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Decision-making framework to support green-blue infrastructure multifunctionality

Cumulative dissertation to obtain the doctoral degree

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submitted by

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Manter em pé o que resta não basta

Que alguém vira derrubar o que resta

O jeito é convencer quem devasta

A respeitar a floresta

Gilberto Gil – song, refloresta

To keep standing what remains is not enough

Because someone's going to tear down what's left

The way is to convince those who devastate

To respect the forest

Preface

The present thesis is the result of research activities carried out in several interdisciplinary research projects. It was written as a cumulative dissertation and consists of two sections. The first section contains an introduction to the topic, a description of the conceptual framework of the thesis, a synopsis of the research work and final conclusions. The second section is the appendix that consists of the eight articles that form the core of this thesis and a CV. Each of the articles is presented in the format of the print layout of the journal in which it was published.

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Abstract

Natural areas are able to perform several functions and provide multiple benefits for human well-being. In view of growing pressures on the natural balance due to the increasing use of natural resources and the impacts of climate change, there is an urgent need for instruments and tools that help to better consider ecological services in decision-making processes. This thesis addresses the operationalisation of the two complementary concepts of green-blue infrastructure (GBI) and nature-based solutions (NbS). In particular, because the GBI and NbS concepts are very broad, there is a need for unified frameworks that support decision-making. Ecosystem service (ES) assessment approaches are presented that aim to support the design of NbS so that specific combinations of provisioning, regulating and cultural services can be achieved. Effects of ecosystem functions that are adverse to humans, the state of ecosystems and subsequent negative environmental impacts were also incorporated into the framework. Vegetation structures along railways and watercourses were addressed as GBI, for which there is a high demand for ES and which are subject to special technical requirements. The periodical survey of vegetation data by means of remote sensing technologies and subsequent data analysis guaranteed the quantification of ES on the one hand and the identification of risk areas on the other. In this context, one can speak of NbS, which have the potential to contribute to climate change adaptation and mitigation in addition to biodiversity conservation. Information about the multifunctional potentials of NbS, their demonstrable benefits and added values is the basis for technical standards in design and operationalisation. This work provides methodological approaches, for the installation of NbS and for the periodic monitoring and evaluation of the multifunctionality of GBI. This is a fundamental requirement, as these systems develop dynamically and, thus, their functionality also changes over time.

Keywords: green-blue infrastructure; nature-based solutions; soil and water bioengineering; remote sensing; ecosystem services; lineside vegetation; riparian ecosystems; decision-making framework; multifunctionality

Kurzfassung

Naturräume erfüllen verschiedenste Funktionen und bieten vielfältigen Nutzen für das menschliche Wohlergehen. Angesichts wachsender Belastungen des Naturhaushaltes durch die zunehmende Nutzung natürlicher Ressourcen und der Auswirkungen des Klimawandels besteht ein dringender Bedarf an Instrumenten und Werkzeugen, die helfen, ökologische Leistungen in Entscheidungsprozessen besser zu berücksichtigen. Diese Arbeit befasst sich mit der Operationalisierung der beiden komplementären Konzepte der grün-blauen Infrastruktur (GBI) und der naturbasierten Lösungen (NbS). Aufgrund der sehr allgemeinen Ausrichtung beider Konzepte besteht ein Bedarf an einheitlichen Rahmenwerken. Es werden Ansätze zur Bewertung von Ökosystemdienstleistungen (ÖSD) vorgestellt, durch die die Planung von NbS unterstützt wird und spezifische Kombinationen bereitstellender, regulierender und kultureller ÖSD erreicht werden können. Auch nachteilige Wirkungen von Ökosystemfunktionen, der Zustand von Ökosystemen und mögliche negative Umweltauswirkungen wurden in das Rahmenwerk eingebunden. In dieser Arbeit werden Vegetationsstrukturen an Bahnanlagen und Fließgewässern behandelt, an die eine hohe Nachfrage an ÖSD besteht und die spezifischen technischen Anforderungen unterliegen. Die periodische Erhebung von Vegetationsdaten mittels Fernerkundungstechnologien und die anschließende Datenanalyse gewährleisteten zum einen die Quantifizierung von ÖSD und zum anderen die Identifizierung von Risikobereichen. In diesem Zusammenhang kann man von NbS sprechen, die das Potenzial haben, zur Anpassung und Minderung des Klimawandels sowie zur Erhaltung der Biodiversität beizutragen. Informationen über die Multifunktionalität von NbS sind die Grundlage für die Entwicklung technischer Standards. Diese Arbeit liefert methodische Ansätze, sowohl für die Installation von NbS als auch für das periodische Monitoring und die Bewertung, wodurch auch eine dynamische Entwicklung der Systeme berücksichtigt werden kann.

Table of content

1 Introduction

Natural systems are able to perform several functions and provide multiple benefits for human well-being. Against the background of increasing demands of the human being on limited natural resources, and in view of growing pressure on the natural balance, there is great demand for concepts that help to better consider ecological services in decision-making processes and to ensure sustainable land use. As a consequences of climate change and numerous anthropogenic stressors, the balance of nature is changing. This means that the natural systems themselves are under increasing pressure, leading to both a greater need for protection and a demand for management strategies adapted to changing circumstances. The accelerating climate and biodiversity crisis requires a progressive shift from the economistic, industrialisation paradigm to a sustainability paradigm, which entails fundamental changes in attitudes, action, organisation and regulation (Burns 2012).

The need of re-framing human-nature relationships is evident and different approaches are discussed how to peruse this transformation. According to Massarella et al. (2021) there are three major conceptualisation for biodiversity conservation: (1) "naturalism" paradigm – transformation towards pre-existing states largely based on imaginaries of pre-human wilderness (2) the "post-wild" world concept - a shift away from the idea of wilderness as the basis of nature conservation towards the idea of a world in which humans and nature coexist in dynamic configurations, and (3) "just transformations" - the pursuit of justice, aiming for transformative change in sustaining a more just world for both humans and non-humans. In the political context the need for a transformative change is demonstrated by a range of water-soil, hydro-climatic, land-use and socio-political issues which have been noted by the international community. In 2015, the resolution "Transforming our World: The 2030 Agenda for Sustainable Development" was adopted by the United Nations General Assembly and all 193 member states committed to its implementation. It contains the 17 Sustainable Development Goals (SDGs), which aim to contribute to a socially, ecologically and economically positive and urgent transformation of our world. A rethink of water policy is marked by the Water Framework Directive (200/60/EC, WFD) and the US Clean Water Act (US CWA), which together form a statutory framework for the protection and restoration of freshwater ecosystems. The European Commission has published a number of directives and regulations, notably the Birds Directive 2009/147/EC, the Habitats Directive (Council Directive 92/43/EEC) and the Regulation on Invasive Species (Regulation 1143/2014), all of which have enormous implications for the management of ecosystems.

It seems that the preservation and protection of healthy ecosystems has reached the status of a top political priority, but at the same time requires design and operational concepts that can provide solutions to the existing challenges. Two complementary concepts that are gaining political momentum and are increasingly being applied in both planning theory and policy are that of “nature-based solutions” (NbS) and “green infrastructure” (GI) (e.g. Wright, 2011; Lennon, 2014; Baró, 2016). The European Commission (2016) defines NbS as “solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience”. NbS is considered as an umbrella concept that covers a whole range of ecosystem-related approaches, all of which address societal challenges (Cohen-Shacham et al., 2016). GI is recognised as a tool for addressing needs for ecological preservation and environmental protection as well as societal needs in a complementary manner (Naumann et al., 2011) and therefore fits well the scope of NbS. As yet, there is no single widely recognised definition for GI, as different interests attach different environmental, social and economic meanings to the concept (Wright, 2011). But there are key underlying features and principles of the definitions, including connectivity, multifunctionality and smart conservation (EEA, 2011). The Green Infrastructure Strategy by the European Commission defines GI as a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services. The concept incorporates both green and blue spaces and other physical features in terrestrial and marine areas (European Commission, 2013a). When aquatic ecosystems are included, the term green-blue infrastructure (GBI) is commonly used.

The present thesis employs the term GBI with a broader approach that includes not only environmental features but the whole landscape in assessment tools. This distinguishes it from the political concept of GBI which focuses on the connectivity of environmental areas but does not explicitly include the improvement of the ecological value of highly modified landscape elements such as agricultural landscapes or “grey infrastructure”. An isolated consideration of selected environmental characteristics could lead to a segregation of different landscape units and move already impaired areas even further out of the political focus. Ecological planning should not primarily focus on the conservation of natural spaces, but on improving the naturalness and ecological functionality of anthropogenic spaces. This also corresponds to the contemporary paradigm in ecology (Pickett, Parker and Fiedler, 1992), which conceives of natural systems as open and demands that they be put into context with their environment. The thematic focus of this work is on lineside vegetation and riparian vegetation, often referred to in the literature as GBI elements (e.g. Burdon et al., 2020; Lovell and Taylor, 2013). Scientific approaches for the periodic and multi-scale analysis of these vegetation systems are presented, which can support sustainable management.

NbS can offer alternatives to conventional engineering approaches and have the potential to contribute to climate-change adaptation and mitigation whilst preserving biodiversity and contributing to the overall resilience of landscapes (Pauleit et al., 2017). However, the current lack of clear guidelines, according to which decision makers can assess the efficiency, effectiveness and sustainability of any particular NbS, is obstructing the upscaling of the concept in practice (Cohen-Shacham et al., 2016). The techniques of soil and water bioengineering are well recognised to provide NbS for natural-hazard control or restoration of degraded areas (Furuta et al., 2016; Saltar et al., 2020;), to bridge natural and man-made environments and create networks and are therefore an effective tool in the implementation of GBI (Rey et a., 2014). Soil and water bioengineering is based on the combination of dead and living plant materials and the emerging positive synergistic effects. Accordingly, knowledge of the biotechnical properties of local plants (e.g. growth strength, hydraulic and mechanical resilience), as well as that of plant community processes (e.g. plants' sociability and successional processes), is fundamental. Furthermore, the planning processes must consider short-, medium- and long-term effects of the structures. In this thesis, studies are presented that can contribute to decision making in soil and water bioengineering projects.

Due to the complexity and breadth of the topic, case-specific tools are needed to implement the strategic NbS and GBI concepts. In fact, there is a lack of universally accepted evaluation methods and a large variety of terms and definitions used in the different relevant disciplines. A wide range of processes, effective on different temporal and spatial scales, make the identification of measurable criteria challenging. The GBI concept stresses the multifunctional characteristics of environmental features, but these functions can be difficult to assess as they are strongly correlated with the specific site conditions in question.

The decision-making framework presented is aligned with the concept of ecosystem services (ES) and ES assessment tools are provided in this thesis. Through their multifunctional characteristics, GBI features can provide provisioning, regulating and cultural ecosystem services. The GBI features covered in this thesis are human influenced or human induced, and corresponding ecosystems are subject to management practices that support very specific functions. Through the ES framework, potential but as yet unrecognised or suppressed ecosystem capacities can be identified and the value of an ecosystem to society can be demonstrated. In this way, the thesis aims to support decision-making in ecosystem management.

Lineside vegetation structures along infrastructure networks and riparian vegetation structures along river networks are linear and extensive landscape elements. For these landscape types, spatial data collection is complex. Due to their shape as vegetation strips that extend over a large area, the data must have a high spatial resolution and, at the same time, cover large areas. Furthermore, these areas are highly dynamic, due to biotic and abiotic natural processes as well as human disturbances. Therefore, a high temporal resolution of spatial data is required for design and management issues. A fundamental part in the field of ecosystem service research is mapping and modelling. The provision of ES is a process that is spatial in nature. The functions and processes that are responsible for ES production vary greatly in space and time and are scale dependent (Ruskule et al., 2018). Maps are very important tools to communicate complex spatial information and to assess ecosystem service supply, flows and demand (Burkhard & Maes, 2017). In this thesis, a large-scale mapping and modelling approach for the ecosystem service assessment on GI lineside vegetation is presented. Based on the maps and models created, measures can be adapted and sustainable management of GI lineside vegetation can be supported.

For practitioners, technical standards in design and operationalisation, demonstrable benefits and added values, as well as information on expected life-cycle costs are the basis for the broad application of NbS. The present thesis aims to contribute to a transfer of the theoretical concepts into practice. For this purpose, the individual components of the decision-making framework were applied in concrete case studies that comprise transdisciplinary research fields. The overall objectives of the thesis are to provide a praxis-oriented GBI assessment framework and to enhance the multifunctionality characteristics of GBI actions. To achieve this, the following research questions were designed and will be addressed in the articles presented below:

[RQ 1]: Which data sources and data collection methods are suitable for the analysis of green-blue infrastructure features on different temporal and spatial scaling levels?

[RQ 2]: Which modelling and mapping approaches can support the assessment of ecosystem services and disservices of green-blue infrastructure?

[RQ 3]: How can technical issues and ecological pressures be identified and mitigated in the planning, construction and maintenance processes of nature-based solutions?

2 Conceptual and methodological framework

Green-blue infrastructure (GBI) is a conceptual framework that interlinks various concepts to provide a more holistic understanding of the complex interrelations and dynamics of social-ecological systems (Hansen and Pauleit, 2014). Each comprising concept has an integral role and is in relation to each other (Pakzad & Osmond, 2015). The concept of ecosystem services (ES) is a fundamental component in the assessment of GBI features and there is even a tendency to synthesize the GBI and ES theory into one framework (e.g. European Commission, 2013a). In accordance with "The Economics of Ecosystems and Biodiversity study" (TEEB, 2010) all direct and indirect contributions to human well-being are subsumed under the generic term ecosystem services.

