M. J., Juez, C. and De Cesare, G., 2016. Reservoir sedimentation, vision paper.
623 *Journal of Hydraulic Research* 54, 595-614.

624 Schwarz, M., Cohen, D., Or, D. 2012. Spatial characterization of root reinforcement at stand scale:
625 theory and case study. *Geomorphology* 171–172, 190-200.

- 626 Smith, A.B., Katz, R.W., 2013. US billion-dollar weather and climate disasters: data sources, trends,
627 accuracy and biases. *Natural Hazards* 67, 387-410.
- 628 Staab, K., Yannelli, F.A., Lang, M., Kollmann, J., 2015. Bioengineering effectiveness of seed mixtures
629 for road verges: Functional composition as a predictor of grassland diversity and invasion
630 resistance. *Ecological Engineering* 84, 104-112.
- 631 Steiger, J., Gurnell, A.M., Petts, G.E., 2001. Sediment deposition along the channel margins of a reach
632 of the middle river Severn, UK. *River Research and Applications* 17, 443-460.
- 633 Stock, P., Burton, R.J.F., 2011. Defining Terms for Integrated (Multi-Inter-Trans-Disciplinary)
634 Sustainability Research. *Sustainability* 3, 1090-1113.
- 635 Stokes, A., Douglas, G., Fourcaud, T., Giadrossich, F., Gillies, C., Hubble, T., Kim, J.H., Loades, K., Mao,
636 Z., McIvor, I., Mickovski, S.B., Mitchell, S., Osman, N., Phillips, C., Poesen, J., Polster, D., Preti,
637 F., Raymond, P., Rey, F., Schwarz, M., Walker, L.R., 2014. Ecological mitigation of hillslope
638 instability: ten key issues facing practitioners and researchers. *Plant and Soil* 377, 1-23.
- 639 Stokes, A., Raymond, P., Polster, D., Mitchell, S.J., 2013. Engineering the ecological mitigation of
640 hillslope stability research into the scientific literature. *Ecological Engineering* 61, 615-620.
- 641 Stokes, A., Spanos, I., Norris, J.E., Cammeraat E., (Eds). 2004. Eco- and ground bioengineering: the use
642 of vegetation to improve slope stability. *Developments in plant and soil sciences* 103, CD-
643 ROM.
- 644 Tardío-Cerrillo, G. and García-Rodríguez, J.L., 2016. Monitoring of erosion preventive structures based
645 on eco-engineering approaches: the case of the mixed check dams of masonry and forest
646 residues. *Journal of Engineering Science and Technology Review* 9, 103–107.

647 Tardio, G., Mickovski, S.B., 2015. Method for synchronisation of soil and root behaviour for
648 assessment of stability of vegetated slopes. *Journal of Ecological Engineering* 82,222–230.

649 Tardio, G., Mickovski, S.B., 2016. Implementation of eco-engineering design into existing slope
650 stability design practices. *Ecological Engineering* 92, 138-147.

651 Tardio, G., Mickovski, S.B., Stokes, A., Devkota, S., 2017. Bamboo structures as a resilient erosion
652 control measure. *Proceedings of the Institution of Civil Engineers* 170, 72-83.

653 Tron, S., Dani, A., Laio, F., Preti, F., Ridolfi, L., 2014. Mean root depth estimation at landslide slopes.
654 *Ecological Engineering* 69, 118-125.

655 Vallauri, D., Aronson, J., Barbero, M., 2002. An analysis of forest restoration 120 years after
656 reforestation on badlands in the Southwestern Alps. *Restoration Ecology* 10, 16-26.

657 Vandaele, K., 2010. From mudflow prevention to ecosystem services development, The Melsterbeek
658 catchment, Sint-Truiden, Belgium. *The Economics of Ecosystems & Biodiversity (TEEB)*.
659 TEEBcase: Changed agro-management to prevent muddy floods, Belgium. Available at:
660 www.TEEBweb.org.

661 Verstraeten, G., Poesen, J., Gillijns, K. and Govers, G., 2006. The use of riparian vegetated filter strips
662 to reduce river sediment loads: an overestimated control measure? *Hydrological Processes*
663 20, 4259-4267.

664 Walker, L.R., Velázquez, E., Shiels, A.B., 2009. Applying lessons from ecological succession to the
665 restoration of landslides. *Plant and Soil* 324, 157-168.

666 Wang, J.H., Lu, X.G., Tian, J.H. 2008. Theory and application technology of riparian wetland. *Wetland*
667 *Science* 6, 97-104.

668 Wilson, C., Yagci, O., Rauch, H. & Stoesser, T., 2006. Application of the drag force approach to model
669 the flow-interaction of natural vegetation. *Journal of River Basin Management*, Band Issue 2,
670 1-10.

671 Woolsey, S., Capelli, F., Gonser, T., Hoehn, E., Hostmann, M., Junker, B., Paetzold, A., Roulier, C.,
672 Schweizer, S., Tiegs, S. D., Tockner, K., Weber, C., Peter, A., 2007. A strategy to assess river
673 restoration success. *Freshwater Biology* 52, 752-769.