In the following, the decision-making framework that structures this thesis and its individual components is described (see Fig. 1):

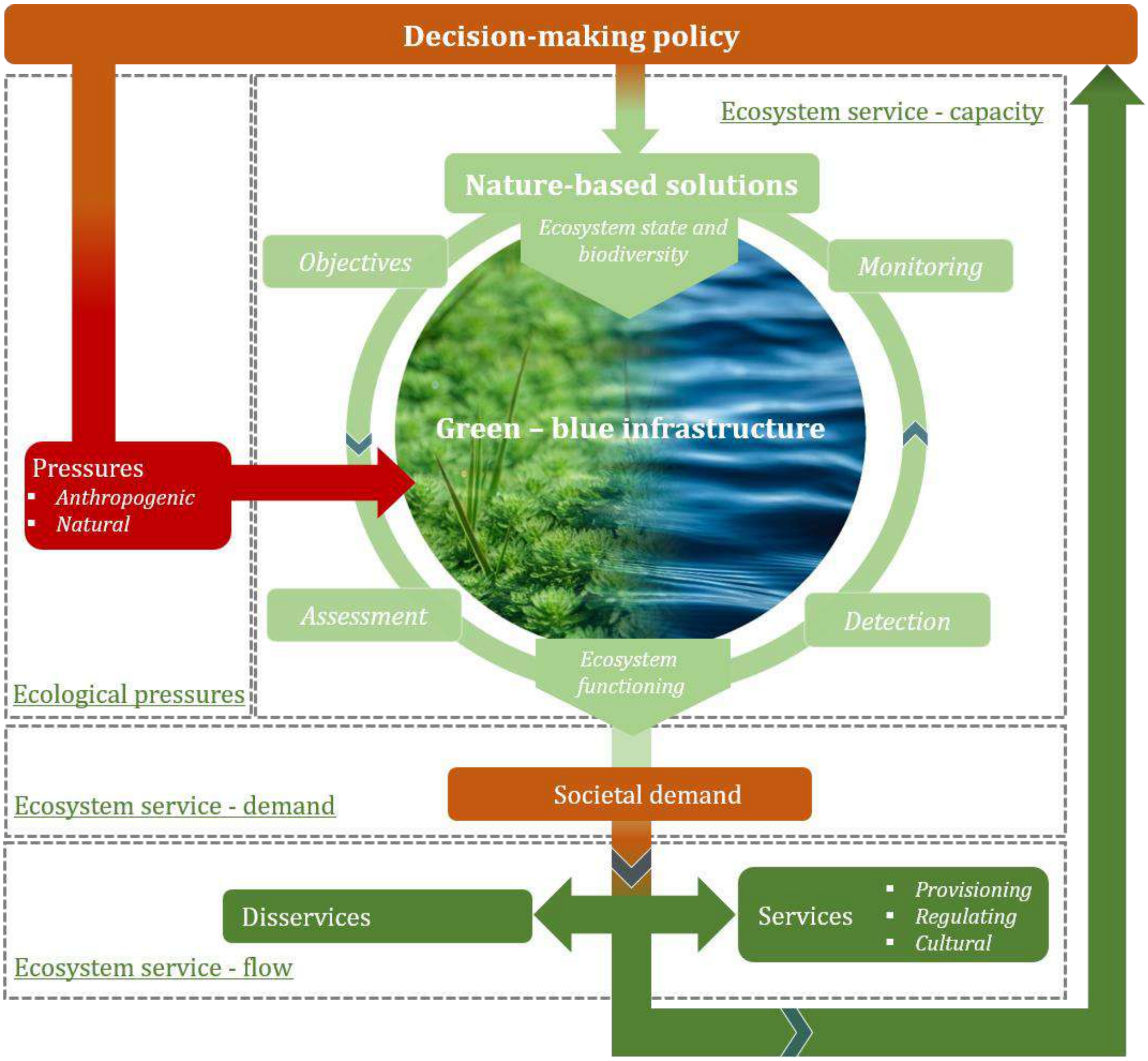

Fig. 1. Illustration of the decision-making framework that structures the thesis.

Villamagna et al., 2013 suggest to distinguish four ecosystem service deliverables and three ecosystem service categories. This clear categorisation should provide planners with better information for decision making. Accordingly, the presented decision-making framework distinguishes four ES delivery processes: 1.) ecosystem service capacity (an ecosystem's potential to deliver services based on biophysical and social properties and functions), 2.) ecosystem service demand (the amount of a service required or desired by society), 3.) ecosystem service flow (the actual production or use of the service) and 4.) ecological pressures (anthropogenic and natural stressors that affect capacity or flow of benefits); and three ES categories: 1.) provisioning (e.g. timber, drinking water), 2.) regulating (e.g. erosion and flood control, water purification) and 3.) cultural (e.g. building of knowledge, recreation).

As a further component of the ecosystem service flow, disservices are included. In accordance with Baró et al., (2016), disservices are only considered as endpoints and not as intermediate ecological processes. For example, the development of riparian vegetation is part of the functioning of the riparian ecosystem and is linked to various ecological processes. Damage by driftwood could be a potential endpoint that is causing damages to infrastructure and disservices. At the same time, deadwood is an important component in aquatic systems by providing habitats. Furthermore, there are a myriad of ecosystem services associated with riparian vegetation. When it comes to the management of anthropized ecosystems it is crucial to consider both ecosystem services and disservices. Emphasising only the benefits that ecosystems provide is likely to result in ignoring these negative impacts.

The development of anthropized ecosystems and consequently their capacity to supply ES is highly connected to human activities. The following definition of Burkhard et al., (2012) describes this well: "Ecosystem services are the contributions of ecosystem structure and function – in combination with other inputs – to human well-being". This definition incorporates anthropogenic inputs within the ES concept and provides the link to nature-based solutions (NbS). The state of the ecosystem and the supply of ecosystem functions can be influenced by both human inputs and exerted ecological pressures on the environment. Due to the dynamic nature of GBI features, a planning cycle with four components - monitoring, detection, assessment and objectives - is integrated into the decision-making framework. It is important that alternatives and options (including the zero option) are considered in the assessment process. Throughout the planning cycle, the target-oriented adaptation of inputs to the respective development status of the GBI elements should be supported.

3 Presentation of the articles

The articles presented are the result of interdisciplinary research activities and are based on experiences from national and international research projects. In the following, the background and aims as well as the methods used and the results achieved in the articles are briefly presented:

Article [1]: Hoerbinger, S., Obriejetan, M., Rauch, H.P., Immitzer, M. (2020). Assessment of safety-relevant woody vegetation structures along railway corridors. Ecological Engineering, Volume 158, 106048.

Background and aims: This article presents follow-up research to article [2], with a focus on technical issues related to the safe operation of rail traffic. Both studies were carried out on the same railway section and are based on high-resolution geo-data that are collected periodically by the local authorities. The aim of the study was to create a large-scale model of the safety-relevant vegetation and thereby support tree care management and contribute to maintaining safe and functional lineside vegetation.

Methods: The basis for the study was accurate surface and terrain data, from which precise models of the lineside vegetation and the railway corridor were created. Through proximity analyses, woody vegetation elements were identified that were tall enough and close enough to strike the railway infrastructure in the case of failure. To indicate the areas of the railway corridor where trees pose a potential risk to the railway, the falling curves of the safety-relevant vegetation were calculated. The analyses were performed with data from two years. A vegetation risk index (VRI) was calculated to make the results more comparable and to visualise the assessed risk for individual sections of the railway corridor. For the calculation of the VRI, evaluation units were created along the corridor and the proportional area of safety-relevant vegetation was assessed for each evaluation unit. Based on the VRI, the distribution of safety-relevant was analysed.

Results: By combining airborne laser scanning data and high-resolution orthophotos, the safety-relevant vegetation was successfully mapped and railway sections with increased risk could be identified. It was shown that lineside vegetation is dynamic and that there are considerable changes in its composition over time. Through the VRI, it was visualised that there are both sections of high presence and sections where safety-relevant vegetation is completely absent. The methodology developed is based on widely available geospatial data and is applicable on a large scale, which is a major advantage over UAV (unmanned aerial vehicle). The study has confirmed that airborne remote sensing technologies can provide very valuable data for large-scale lineside vegetation assessments.

Relevance to the thesis and relation to the research questions (RQ):

- Presentation of modelling and mapping approaches as tools for assessing potential risks and ecosystem disservices related to GI lineside vegetation (RQ1).
- Testing of with high temporal and spatial resolution for their application in GI lineside vegetation management (RQ2).

Contribution of Stephan Hörbinger: Conceptualization, methodology, investigation, software, visualization, writing- original draft preparation.

Article [2]: Hoerbinger, S., Immitzer, M., Obriejetan, M. Rauch, H.P. (2018). GIS-based assessment of ecosystem service demand concerning green infrastructure line-side vegetation. Ecological Engineering, Volume 121, 114-123.

Background and aims: The article is built on the research activities carried out within the research project "Greenslopes". In this project, extensive research was carried out with the aim of optimising the maintenance management of vegetation in railway corridors. The need for further research into approaches for large-scale and simultaneously high-resolution linear vegetation analyses became apparent during the project work. The article follows on from this and presents a module-based green infrastructure (GI) and ecosystem service (ES) assessment approach that is built on high-resolution remote sensing data.

Methods: A GIS-based methodological approach for the ecosystem service demand assessment (ESDA) of GI lineside elements was developed. Object-based image analyses and the Random Forest classifier were used for land cover classification. Detailed land-cover and thematic maps were created and an ESDA concerning “structural landscape diversity” and “water and climate regulation” was performed at a study site.

Results: The results of the publication represent the composition of landscape types, the distribution of GI lineside elements, vegetation landscape features and hotspots of land consumption in the study area. Although the mapping of lineside vegetation is challenging due to its linear extension, different lineside vegetation types could be successfully mapped. The analysis of the distribution of lineside elements showed their significant potential to enhance “structural landscape diversity”. Furthermore, basic information concerning the potential of lineside vegetation to provide “water and climate regulation” was created.

Relevance to the thesis and relation to the research questions (RQ):

- Presentation of large scale ecosystem service demand assessment (RQ1).
- Analysis of ecosystem service capacity of GI lineside vegetation (RQ1).
- Testing of remote sensing datasets for use in GI lineside vegetation management (RQ2).

Contribution of Stephan Hörbinger: Conceptualization, methodology, investigation, software, visualization, writing- original draft preparation.

Article [3]: Li, J., Hoerbinger, S., Weissteiner, C., Peng, L., Rauch, H.P., (2020). River restoration challenges with a specific view on hydromorphology. Frontiers of Structural and Civil Engineering, Volume 14, 1033–1038.

Background and aims: Within the interdisciplinary research project "Nanxi18" the application of European hydromorphological assessment methods in Chinese river basins was investigated. Complementary to the project work, a literature review on hydromorphological assessment methods and their application in the context of river restoration was prepared together with Chinese partners. The aim of the article is to give an overview of the state-of-the-art of hydromorphological assessment methods and their use in river restoration measures.

Methods: The article is based on analysis of state-of-the-art hydromorphological assessment methods in the context of their application in river restoration. First, the development of the most commonly used hydromorphological assessment methods were summarised. The key concepts of the different methods were assessed and their applicability for river restoration was discussed. Two research projects are used to give brief examples of the application of hydromorphological assessments in Chinese rivers and to demonstrate their role in river restoration.

Results: The main ecological pressures on river systems are discussed with a specific focus on Chinese rivers. A socio-ecological approach for urban rivers is proposed which is based on the dynamic structure of river systems and incorporates societal, physical, chemical and biotic factors as well as their cumulative, antagonistic and synergistic effects.

Relevance to the thesis and relation to the research questions (RQ):

- Presentation of assessment methodologies and data collection strategies to identify ecological pressures on river basin scale (RQ1).
- Discussion of ecological pressures, restoration measures and water management strategies (RQ3).

Contribution of Stephan Hörbinger: Conceptualization, investigation.

Article [4]: Rauch, H.P., Sutili, F.J., Hörbinger, S., (2014). Installation of a Riparian Forest by Means of Soil Bio Engineering Techniques — Monitoring Results from a River Restoration Work in Southern Brazil. Open Journal of Forestry, Volume 4, No. 2, 161-169; ISSN 2163-0429.

Background and aims: During research stays at the Universidade Federal de Santa Maria in southern Brazil in 2013 and 2019/2020, I was able to conduct basic and practice-oriented research in the field of soil and water bioengineering. In this article, monitoring results of a soil and water bioengineering river restoration work are presented. Both the development of the species used and the effectiveness of the structures applied were studied. A particular added value of this research is that this intervention was one of the first soil and water bioengineering riverbank restoration works implemented in Brazil and the findings from the study may be useful for similar future projects. In 2019/2020, we monitored the long-term development of the intervention. The results have not yet been published but are briefly described in this thesis.

Methods: The study is based on two onsite vegetation surveys and an evaluation of the applied structures and its effectiveness. In the vegetation surveys, the applied species in the soil and water bioengineering construction were examined for their ability to establish in the riverbank. The structures were assessed in terms of effective erosion control and their condition.

Results: As a whole, the intervention was assessed as functional and safe. This means that the embankment is well protected and no imminent failure should be expected. Several native species showed good growth development and proved suitable for bank stabilisation works. From the first to the second vegetation survey, the proportion of spontaneous vegetation increased significantly. The strong increase of spontaneous vegetation is undesirable due to less flood resistance and its further development must be monitored.

Relevance to the thesis and relation to the research questions (RQ):

- Development of a monitoring approach to evaluate the technical functionality of a nature-based solution (RQ1 and RQ3).
- Demonstration of regulating ecosystem services of soil and water bioengineering constructions (RQ3).

Contribution of Stephan Hörbinger: Conceptualization, methodology, investigation, visualization, writing- original draft preparation

Article [5]: Hoerbinger, S., M. Rauch, H.P. (2019). A Case Study: The Implementation of a Nature-Based Engineering Solution to Restore a Fallopia japonica-Dominated Brook Embankment. Open Journal of Forestry, Volume 9, No. 3, 183-194; ISSN 2163-0429.

Background and aims: Invasive alien plants (IAPs) exert pressure on the riparian system and its management is an urgent matter in the discipline of soil and water bioengineering. One of the worst invasive plants worldwide is *Fallopia Japonica "knotweed", which* can severely impact ecosystem functions provided by riparian vegetation. While a primary aim of weed management is to reduce the population of an invasive plant species, the goal of the nature-based engineering solution (NABES) presented in this article is to reinstall native riparian forests and to restore ecosystem functioning. The concept of NABES is to support the implemented species by frequent removal of the invader's shoots until the native vegetation represses the invasive plant by root competition and shadow pressure.

Methods: A willow brush mattress (a common technique for controlling riverbank erosion) was constructed on a Fallopia japonica-dominated brook embankment. The species *Salix purpurea* was used due to its high ecological amplitude and excellent soil biotechnical properties. At regular intervals, the knotweed shoots were removed and the dry biomass determined in the laboratory. In addition, the development of the plants was monitored by photo-based analysis of the cover ratio.

Results: The strongest biomass production of *F. japonica* was observed in the months April and May. Even though the temporal interval between shoot removal was increased, shoot production decreased sharply and almost stopped in August. Branches of *S. purpurea* in contact with the water of the brook showed good development while branches without water contact partly did not sprout. By the removal of knotweed shoots, the development of *S. purpurea* could be effectively supported. Further research will be needed to monitor the long-term development of the plants and to support the timing at which maintenance measures are most efficient.

Relevance to the thesis and relation to the research questions (RQ):

- Assessment of the suitability of nature-based solutions to mitigate ecological pressures from invasive alien plants (RQ3).
- Presentation of monitoring approaches to evaluate the plants development in nature-based solutions (RQ1).

Contribution of Stephan Hörbinger: Conceptualization, methodology, investigation, visualization, writing- original draft preparation

Article [6]: von der Thannen, M., Hoerbinger, S., Paratscha, P., Smutny, R., Rauch, H.P., Strauss, A. (2016). Energy balance and global warming potential of soil bioengineering structures. [IALCCE 2016 (Int. Association for Life-Cycle Civil Engineering), Delft, NL, OKT 16-19, 2016] in: Jaap Bakker. Dan M. Frangopol, Klaas van Breugel (Eds.), Life-Cycle of Engineering Systems: Emphasis on Sustainable Civil Infrastructure; ISBN: 978-1-138-02847-0.

Background and aims: Although soil and water bioengineering is characterized as an ecological construction technique, there are no methods that allow an assessment of potential environmental impacts. In the articles [6, 7 and 8], methodological approaches of life cycle assessments (LCA) for the evaluation of soil and water bioengineering structures are presented. The aim of the studies was to adapt the already well-established method of LCA to the field of soil and water bioengineering and provide a tool for a more holistic evaluation of its structure types. The articles were published as part of the research project "E-Protect - Energy Balance and Global Warming Potential of Alpine Protective Structures". Article [6] provides the basic concept for a life cycle assessment model in soil and water bioengineering.

Methods: A systematic scheme with differentiation of the natural hazard processes for soil and water bioengineering constructions has been developed. The standardised LCA method of ISO 14040 was used as the basis for an Environmental LCA in the discipline of soil and water bioengineering. Available databases within the Open LCA software were identified that provide relevant data for the different construction types. The life cycle phases of soil and water bioengineering projects were structured and a decision path was created.

Results: Through the developed scheme, a list of required materials for each soil and water bioengineering construction type is provided. This information is necessary as input data for LCA models and working with the OpenLCA software. This article provides the basis and conceptional considerations of an Environmental LCA model for soil and water bioengineering structures.

Relevance to the thesis and relation to the research questions (RQ):

- Presentation of the basic concept for a life cycle assessment model in soil and water bioengineering (RQ2).
- Preparation of an LCA approach for use in the planning and construction phase of soil and water bioengineering constructions (RQ3).

Contribution of Stephan Hörbinger: Conceptualization, investigation.

Article [7]: von der Thannen, M., Hoerbinger, S., Paratscha, R., Smutny, R., Lampalzer, T., Strauss, A., Rauch H.P. (2017). Development of an environmental life cycle assessment model for soil bioengineering constructions, European Journal of Environmental and Civil Engineering, DOI: 10.1080/19648189.2017.1369460.

Background and aims: In this article, the developed LCA method is applied in practice to evaluate soil and water bioengineering structures with regard to their energy consumption during the construction phase.

Methods: A soil and water bioengineering construction site for the revitalisation of an inner-city watercourse was analysed using the LCA method. Three different types of structures were investigated and the system boundary was defined as "cradle-to-gate". The focus was on the analysis of environmental impacts during the construction phase. Environmental impacts were assessed on the basis of the cumulative energy input.

Results: It was possible to identify environmental impacts that arise during the construction of soil and water bioengineering structures. In the case study, most of the energy was used for the construction machinery. However, it also became clear that the use phase is essential for the overall assessment of soil and water bioengineering structures.

Relevance to the thesis and relation to the research questions (RQ):

- Investigation of the energy consumption of exemplary soil and water bioengineering and conventional engineering constructions (RQ3).
- Investigation of the applicability of the LCA modelling approach to assess environmental impacts associated with the construction of soil and water bioengineering structures (RQ3).

Contribution of Stephan Hörbinger: Conceptualization, investigation.

Article [8]: von der Thannen, M., Hoerbinger, S., Paratscha, P., Lampalzer, T., Smutny, R., Strauss, A., Rauch H.P. (2018). Development of a concept for a holistic LCA model for soil bioengineering structures. The Sixth Int. Symposium on Life-Cycle Civil Engineering (IALCCE 2018), Ghent, BE, OCT 28-31, 2018. In: Robby Caspeele, Luc Taerwe & Dan M. Frangopol (Eds.), Life-Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision, ISBN: 978-1-138-62633-1.

Background and aims: The application of LCA models for soil and water bioengineering construction materials and structures is complex because the building state changes due to the dynamic development of the living plant materials. Since the degree of function as well as the energy demand differ greatly over time, it is imperative to consider the entire lifetime of a structure. The aim of the study was to design a conceptual LCA model that considers both the functions and environmental impacts of soil and water bioengineering structures over their lifespan.

Methods: A conceptual approach for an LCA model was developed that is applicable to the entire lifespan of soil and water bioengineering structures. Building on articles [6 and 7], which primarily addressed the used products and construction phases, the focus here is on an evaluation of the use phase. This includes maintenance work as well as the lifespan of the building materials.

Results: A first concept for the holistic assessment of soil and water bioengineering structures in an LCA model is presented. This also includes the use phase, which is highly relevant due to the dynamic development of the structures. The study also showed that the use phase of the different soil and water bioengineering construction types depends strongly on the necessary maintenance measures. This study can serve as a basis for future studies in which the lifetime of structures with living plant material is analysed in more detail. In addition, future studies should take into consideration the further utilisation of biomass produced during maintenance work and the ecosystem services which are provided by soil and water bioengineering systems.

Relevance to the thesis and relation to the research questions (RQ):

- Presentation of a conceptual LCA modelling approach that considers both functions and environmental impacts associated with soil and water bioengineering constructions (RQ3).

Contribution of Stephan Hörbinger: Conceptualization, investigation.

4 Thematic context of the articles

This thesis consists of case studies that cover a wide range of data collection techniques and strategies that explore specific issues in the implementation of nature-based solutions (NbS). The presented approaches are module-based methodological frameworks [articles 1 and 2], designed as concurrent and consecutive models [articles 6 to 8] and combine assessment methods for large spatial scales [articles 1, 2 and 3] with site-specific NbS [articles 4 and 5]. Its underlying methods can be used in a complementary fashion and can also be transferred to other fields of application.

Data on both large-scale entities, such as the arrangement of landscape elements or land-use units, and ecological processes are fundamental for the assessment of various ecosystem services and trade-offs. GIS-based methods and models have been developed to integrate landscape structures and geographical context into the decision-making framework. In combination, articles [1] and [2] provide decision-making bases that include socio-ecological (e.g. increasing structural landscape diversity) and technical components (e.g. identifying safety-relevant vegetation). When it comes to the implementation and maintenance of NbS, knowledge of the technical properties and the temporal development of the measures is crucial. Article [4] provides a methodological approach to monitor the long-term development of a NbS. Based on multi-level spatial and temporal information, development goals for NbS and the measures necessary to achieve them can be defined. New technologies (e.g. automated measurements and sample collections, geographic information systems, remote sensing) can support the monitoring of measures and provide a basis for assessing ecosystem services at different scales.

Consideration of ecological pressures is an important component of the decision-making framework and is incorporated into the thesis at different levels. Hydromorphological processes and assessment approaches on river basin scale are addressed in article [3]. Knowledge of the hydromorphological status of a river is a basis for planning and implementing restoration measures. NbS, such as soil and water bioengineering techniques, can be employed to restore areas infested with invasive alien plants [article 5] or degraded areas, and offers a "soft" alternative to conventional hazard control methods [article 4]. The use of living and natural construction material is associated with difficulties in determining resistance thresholds and estimating the service life of a structure. Besides engineering functions, there are also a variety of ecosystem services attributed to soil and water bioengineering (e.g. aesthetical values, biodiversity promotion) that can be difficult to assess and quantify. An important component in the assessment of the dynamic development of soil and water bioengineering measures are monitoring concepts designed to evaluate different functions over a longer period of time.

The implementation of "soft" techniques also means an intervention in nature and the use of resources. Therefore, the planning process should be based on clearly defined objectives, which provide the basis for an efficient and low-impact implementation of the measures. Also, a zero option should be considered. Increased transparency of impacts is pursued through the LCA models presented. First, the basics for an LCA model in soil and water bioengineering were elaborated and the application was prepared in the planning phase [article 6]. Following on from this, article [7] presents a case study of the application of a LCA model on a soil and water bioengineering construction site. Article [8] shows a conceptual approach for an evaluation of the use phase of soil and water bioengineering structure types. The maintenance measures associated with the different types of structures are taken into consideration, which is a basis for a holistic life cycle assessment.

5 Syntheses

Having been distinguished into the components of ecosystem service delivery, the methodologies and results of the articles were assembled to build up a decision-making framework. Nature-based solutions (NbS) are linked with each ecosystem service component and the decision-making processing steps.

5.1 Ecosystem service capacities

In the design and managing of green-blue infrastructure (GBI), knowledge of the ecosystem service capacities of different GBI features is crucial. Based on this, NbS can be designed to promote and sustain specific ecosystem functions. Figure 2 provides a general overview of potential ecosystem functions provided by green infrastructure (GI) lineside vegetation and GBI riparian vegetation.

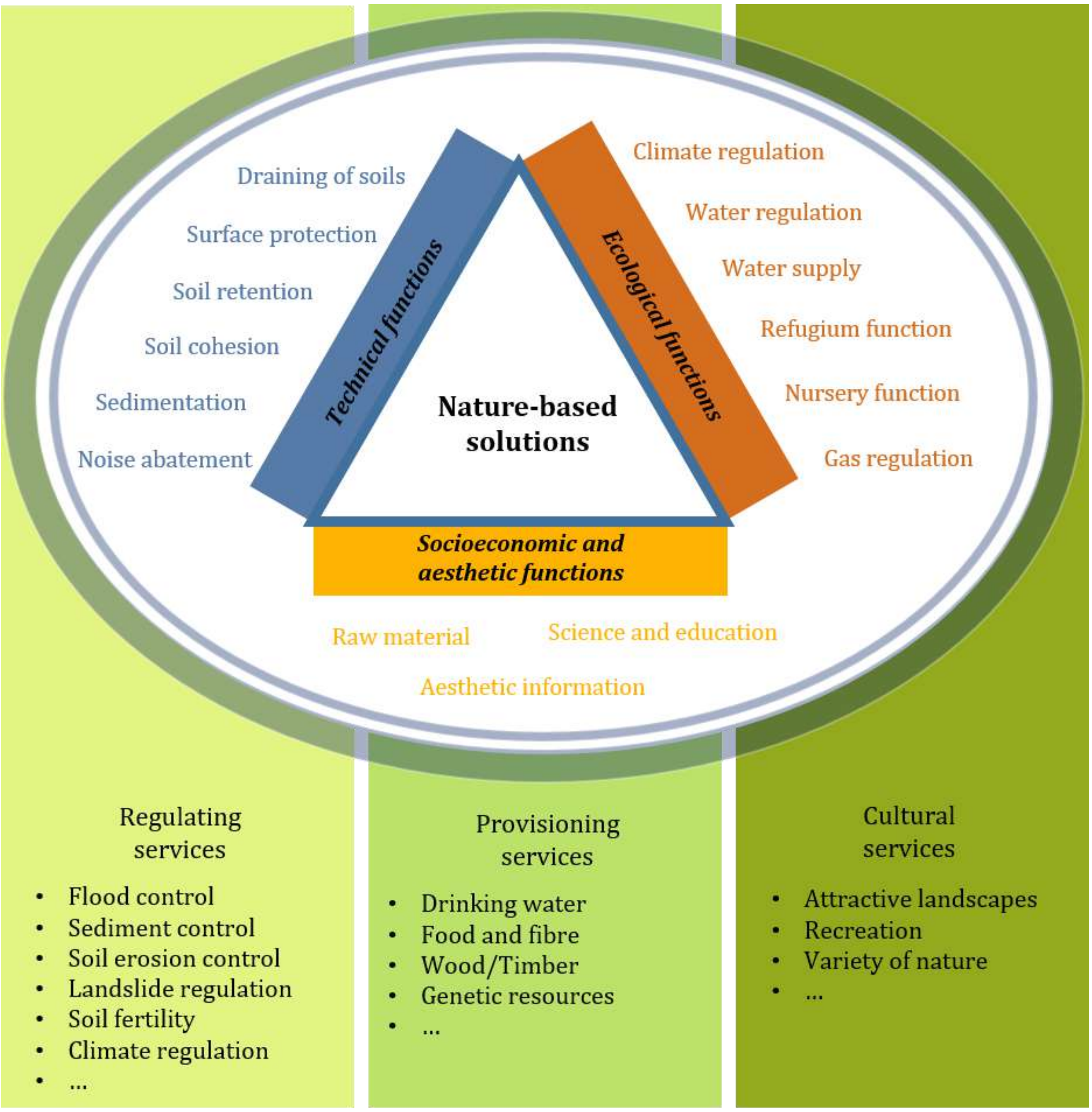

Fig. 2. Exemplary ecosystem functions and ecosystem services provided by nature-based solutions.