674 Xiao, H., Huang, J., Ma, Q., Wan, J., Li, L., Peng, Q., Rezaeimalek, S., 2017. Experimental study on the
675 soil mixture to promote vegetation for slope protection and landslide prevention. *Landslides*
676 14, 287-297.

677 Yildiz, A., Askarinejad, A., Graf, F., Rickli, C., Springman, S.M., 2015. Effects of roots and mycorrhizal
678 fungi on the stability of slopes, in: Winter, M.G., Smith, D.M., Eldred, P.J.L., Toll, D.G. (Eds.),
679 XVI ECSMGE Geotechnical Engineering for Infrastructure and Development. ICE Publishing,
680 pp. 1693–1698.

681 Yildiz, A., Rickli, C., Graf, F., Springman, S.M., 2018. An assessment of plant-induced suction and its
682 effects on the shear strength of root-permeated soils. *Geoderma*. submitted in revised form
683 08 Feb 2018 (GEODER_2017_1623).

684 Zeh, H. 2007. *Soil Bioengineering Construction Type Manual*. Verein für Ingenieurbioogie Vdf-EFIB,
685 441 p.

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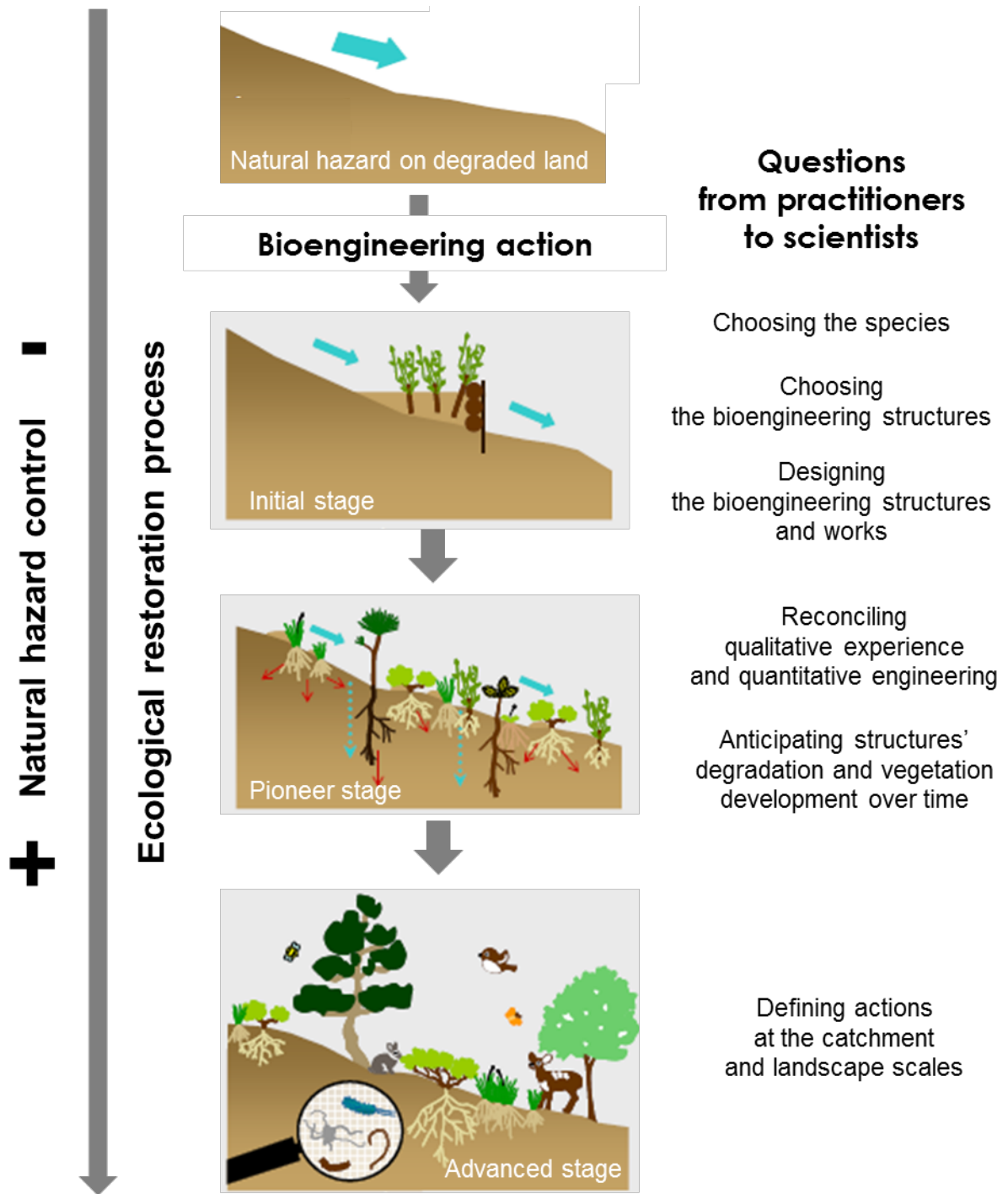
738 **Figure 2:** Which bioengineering structures to use to restore this degraded stream while protecting the
739 railway against floods? (photo: F. Rey)



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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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