Articles [1] and [2], address functions of GI lineside vegetation and its capacity to provide multiple ecosystem services. GI lineside vegetation provides several functions that contribute to the provision of safe railway operations. Amongst them are the improvement of the embankments and cuttings, erosion control or the protection from natural hazards. It is important to consider that the different functions are interdependent or synergistic. For instance, soil formation and water regulation influence the stabilisation of embankments.

The capacity to deliver an ecosystem service is strongly related to site-specific conditions. GI lineside vegetation can also cause high maintenance costs or pose severe safety risks. To detect safety-relevant vegetation along railway corridors a large-scale assessment approach was developed that is based on high-resolution geo-data. Based on precise models, a proximity analysis was performed to assess elements of woody vegetation in a railway corridor that is tall enough and close enough to strike the railway infrastructure in the case of failure. As additional information to assess the potential risk, the model distinguishes between vegetation types and the geometric position of identified safety-relevant vegetation in the railway corridor. Figure 3 shows the results at an exemplary railway section: the mapped safety-relevant vegetation, the affected railway track and a cross section of the railway. The created maps show both the safety-relevant vegetation within the railway corridor and all vegetation that is not safety-relevant and consequently can provide a wide range of ecosystem services, which are not solely linked to the operational performance of the railway [article 1].

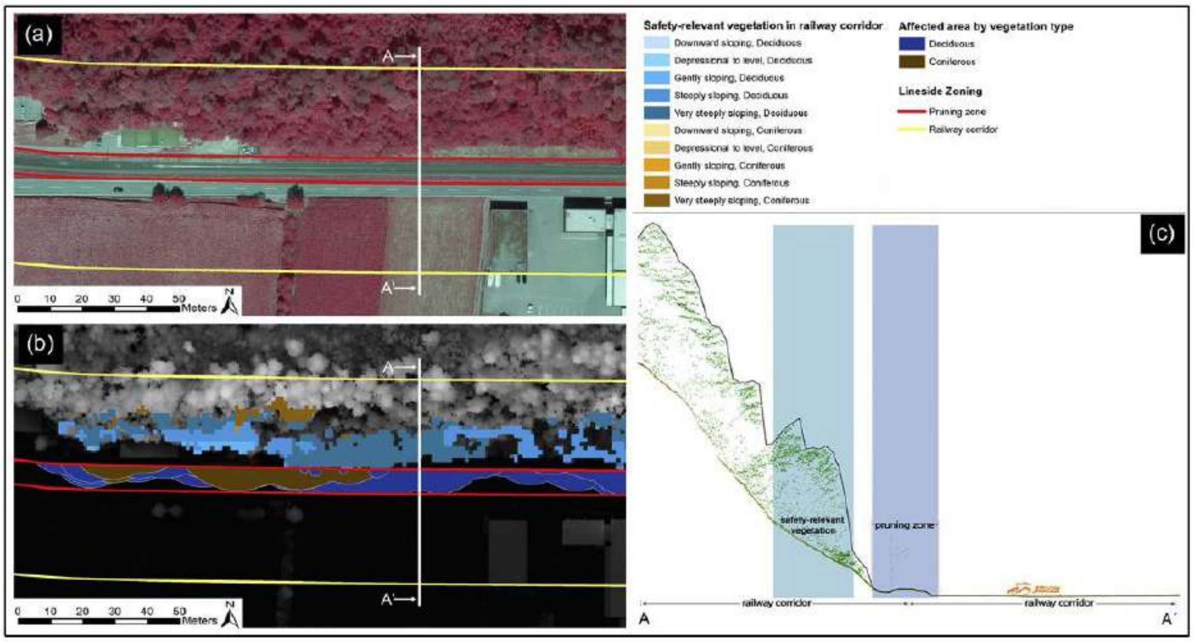

Fig. 3. Results at an exemplary railway section: (a) The colour infrared (CIR) orthophotos (b), the canopy height model (CHM) with both the identified safety-relevant vegetation structures and the pruning zone within the falling curves and (c), the airborne laser scanning (ALS) point cloud of a cross section (2 m width) of the railway corridor.

At the same railway section, a second study with the aim of developing ecosystem service assessment approaches was performed [article 2]. The emphasis was put on assessing the capacity of GI lineside vegetation to provide ecosystem services that are not related to the operational performance of rail traffic. Although GI lineside vegetation systems are disturbed or semi-natural ecosystems, they can provide important structural landscape elements. In environments with a high degree of sealing (e.g. urban environments), GI lineside vegetation can provide a significant supply of climate and water regulating services. By using high-resolution geo-data, GI lineside vegetation structures were mapped and detailed land cover maps were created (see Figure 4). In relation to the surrounding environment, the ecosystem service capacity of GI lineside vegetation was quantified in the categories "water and climate regulation" and "structural landscape diversity".

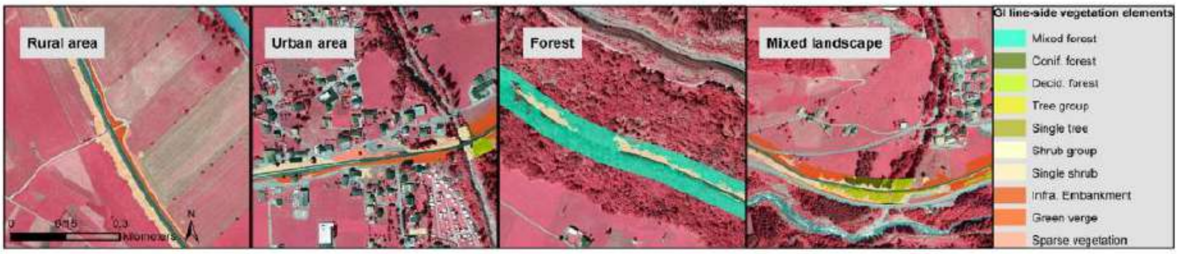

Fig. 4. Dominant land cover map of the study site and mapped GI line-side elements.

In the field of soil and water bioengineering, knowledge about the capacity of the species used to provide technical functions is fundamental to the successful implementation of an intervention. The case study presented in article [4] examines the capacity of local riparian species and soil and water bioengineering structures to stabilize an eroding riverbank. Figure 5 illustrates a sectional view of the engineered biological soil construction under investigation. The development of the construction is shown later in figure 7. Species potentially capable of withstanding high hydraulic shear stresses and growing under extreme growth conditions were tested for their applicability in soil and water bioengineering structures. Auxiliary materials were used to protect the plants until they established well and undertook technical functions. In sections of augmented hydraulic loads (at the toe of the embankment) more solid auxiliary materials were used to provide permanent support of the construction. By means of vegetation surveys, the technical performance of species was examined. Additionally, the structures of the reinforcement work and its effectiveness in different development phases were evaluated. On the basis of the monitoring results, riparian species of the Atlantic Forest Biome could be identified that proved to be appropriate for slope reinforcement intervention projects.

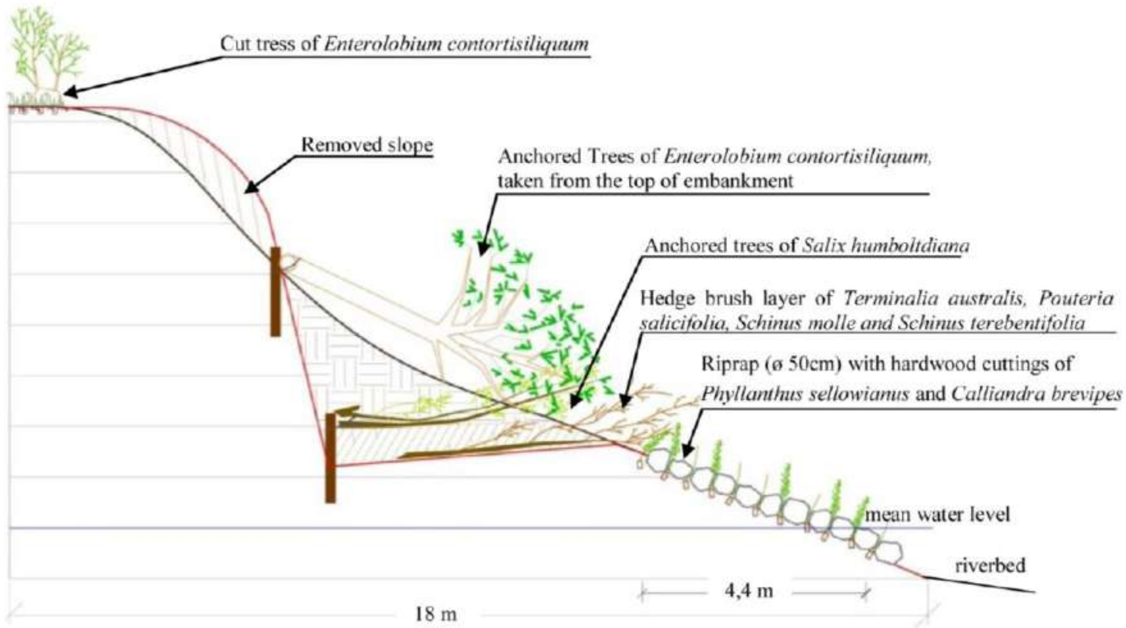

Fig. 5. Sectional view, illustrating a soil and water bioengineering riverbank restoration work in southern Brazil (Sutili, 2010).

5.2 Ecological pressures

The assessment of ecological pressures is an essential component in the planning and management of NbS. Ecological pressures are affecting the ecological integrity, biodiversity and the functions of an ecosystem. The success of NbS can be adversely affected by ecological pressures. At the same time, NbS can be implemented as a response to ecological pressures and to restore affected ecosystems.

Human activities have a huge impact on the hydromorphlogical conditions of rivers and its ecosystems. At present, many rivers, almost throughout the world, are heavily modified and in a morphologically degraded state. The hydromorphological functions of a riverine ecosystem are a key element for its health and capacity to provide ecosystem services. When evaluating the status and the integrity of a river corridor, hydromorphological assessment approaches are useful tools. In article [3] different sources of hydromorphological pressure and its impacts are addressed. A literature overview of hydromorphological assessment methods and their application in the context of river restoration is presented. These methods are increasingly applied in the assessment of the ecological condition of surface water bodies and to support river management. By means of hydromorphological assessments, large-scale processes and channel dynamics can be integrated in the planning of restoration projects.

The health of a riparian ecosystem is closely linked to the presence of site-appropriate and native vegetation. Invasive alien plants impact multiple ecosystem functions provided by riparian vegetation and jeopardise river systems. They are a pressure on the riparian system by themselves, often with a major impact if they act in combination with other pressures. A nature-based engineering technique presented in article [5] aims to provide a sustainable control method for *Fallopia japonica*. The intervention comprises immediate erosion control by the auxiliaries to prevent further downstream colonization and active support of the natural vegetation until it can repress the knotweeds by root competition and shadow pressure. In this way, the ecological pressure exerted by the invasive alien plants should be reduced and the functioning of the ecosystem restored.

The application of NbS does not only result in positive ecological benefits, but also constitutes an intervention in nature. A methodical approach was developed to make potential negative environmental impacts of soil and water bioengineering constructions transparent and quantifiable [articles 6, 7 and 8]. The studies showed that the use of LCA models for soil and water bioengineering building materials and structures is complex, since building state changes along with the dynamic development of living plant materials. As the functional grade as well as the energy demand differ strongly along time, it is absolutely necessary to consider the whole lifespan of a structure. Conventional structures are characterized by a high-energy input in the construction phase and a high functional grade directly after being constructed. During the operational phase, the constructions have to be restored in order to maintain their functional integrity. In this process, energy has to be expended. At the same time, the initially obtained functionality cannot be re-established due to a decrease in the strength of materials. After a certain time, the construction has to be removed and rebuilt. The construction materials can possibly be recycled or reused. On the other hand, considering bioengineering structures, the majority of the energy input is required during the construction phase. This is mainly due to the cumulative energy demand of the inert materials used and the machinery [article 7]. During the operational phase of the structure, maintenance work has to be done in order to maintain the protective properties of the used plants. Through measures like cutting the vegetation back to the trunk, energy will be put into the system (through machine use etc.), but will also be put out in the form of biomass. Additionally, carbon is sequestered by the biomass production of the plants. In contrast to conventional protective structures, soil and water bioengineering approaches are designed to have a subsequent use phase. This means that, after the actual lifespan of the construction, a stable vegetation stand should have developed that maintains its balance through natural succession (i.e. by dynamic self–control, without artificial input of energy).

5.3 Ecosystem service demand

In terms of effective GBI management, knowledge about the demand for specific functions is crucial when it comes to the implementation of measures. On the basis of known demands, specific target systems can be defined and supported by adapted inputs.

The technical requirements and, therefore, the demand on specific vegetation functions of lineside vegetation is closely correlated with its distance to the railway track and the geometric properties of the railway corridor. Based on the model presented in article [1], site-specific requirements that result from the position of a vegetation element in the railway corridor were mapped. This information can be useful in defining target vegetation systems and in supporting the management of measures. In article [2] a site-specific ecosystem service demand assessment is presented. A detailed mapping of GI lineside vegetation structures and the surrounding land cover formed the basis for the analysis. The demand for the ecosystem service "structural landscape diversity" was assessed by the evaluation of the statistical distribution of the coverage area of vegetation elements in the surroundings, and in the zone adjacent to the railway track. In this way, it was possible to identify sections of the railway where vegetation structures similar to the lineside vegetation were represented on a low level or absent. Consequently, a greater demand for services regarding the structural landscape diversity could be assumed for the respective railway section. In a next step, the surface sealing degree of the surrounding environment of the railway corridor was assessed. With a high degree of sealing, a demand for water- and climate-regulating services can be assumed.

At the site of the intervention, as presented in article [4], a continuous process of erosion and bank mass failure caused very steep angles in the embankment that prevented the vegetation from establishing itself spontaneously. The erosion process was initiated in the course of the construction of a water pipeline when the river axis was deflected towards the left bank. The soil and water bioengineering project was implemented as an alternative to a conventional "grey" river bank protection. Therefore, the primary demand on the installed riparian vegetation was and is to provide the river-bank with protection. Further demands, that are not directly related to the technical functionality for river bank stabilisation (e.g. regulating runoff, habitat for natural communities) were not included in the scope of the study.

5.4 Ecosystem service flow

The term ecosystem service flow involves the services and disservices that are experienced by people. Quantified and mapped ecosystem services and disservices, as well as consistently described ecosystem service processes, can support decision-making sovereignty. An understanding of ecosystem flows and their visualisation is a basis for the application of the NbS and GBI concepts.

GI lineside vegetation must be continuously monitored and maintained, which incurs substantial costs and resource expenditures. Remote sensing analysis [article 1] can support tree-care management in railway corridors and contribute to maintaining safe and functional GI lineside vegetation. On the basis of high-resolution geo-data, all woody vegetation elements that constitute potentials risk to the railway facilities were mapped as they can cause disservices, due to their proximity to the railway track or height. A vegetation risk index (VRI) was developed, which can be used to evaluate railway sections with regard to the presence of safety-relevant vegetation. On the basis of change analyses, the dynamic development of the safety-relevant vegetation along the railway corridor was analysed between the years 2012 and 2017. The results show significant VRI changes, which demonstrates a dynamic development of safety-relevant vegetation and considerable changes in the composition of lineside vegetation over time. This also reveals that the flow of ecosystem services can shift over time from disservice to service and vice versa. It should be noted that safety-relevant vegetation does not solely pose risks but can also provide important functions for the safety of the railway infrastructure related to natural hazards and bank stability. At the same study site, a variety of lineside vegetation structures with high coverage area was mapped [article 2]. A high presence of lineside vegetation structures was found in areas with a high demand for water and climate regulating services, such as urban environments. Ecosystem services such as cooling effects on the surrounding built-up area, provision of air humidity, binding of dust, lowering of air temperature and reduction of wind speed can be provided by these GI lineside vegetation structures. Furthermore, GI lineside vegetation structures proved to be of contrasting characteristics to its surroundings. When similar structures are absent in the surrounding environment, lineside vegetation could significantly contribute to enhancing the structural landscape diversity. For example, through groups of shrubs and trees in rural-dominated landscapes or herbaceous vegetation structures in forest-dominated environments. Figure 6 shows an exemplary section of the study site and results of the two modules presented. It illustrates the results of the land cover analysis that provide an overview of the characteristics of the surrounding environment and display an overall description of the landscape composition. This gives a quick overview of the state of structural landscape diversity, and allows demand tendencies be assessed. The section to the right of the figure shows the safety-relevant vegetation in the railway corridor. In the upper part of the figure (a.) there is safety-relevant vegetation, while in the lower part (b.) there are woody structures that do not pose a safety risk due to their height and proximity to the railway track. As the dominant land cover type in this section is "rural dominated", there is great potential for woody lineside vegetation to contribute to increasing the structural landscape diversity in this section.

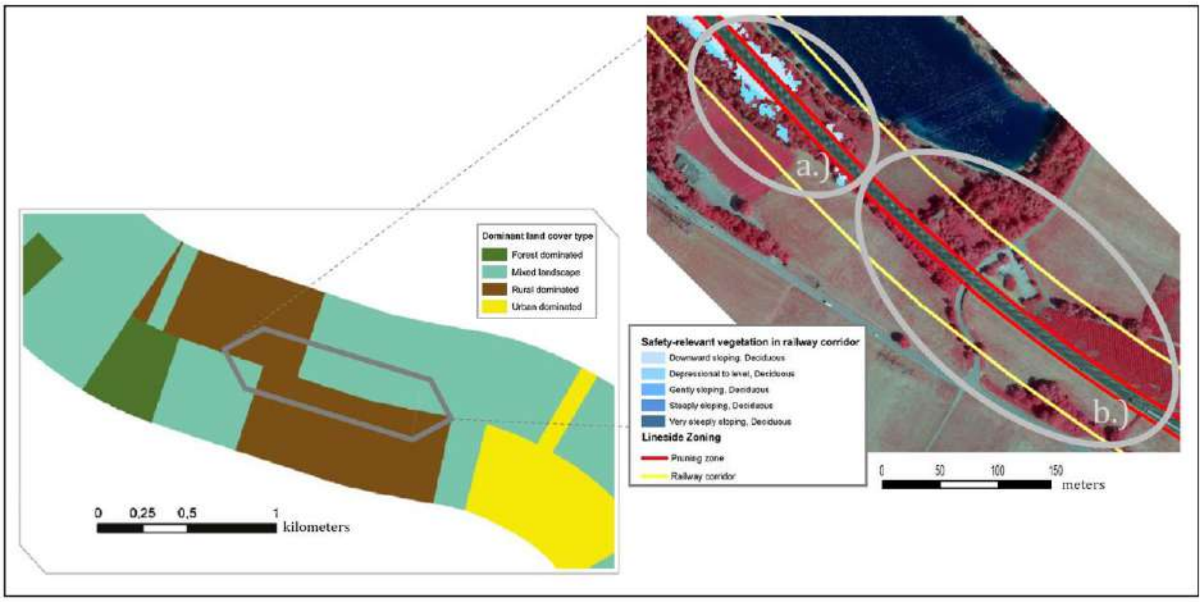

Fig. 6. Exemplary section of the study site: Dominant land cover within the evaluation units, providing basic information for the Ecosystem Service Demand Assessment (ESDA) concerning "Structural landscape diversity" (left). Section with present safety-relevant vegetation (a.) and woody structures that do not pose a safety risk due to their height and proximity to the railway track (b.).

The monitoring results of the soil and water bioengineering intervention showed that both technical, as well as ecological functions, were fulfilled [article 4]. Three years after its establishment, the installed riparian forest provided bank protection against erosion and created new ecological habitats. Although the primary objective of the study was to evaluate the technical functionality of the structure, additional values could be observed. In the vegetation surveys, rare plant species that were established during the construction or that later colonised the embankment were recorded. This shows that the construction is providing a suitable living space for plants and it can be reasonably assumed that also habitats for wild animals have been created. The spontaneous establishment of new plant species was enabled by both the constructive measures (e.g. correction of the top angle, toe erosion protection) and the amelioration of site conditions by the used species (e.g. improvement of soil and microclimatic conditions). Sediment deposition was also observed, which is probably related to increased roughness due to the vegetation cover.

In a study ten years after the intervention (unpublished), further positive development of the structure in terms of bank stability, soil ecosystem formation and plant species richness were surveyed. The invasive alien plant species *Pennisetum purpureum*, which was still present at the time of the 2013 survey, has been pushed back completely. Figure 7 shows the development of the embankment from an eroding river bank to a stable riparian forest. During the ten years of the survey, no maintenance work was necessary to preserve the function of the structure.

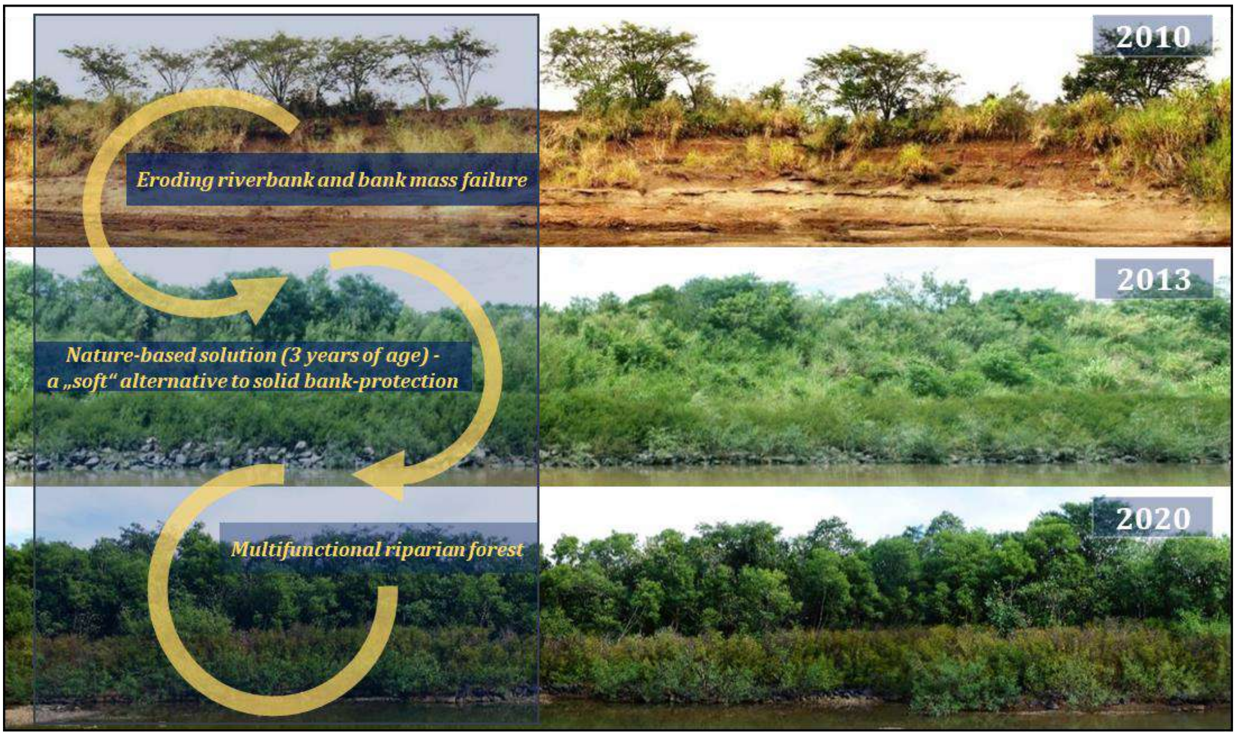

Fig. 7. Illustration of the process flow of a nature-based solution on the example of a riverbank restoration in southern Brazil. Embankment before the implementation of reinforcement works (Sutili, 2010), three years and ten years after its completion.

6 Discussion

Green-blue infrastructure (GBI) elements are manifold, ranging from small-scale structures up to extensive landscape elements, and can be constantly changing due to prevailing physical and biological conditions or human disturbances. The presented studies show that multi-level information and data are needed and usually case-specific methods have to be developed to operationalise the GBI and NbS strategies. Particularly because the GBI concept is very broad, there is a need for unified frameworks that support decision-making processes. Although the concept of ecosystems as infrastructure has become established in academia there is no consensus on how to name and define this type of infrastructure (Cardoso da Silva and Wheeler, 2017). The aim of the present work is not to provide a new formalisation of the GBI concept. Rather, the work provides tools and scientific approaches to assess lineside vegetation structures and riparian vegetation structures at different scales. In this way, the work seeks to promote an expansion of the GBI concept. The tools provided enable the integration of all landscape entities into consideration and no longer limit the focus to natural and semi-natural ecosystems.

6.1 Ecosystem service assessment

The presented framework specifically addresses the fields of ecological engineering and landscape planning and is designed for its application in the context of GBI features that are highly influenced by anthropogenic activities. According to Baró et al., (2017), the ecosystem service (ES) framework is a useful tool that helps decision makers define policies to achieve specific combinations of provisioning, regulating, cultural services, disservices and ecosystem state, and that promotes service delivery whilst mitigating subsequent negative environmental impacts. For this reason, the presented decision-making framework was very much aligned with the concept of ES. To avoid overlooking the potential negative impacts of ecosystems, it is particularly important to consider ecosystem disservices when deciding on measures and defining target systems. A one-sided approach could limit the added value of an action or even have negative effects. The inclusion of disservices in the assessment framework is also important in the argumentation of measures, as its exclusion can easily lead to controversy and criticism from actors and practitioners who are confronted with the concrete impacts of ecosystems (Lyytimäki 2014). For stakeholders, maps and models can be helpful tools to identify areas of conflict and define adapted management strategies. Based on spatial analysis, cross-sectoral interactions, synergies and trade-offs, such as the impact on one ES as a result of alterations in another, can be integrated into decision making (Burkhard & Maes, 2017).

In intensely used areas, where human-environmental interaction is on a high level, the requirements for GBI elements are heterogeneous and there are specific technical conditions to be considered in their management. GBI elements can provide several ES when they are in a healthy state and especially in areas of intensive human use there is a high demand for these services. At the same time, human actions and pressures impact the "functioning" of ecosystems when ecological processes are altered. This interaction often leads to discrepancies in the demand and supply of ES, thus showing the exchange feature of this dynamic. The inclusion of ecological pressures in the decision-making framework aims to emphasise the correlation of ecosystem health and ES capacity.

The studies have shown that nature-based solutions (NbS) have the potential to improve the ecosystem state of GBI, which is the basis for ecosystem functioning. Furthermore, NbS proved to be suitable for engineering purposes, where not only technical but also environmental, sustainable and socio-economic aspects are taken into account. Environmental LCA models that can support institutional feasibility to implement policies (e.g. Green Public Procurement) are effective tools in decision-making processes in the field of NbS. This is particularly important in cost-benefit analyses, wherein NbS such as soil and water bioengineering measures perform in many ways worse than conventional technical measures. In the case of an engineered design, the service life can be estimated approximately, whereas this is more difficult in the case of an engineered biological design. In addition, engineering designs achieve their desired benefits immediately. Engineered biological designs, on the other hand, require a certain amount of time to fully achieve the desired benefits. This, in turn, has a bad effect on the cost-benefit analysis, as benefits that accrue late are devalued in the balance sheet (Grossmann, 2010). However, especially in the delivery of intangible benefits and ES, NbS often have an advantage over conventional engineered constructions. One example of a major positive but still under-appreciated impact of soil and water bioengineering practices is the carbon sequestration provided by the plants used. Through re-vegetation, a large positive benefit is provided in mitigating climate change. Land with vegetation cover holds more carbon in its soils and biomass than land with sparse vegetation or no vegetation (Post and Kwon, 2000). The rate of carbon sequestration in slow-growing forests is low and maintaining the carbon pool by minimising forest disturbance is important (Jandl and Schindlbacher, 2014). As trees reach maturity, their CO_2 sequestration potential decreases (associated with a decrease in their growth rate). Willows, which are a key species for implementing soil and water bioengineering, produce high amounts of biomass and effectively sequester carbon. By continuously rejuvenating willow shrubs, they retain their optimal sequestration capacity (Volk et al., 2004). According to Rugani et al., (2019) the integration of ES into life cycle assessments can improve both the identification of trade-offs and synergies and foster the identification of new intermediate and final beneficiaries. The results of the studies can contribute to the definition of technical standards in planning and operation of NbS, to the visualisation of benefits and added values as well as to the estimation of expected life cycle costs.

6.2 Multi-scale data acquisition and analysis

The practical applicability of the GBI concept depends on the availability of comprehensive data sets and indicators as well as on the accurate aggregation of the information. During data acquisition, geo-biophysical structures and processes as well as societal aspects must be taken into account. One major challenge is the different spatial and temporal scale of the required data sources.

Remote sensing techniques can contribute to meeting various data requirements in the context of the GBI assessments. They provide a wide range of spatial data and offer flexible and efficient options for computer-aided data extraction, data analysis and data modelling. The main advantage compared to pointwise field inventories is the potential of area-wide mapping and a cost-effective way to collect diverse environmental data of large corridor areas. Thus, these techniques also have great potential for identifying and quantifying ecological pressures. For example, the use of remote sensing technologies can improve the early detection of invasive alien plants and promote more efficient and cost-effective management. Remote sensing can offer the timely and fast detection of individual species, and can assist in the monitoring of eradication efforts (Dvořák et al., 2015). Compared to traditional extensive field campaigns, remote sensing facilitates coverage of considerable areas, whilst being significantly less resource intensive (Underwood et al., 2003). This is of high value, as current research activities analysing the dispersion patterns of invasive alien plants and modelling future scenarios related to climate change lack reliable data on their actual occurrence. In this thesis, state-of-the-art hydromorphological assessment approaches are presented, which are applied in collecting comprehensive information on the physical and biological conditions of river systems. Hydromorphological data can provide information on the overall status of rivers and floodplains and form the basis for restoration and management measures. Such studies are conducted at the river basin scale, which presents significant challenges in terms of data collection. The use of remote sensing technologies can significantly increase the spatial coverage of the morphological information gathered by field campaigns. It is also of increasing importance in hydromorphological assessment approaches and helps support sustainable management of rivers (Bizzi et al., 2016).

Throughout the life cycle of NbS, different data and information are required on both landscape- and site-level. This includes data on abiotic (e.g. climate, soil) and biotic (e.g. plant interaction, tree size) factors or components that shape an ecosystem. With regard to the anticipated ecosystem functions, specific data are required in the GBI management. The survey methods presented in this thesis provide a basis for investigating the long-term development of soil and water bioengineering projects. The results of the investigations provide information on the establishment of the plants used and their biotechnical properties, the durability of the structures as well as the environmental balance of the materials used and the construction process.

7 Conclusions and outlook

Due to the thematic range that the concepts of green-blue infrastructure (GBI) and nature-based solutions (NbS) encompass, it is challenging to define universal assessment methods. It has to be noted that the concepts provide a foundation for political strategies but do not themselves provide technical or application-related solutions. Rather, the concepts can be considered as an umbrella under which different research disciplines cohere and interact. The tools and scientific approaches presented in this thesis can help to promote multifunctionality in vegetation management. It is shown that even highly modified landscape elements, such as lineside vegetation structures, can provide multiple ecosystem services. Thus it is important to include the globality of the landscape, irrespective of its more or less anthropogenic influence or modification, in the context of GBI assessments.

Natural systems are manifold, perform different functions and can provide several ecosystem services. At the same time, there can be specific technical requirements that have to be considered in its management. Both studied GBI groups – green infrastructure (GI) lineside vegetation and GBI riparian vegetation – showed specific characteristics and different social requirements that are however highly variable within the groups. Analytical frameworks based on GIS technologies have been created for modelling and mapping of ecosystem services provided by GI lineside vegetation structures. A module-based tool was developed to identify areas of conflict where GI lineside vegetation structures pose a concrete risk in a railway corridor. Based on this, a methodological approach was presented for the assessment of selected ecosystem services. The studies are a component for quantifying ecosystem services, which is an essential step towards operationalising the GBI concept. The combination of standard geo-data, such as periodically collected orthophotos and accurate airborne laser scanning data (ALS) with state-of-the-art analysis tools, proved to be a suitable method for multi-scale GBI analyses. The presented approaches are based on widely available geo-data and can be applied to different linear landscape elements and analytical focuses.

The need for holistic approaches is exemplified by countless ecosystems that have been reduced to a few functions (e.g. rivers as transporters of mainly water and sediments), leading to degradation and environmental problems. Geospatial analyses form a basis for understanding the mechanisms involved in linking GBI networks to the larger landscape. In this way, complex ecosystem processes can be integrated into decision-making processes and the multifunctionality of GBI structures enhanced. In the planning of river restoration projects, hydromorphological assessments can provide data and information to integrate large-scale processes and channel dynamics into the design of interventions. Furthermore, it gives the basis for assessing ecological responses to restoration measures. Only if ecosystems are in a healthy state can their multifunctionality be in effect. In the context of this thesis, no specific assessments of NbS measures were carried out with regard to their influence on the development of biodiversity or the resilience of ecosystems. The further development of Environmental LCA models and assessment methods is a promising approach for integrating the ecological conditions into the decision-making process.

Soil and water bioengineering techniques fulfil technical as well as ecological functions and are a suitable means to provide NbS. The construction techniques are based on the principle of combining dead and living materials and the resulting positive synergy effects. A holistic assessment of soil and water bioengineering interventions is complex due to the dynamic development of structures, the different technical properties of building materials and the multiple ecological functions associated with them. The monitoring results of a soil and water bioengineering design presented in this thesis provide valuable information on suitable plants and construction types for alternative riverbank restoration works. Furthermore, the potential of soil and water bioengineering interventions to control invasive alien plants and restore ecosystem functions was demonstrated. It has to be noted that also the use of "soft" techniques means an intervention in nature and the use of resources. The presented LCA models for soil and water bioengineering constructions provide a tool for assessing the sustainability performance of interventions.

In conclusion, the presented studies constitute tools that support holistic management strategies for natural and semi-natural ecosystems. With this thesis, a decision-making framework is presented through which operationalisation of GBI and NbS strategies should be promoted.

Based on the findings of this thesis, the following continuative research activities are proposed:

- developing data collection strategies that combine large-scale and on-site information on green-blue infrastructure and its management;
- establishing further indicators to assess ecosystem services provided by nature-based solutions at different life-cycle phases;
- the extension and advancement of geospatial models to support consistent assessment approaches of ecosystem services;
- developing standardised methods for identifying the costs and benefits of nature-based solutions.

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9 Appendix

The Appendix consists of the presented articles in their original layout. Article order corresponds to the numbering in the framework of the thesis.

1. Hoerbinger, S., Obriejetan, M., Rauch, H.P., Immitzer, M., (2020). Assessment of safety-relevant woody vegetation structures along railway corridors. Ecological Engineering Volume 158, 1 December 2020, 106048.

2. Hoerbinger, S., Immitzer, M., Obriejetan, M. Rauch, H.P., (2018). GIS-based assessment of ecosystem service demand concerning green infrastructure line-side vegetation. Ecological Engineering Volume 121, 1 October 2018, Pages 114-123.

3. Li, J., Hoerbinger, S., Weissteiner, C., Peng, L., Rauch, H.P., (2020). River restoration challenges with a specific view on hydromorphology. Front. Struct. Civ. Eng. https://doi.org/10.1007/s11709-020-0665-9.

4. Hoerbinger, S., Rauch, H.P., (2019). A Case Study: The Implementation of a Nature-Based Engineering Solution to Restore a Fallopia japonica-Dominated Brook Embankment. Open Journal of Forestry, 9, 183-194; ISSN 2163-0429.

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9.1 Article 1

Assessment of safety-relevant woody vegetation structures along railway corridors

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Assessment of safety-relevant woody vegetation structures along railway corridors

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ABSTRACT

Railway networks are linear landscape elements that are mostly accompanied by adjacent lineside vegetation. In order to maintain safe railway operation, lineside vegetation must be continuously monitored and maintained. A large-scale assessment approach to identify safety-relevant woody vegetation structures along a railway corridor is presented in this paper. Based on accurate surface and terrain data, precise models of the lineside vegetation and the railway corridor were created for a study site. A proximity analysis was performed to assess elements of woody vegetation that are tall enough and close enough to strike the railway infrastructure in the case of failure. Information about the vegetation type and the geometric position of identified safety-relevant vegetation is provided in hazard classes. Falling curves of safety-relevant vegetation were calculated to indicate areas where trees pose a potential risk to the railway track. Analysis of datasets from 2012 and 2017 shows a dynamic development of safety-relevant vegetation along the railway corridor between the two studied years. A vegetation risk index (VRI) was calculated for the study site. Both sections of high presence and sections where safety-relevant vegetation is completely absent could be identified. The study has confirmed that airborne remote sensing technologies have great potential to provide data for large-scale lineside vegetation assessments. Through a combination of airborne laser scanning data and high resolution orthophotos, safety-relevant vegetation could be mapped successfully. The presented approach can support tree care management and contribute to maintaining safe and functional lineside vegetation.

1. Introduction

Lineside vegetation is present on many major parts of the railway corridors of Europe. Due to its linear extension along sensitive railway infrastructure and the diverse environmental conditions across the extent of the rail networks, its management is demanding and requires continuous monitoring. Consequently, railway managers have to balance many competing demands and so new supporting tools offer great advantages (Below et al., 2003). With the integration of lineside vegetation into strategic planning as an element of green infrastructure, the potential of healthy ecosystems can be used and it may help to address the problem of fragmentation, manage trade-offs and ultimately contribute significantly to the development of Green Transport Corridors (European Commission, 2013; Davies et al., 2014). At the same time, vegetation can pose severe safety risks in a railway environment. For example, overgrown shrubs and trees can block clearance zones and trees or broken branches, by falling onto tracks, are a threat to operating traffic and can cause severe damage to railway facilities. As the remediation of facilities and operational interruptions typically incurs high follow-up costs, vegetation control measures are extremely relevant to economic considerations. At the same time, well-managed vegetation is associated with improvement in the stability and resilience of embankments and cuttings (Gallatley et al., 1994; Obriejetan et al., 2017; EFIB, 2015), the reduction of soil erosion (Nolte et al., 2017; Rey et al., 2019; Weissteiner et al., 2019) and the protection of the rail network against damage by wind and snow (Below et al., 2003). Lineside vegetation represents a very special type of landscape component which has a high capacity for delivering ecosystem services (Hoerbinger et al., 2018; Moron et al., 2014; Penone, 2011). In order to maintain safe railway operation, lineside vegetation must be continuously monitored and maintained. Periodical maintenance works, like short rotation coppice practices, are applied in order to control vegetation heights. Regular monitoring of vegetation development must be considered as an integral component of vegetation control measures. The required intensity of maintenance measures for woody vegetation is closely correlated with its position and distance

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to the track bed and the design of the railway track. Additionally, information about species composition, vegetation development, and its vitality are decisive for lineside vegetation control. In this way, vegetation structures can be managed effectively such that technical requirements are fulfilled consistently and necessary interventions can be taken pre-emptively. In addition to vegetation parameters, the geometry of the railway corridor is key for assessing the potential for damage from trees. Unstable trees on an embankment will tend to fall away from the track under all but the most extreme storm conditions, whereas the risk from hazardous trees on cut slopes is considerably higher (Gallatley et al., 1994). The ground conditions, which have a strong influence on the development and stability of the vegetation, often vary strongly within the railway corridor. In the case of cut slopes and embankments, the ground has often undergone stronger modifications and, as a result, shallow soils frequently prevail. Shallow and poorly drained soils can restrict anchoring of roots, whilst deeper, more fertile soils induce the vegetation to grow taller and to compete for more sunlight, which in turn makes it more susceptible to windthrow (Mitchell and Ruel, 2015). When considering large-scale management strategies for extensive areas, there is a great need for resource-saving instruments. A cost-effective way to collect diverse environmental data of large corridor areas is remote sensing (Lillesand et al., 2008). Remote sensing data offers flexible and efficient options for computer-aided data extraction, data analysis and data modelling. This article presents an approach for lineside vegetation assessment based on airborne laser scanning (ALS) data and orthophotos. It makes use of the strengths and advantages of both image- as well as ALS point cloud analysis. At the study site, airborne remote sensing data were collected periodically. Data taken from two years of study, 5 years apart, were used to investigate the dynamic development of safety-relevant vegetation structures. Lineside vegetation was analysed by its height and position within the railway corridor. Woody vegetation close enough or tall enough to strike the rail track in case of failure and, consequently, constitute a potential risk to the railway facilities, was mapped. Different hazard classes were defined and integrated into the analysis.

2. Materials and methods

2.1. Input data and data processing

Remote sensing (RS) data sets from two years and one railway specific data set form the data basis in this study. The railway data set is based on the digitalisation of the centreline of the railway track. The first RS dataset consists of a four band orthophoto (red, green, blue - RGB and near infrared - NIR), with 12 cm spatial resolution, acquired in the year 2011, a digital terrain model (DTM) and a digital surface model (DSM), acquired in the year 2012. These records were used in the land cover classification procedure to map the lineside vegetation. The second RS dataset comprises a DTM and a DSM, acquired in the year 2017. The acquired ALS data were processed to raster data sets with a spatial resolution of 50 cm. Different data collection strategies were applied in the acquisition of the ALS data. In the year 2017, the data was acquired with higher flight altitudes and higher overlaps than in 2012. And, in addition, in the classification process of the ALS point cloud of 2012, the vegetation points were reduced to the maximum values of a vegetation element, whereas in the 2017 data set all vegetation points were maintained during the post-processing. In the first step, all RS datasets were resampled to a grid of 50 cm × 50 cm cell size. The generated railway corridor was used as boundary conditions for the spatial delineation of the vegetation cover and all data within its boundaries were extracted. Analysis of vegetation and topography were carried out for each raster cell. All analyses were performed by using the statistics software R Version 3.6.1 (Core Team, 2019) and ArcMap 10.6. The geoprocessing workflow of the methodology applied in this work is shown in Fig. 1.

2.2. Study site

The study site is located in the federal state of Vorarlberg in western Austria and comprises a 27 km-long stretch of the single track Innsbruck–Bludenz line (Arlbergbahn) and the double-track Lindau–Bludenz line (Vorarlbergbahn) (Fig. 2). The entire railway segment is electrified and connects several smaller railway stations as well as the main station of the district capital, Bludenz. Passing through the plains of the Alpine Rhine Valley, the topography is characterised by variable exposed, flat and undulating areas. The heterogeneous geometries of the railway corridor are represented within the study site, including terrain levels, dams and cut slopes. The vegetation composition is representative of that found around the Austrian rail-network: mixed forests, coniferous forests, shrublands, and green verges. Shrubs and trees are present on a major part of the study site and the railway corridor passes through short segments of forests along its whole length. In the western part of the study site, the railway passes through thickly forested and steep hillslopes. The densely populated region of Bludenz lies at the halfway-point of the study site and the western part has a predominantly agricultural and urban character.

2.3. Railway corridor and zoning

The railway corridor comprises the rail track, the embankments and the unsealed areas outside the tracks, e.g. forests, unsealed surfaces and meadows. All vegetation elements of the railway corridor are subject to vegetation control (Nolte et al., 2017). Starting from the track centreline, the railway corridor specifies the lateral extension of the study site (see Fig. 3). The boundaries of the study site were determined by creating a 50 m buffer on each side from the track centreline. This threshold was selected as it approximates the upper limit of canopy heights in the regional forests. In conformity with guidelines from railway operators (e.g. Below et al., 2003; DB, 2019), the area directly adjacent to the rail track was defined as the pruning zone. In order to maintain the clearance profile, to keep drainage ditches and walking paths clear and to prevent damage to railway facilities, like electrical trackside equipment and signalling systems, vegetation management practices must pay particular attention to this area. The pruning zone is defined as the area between the track axis of the outmost railway track and a buffer area of 6 m each way in the outward, lateral direction.

2.4. Safety-relevant vegetation structures

Safety-relevant vegetation is defined as vegetation elements tall enough and close enough to reach the "pruning zone" in the case of vegetation failure. The mapping of the vegetation structures is based on object-based image classification and the canopy height models (CHM) for the years 2012 and 2017. A detailed description of the applied image classification process can be found in Hoerbinger et al. (2018). Areas assigned the attributes "deciduous" and "coniferous" and with CHM values greater than 1.3 m were considered for the analysis. The vegetation type is a parameter to assess potential risks. Coniferous stands are more often affected by windthrow and budworm outbreak than mixed or deciduous stands (Kneeshaw et al., 2009) and in Europe, coniferous trees are generally taken as being more susceptible to snow damage than deciduous tree species (Nykänen et al., 1997). A proximity analysis was carried out in order to identify risk trees. The proximity was determined by calculating the horizontal distance as well as the inclined distance of each pixel at ground level to the nearest point in the "pruning zone". The purpose is to analyse the differences between the two methods of proximity calculations. Based on the height difference and the distances, the angle α was calculated. Safety-relevant vegetation was classified according to the geometric properties of its position in the railway corridor such as distances and angle to the nearest point of the pruning zone. The hazard classes comprise the geometric properties of the railway corridor and the vegetation type. The following

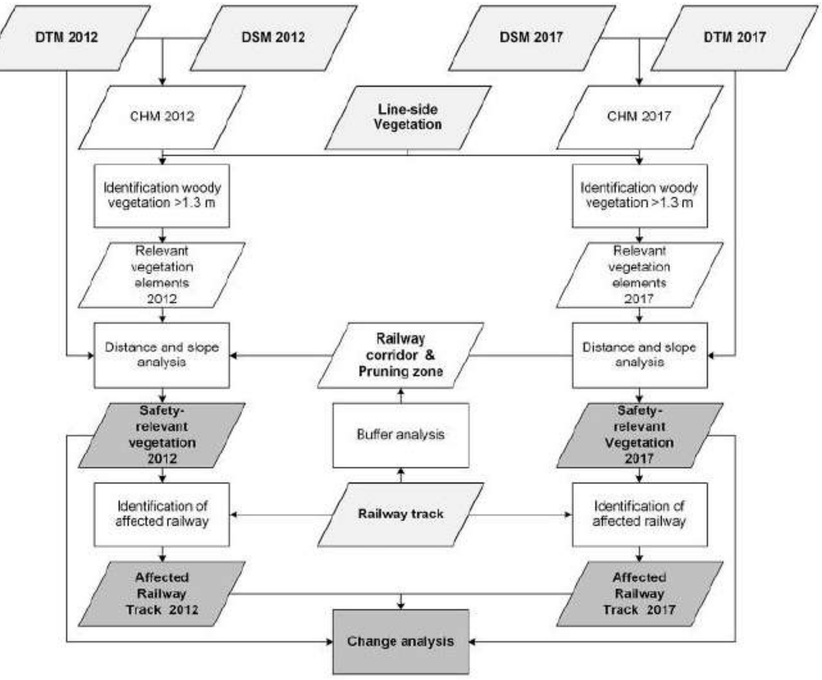

Fig. 1. Geoprocessing workflow including input data, analysis steps, and results.

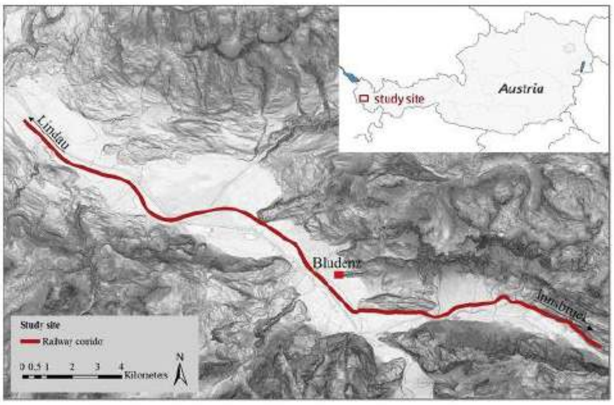

Fig. 2. (a) Map of Austria showing the location of the study site and (b) relief map of the Rhine Valley and the railway corridor.

geometric categories were defined: "depressional to level" ($-10°$ to 10°), "gently sloping" (>10° to 20°), "steeply sloping" (> 20° to 30°), "very steeply sloping" (> 30° to 90°) and "downward sloping" (> -10° to $-90°$). In the next step, the vegetation risk index (VRI) was calculated. The VRI is defined as the proportional area of safety-relevant vegetation in an evaluation unit. For this purpose, evaluation units were created along the railway line. This was done by dividing the railway corridor into 270 segments of 100 m $\times$ 50 m, on each side of the railway track. Subsequently, the proportional area of safety-relevant vegetation was calculated for each segment. Based on the VRI, the distribution of safety-relevant vegetation along the railway corridor was analysed.

2.5. *Identification of affected areas and change analysis*

To investigate the dynamic development of safety-relevant vegetation over time, data from two years was used. In order to map possibly affected railway sections, the falling radius was calculated by creating buffer polygons for each safety-relevant pixel. In this way, the different amount of pixels per vegetation element did not have negative effects on the accuracy of the model. Areas at risk were identified by intersecting the railway section with the falling radius of lineside vegetation elements. Safety-relevant pixels represent parts of a vegetation element but not always its full crown. Multiple safety-relevant pixels can correspond to a single tree. Vegetation heights were specified as the distance from the pixels up to the outer boundaries of the buffer polygons. In the next step, the buffer was dissolved according to the classifications "geometry at position" and "vegetation type". The percentage of the potential area at risk was calculated by intersecting the "pruning zone" area with the area covered by the falling radius of safety-relevant pixels. To prevent double-counting of overlapping falling radii, a rank order, expressing the associated risk of the respective category, was defined (see Table 1). The classes of the category "geometry at position" represent an ascending associated risk from "downward sloping" to "very steeply sloping". The associated risk concerning lineside vegetation types was ranked in the ascending order from "deciduous" to "coniferous". In the case of overlay, polygons of lower-ranked classes were erased where they were overlapped by higher-ranked classes.

3. Results

3.1. *Mapping of safety-relevant vegetation structures*

Based on the accurate surface- and terrain data, precise models to identify safety-relevant vegetation elements were created. The use of horizontal distance proved to be more appropriate in the proximity analysis than the use of inclined distance. In contrast to horizontal distance, inclined distance increases with the steepness of the slope and so fewer vegetation elements were identified as safety-relevant. At steep locations particularly, like high, steep faces, safety-relevant vegetation structures were not identified due to large differences in vertical height. The divergence between the two approaches of proximity analysis were limited to steep locations. The generated maps show safety-relevant vegetation structures, differentiated into hazard classes, and the

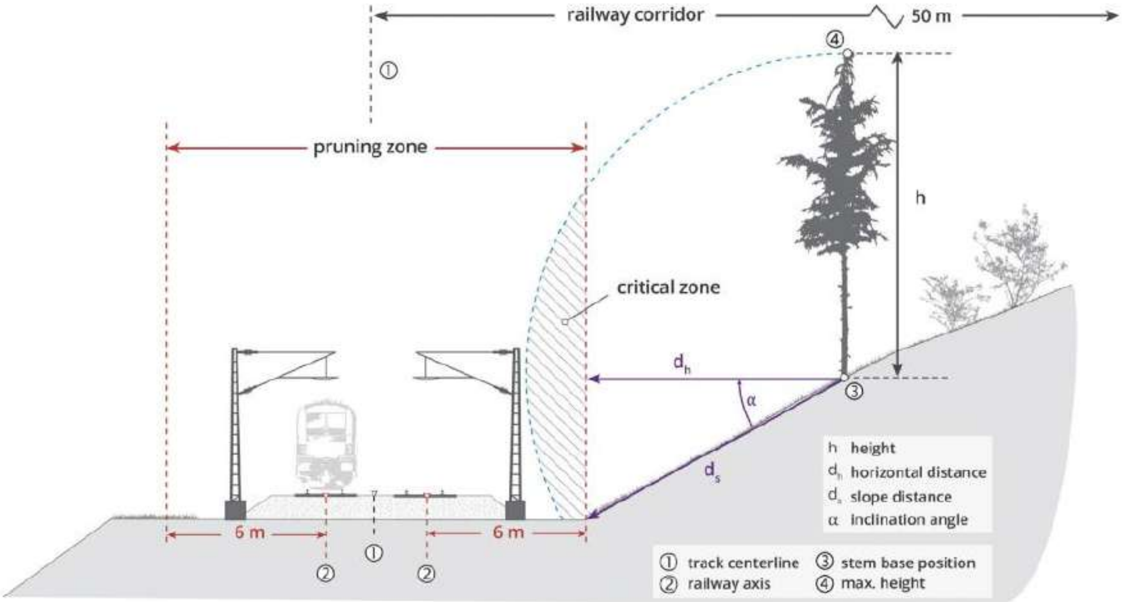

Fig. 3. Schematic view of the railway corridor, safety-relevant areas and the pruning zone.

railway track affected by the respective vegetation type (Fig. 4). Hazard classes provide information about the type and geometric position of woody safety-relevant vegetation structures in the railway corridor. The illustrated falling curves in the pruning zone indicate areas where trees pose a potential risk. It is shown that safety-relevant vegetation is not only positioned directly along the railway line but also in positions to the rear of the railway corridor. Trees which stand in the background can be obscured by vegetation in the foreground and may not be visible from the rail-track level, which impedes a terrestrial assessment. These trees pose a potential risk to the railway infrastructure and, when vegetation in front is cut back, they become free-standing before the railway track such that the risk can increase. The railway corridor proved to be sufficiently large since no safety-relevant vegetation was located in the fringe area. Due to the use of widely available geo-data the model provides the basis for a large-scale assessment of safety-relevant vegetation. When used together with maps, cross sections at any location of the railway corridor can be generated. Fig. 4 shows the mapped safety-relevant vegetation and the affected railway track in the year 2017 and a cross section of the railway corridor at an exemplary railway section.

3.2. Safety-relevant vegetation along the railway corridor

A key factor for the assessment of the potential risk posed by woody vegetation within the railway corridor is its proximity to the railway track. The vegetation risk index (VRI) can be used to evaluate railway sections with regard to the presence of woody vegetation tall enough and close enough to strike the railway infrastructure in the case of failure. Fig. 5 shows the VRI along the studied railway corridor for the respective year. Sections with a high presence of safety-relevant vegetation were identified. Particularly high VRI values were observed between 17 and 27, where the railway line is passing through densely forested and steep hillslopes. At the same time, there are sections where safety-relevant vegetation is completely absent (e.g. between kilometre 4 and 5). Section-wise, there are significant differences between the left and the right side of the railway track. This demonstrates the importance of a differentiation between the tracksides in large-scale lineside vegetation assessments.

3.3. Affected railway track area and changes

The results represent the proportional area of the pruning zone, which can be affected by hazardous vegetation (see Table 1). It is shown that a large area of the study site can possibly be affected by vegetation. In the year 2012, a total of 21.0% of the pruning zone was within the falling radii of lineside vegetation. This proportion decreased in the year 2017 to 20.0%. Considerably lower portions of the study site are possibly affected by safety-relevant vegetation of hazard classes

Table 1
Proportional area of the pruning zone (in %), possibly affected by vegetation of the respective hazard class.

Hazard class		*Vegetation type*					
		Deciduous 2012	*Deciduous 2017*	*Coniferous 2012*	*Coniferous 2017*	***Total 2012***	***Total 2017***
Geometry at position	*Downward sloping*	2.8	1.3	1.1	0.6	3.9	1.9
	Depressional to level	2.7	3.2	3.5	2.9	6.2	6.1
	Gently sloping	0.6	0.7	0.5	0.2	1.1	0.9
	Steeply sloping	1.1	0.6	0.3	0.3	1.4	0,9
	Very steeply sloping	6.4	7.7	2.0	2.5	8.4	10.2
	Total	13.6	13.5	7.4	6.5	**21.0**	**20.0**

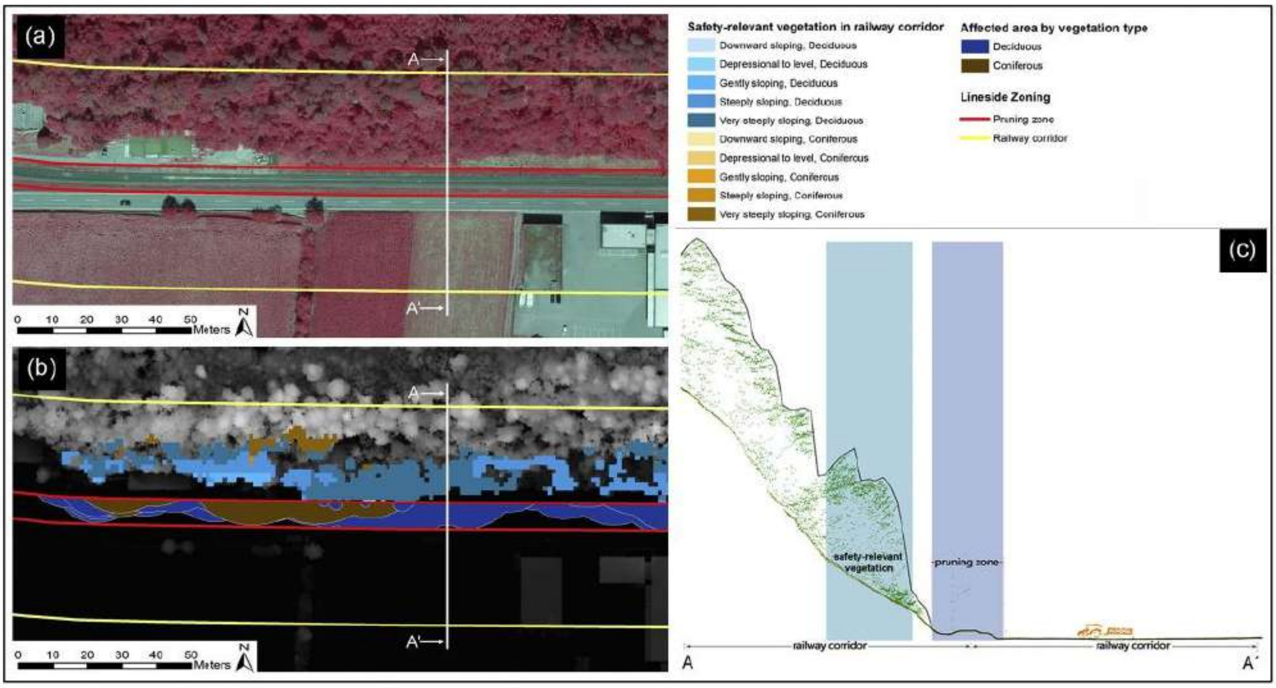

Fig. 4. Results 2017: (a) The colour infrared (CIR) orthophotos (b), the canopy height model (CHM) with both the identified safety-relevant vegetation structures and the pruning zone within the falling curves and (c), the airborne laser scanning (ALS) point cloud of a cross section (2 m width) of the railway corridor.

with high associated risks. In 2012, 9.8% and in 2017, 11.1% of the pruning zone could possibly be struck by trees in steep locations (classes "steeply sloping" and "very steeply sloping"). In both years the most present group was the vegetation type "deciduous" at a very steep location.

In Fig. 6, changes in the mapped safety-relevant vegetation and the affected railway track are shown at an exemplary section (kilometre of railway track: 9.1) of the railway. When comparing the colour infrared orthophotos and the results of the two studied years, changes in the vegetation structures are clearly. The affected area within the pruning zone decreased clearly on this site. Changes in the VRI along the railway corridor between the two studied years are illustrated in Fig. 7. The VRI changes demonstrate a dynamic development of safety-relevant vegetation. It is evident in sections where the area covered by safety-relevant vegetation structures changed clearly in the railway corridor between the two studied years. Smaller changes between the years might be attributable to the different data collection strategies used for the ALS database. In Fig. 8, the development of safety-relevant vegetation between the two studied years is shown for the entire railway corridor. Transformations of the safety-relevant vegetation are represented by the streams between the hazard classes. Lineside vegetation is dynamic and it is shown that there are considerable changes in its composition over time. Also, the affected sections of the railway tracks were shifting during the studied period. In both years, no endangered areas turned into affected areas and vice versa.

3.4. Discussion

The proportion of the railway track possibly affected by hazardous vegetation was found to be at a relatively high level. This can be ascribed to the high proportion of forest stands along the study site and the varied terrain within the railway corridor. It was shown that lineside vegetation structures are very dynamic. Transformation in the vegetation composition are likely to be associated with periodical maintenance works. Safety-relevant vegetation does not solely pose risks but can also provide important functions for the safety of the railway infrastructure: amongst others, it can serve as a protective forest that absorbs much of the danger in mountain zones emanating from avalanches, rock-falls, mud-slides, etc. (Weiss, 2000) and it can improve the stability of the embankment (Preti, 2012; Lammeranner et al., 2005; Gurnell and Petts, 2006; Preti and Petrone, 2013; Schwarz et al., 2010). Non-regulating ecosystem services can be supplied if the technical requirements are fulfilled, which thus ensures that the vegetation presents no risk to the railway infrastructure. It should be noted that vegetation is not static, but is constantly changing in a dynamic behaviour over time due to the prevailing physical, biological and man-made conditions. Consequently, its functions can also shift both positively (e.g. impact on the slope stability) and negatively (e.g. strong development of biomass and overgrowth of technical facilities). In order to achieve the desired functions of the lineside vegetation, its development must be periodically monitored and specific maintenance interventions must be applied. The maps presented can support the management of measures by showing the safety-relevant vegetation within the railway corridor. At the same time, they also show all vegetation that is not safety-relevant and consequently can provide a wide range of ecosystem services, which are not solely linked to the operational performance of the railway. The presented approach is based on proximity analysis, considering the distance and the geometric situation at the position of a vegetation element. A differentiation between the vegetation types "deciduous" and "coniferous" was included in the model. However, for an evaluation of the actual risk posed by lineside vegetation, multiple further parameters need to be considered. A large number of studies have used GIS-based analysis to describe the predisposition of trees to windthrow (e.g. Mitchell et al., 2001; Saarinen et al. 2016; Krejci et al., 2017). But these approaches focus on forest stands rather than on linear vegetation systems. In order to integrate the risk of windthrow or snow pressure into the presented model, climate, landscape, stand, and tree-scale data may be incorporated in future studies. ALS has been used for vegetation monitoring along with infrastructure facilities in previous studies. Wanik et al., 2017

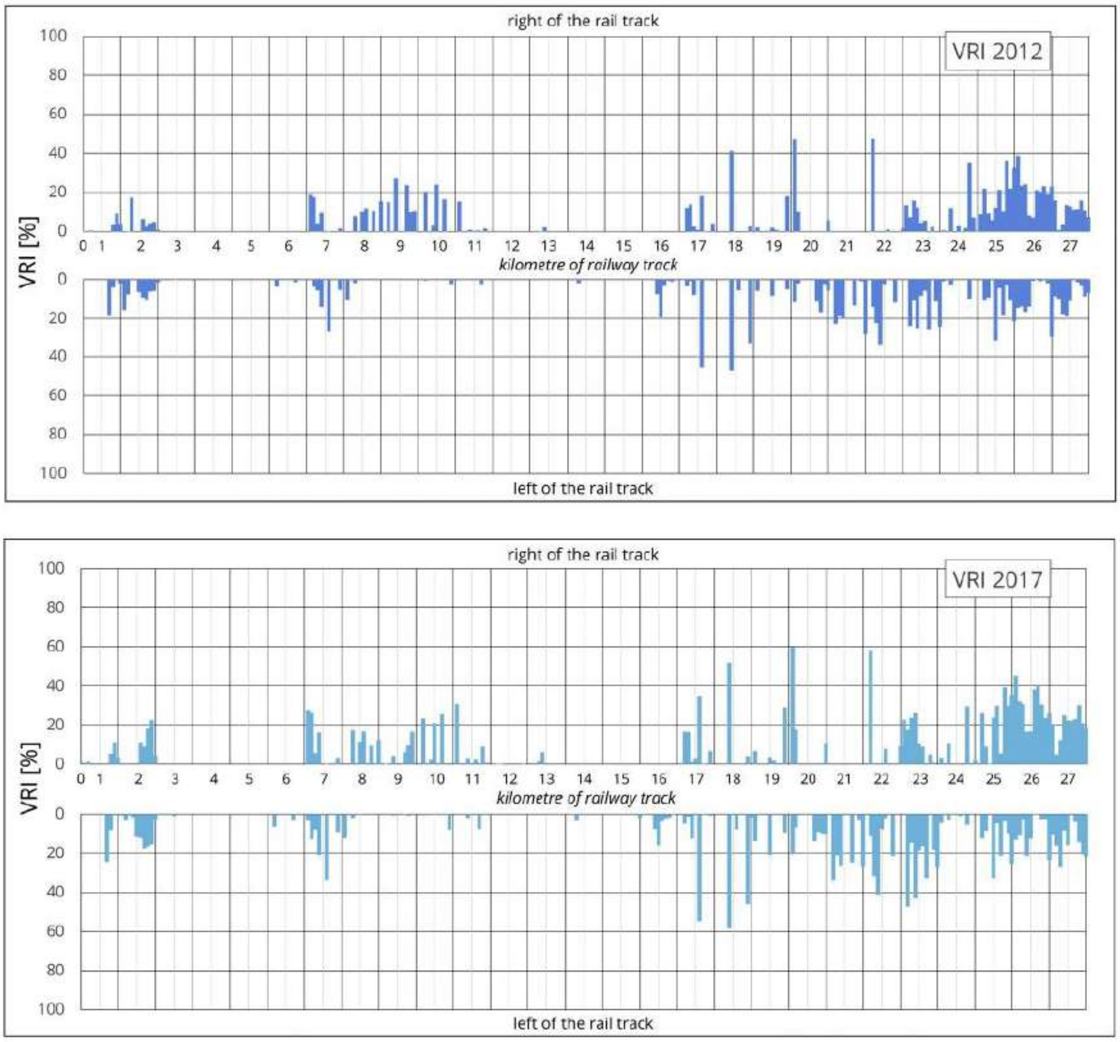

Fig. 5. Vegetation risk index (VRI) along the railway corridor in 2012 and in 2017.

generated a tool that uses ALS data for vegetation height measurement and outage prediction of overhead powerlines due to trees. They found out that proximity trees were more important than weather-related variables such as wind and rain for predicting outages. In the present study, ALS data was combined with orthophotos as the basis for lineside vegetation modelling. In order to obtain information on the species level and improve canopy height modelling, the combination with multispectral datasets should be tested. Several studies have demonstrated the strong potential of high-resolution satellite data such as WorldView-2 for tree classification on individual tree crown level (Immitzer et al. 2012; Waser et al. 2014; Fassnacht et al. 2017). But also, the combination of high-resolution orthophotos with freely available Sentinel-2 data has high potential to refine land cover classification. Such multi-temporal datasets can provide helpful information about vegetation types such as tree species (Immitzer et al. 2019). It has to be noted that in the case of leaning or dangling trees the applied canopy height model leaves room for uncertainty, as it represents not the stem length but the highest point of the crown. Airborne remote sensing technologies provide homogenous data on the supra-regional level and large segments of railway corridors can be covered by each survey flight. Due to its costs, airborne laser scanning is often acquired less frequently than orthophotos. A potential alternative to ALS data is the application of orthophoto matching, which is less expensive and orthophotos are routinely acquired in many regions. However, dense matching is problematic when the image contrast is poor (e.g. in shadowy areas), whereas low contrast or illumination is not a problem for laser data acquisition (Zhang et al., 2019). The applicability of orthophoto matching along a railway corridor has to be tested. For the inspection of lineside vegetation, terrestrial laser scanning with high spatial resolution and on-demand collection is also used by railway authorities (Assali et al., 2013). Remote sensing provides data for large-scale assessments. The presented study has shown that the possibility of analysis is not limited to vegetation adjacent to the railway line but rather that the entire railway corridor can be assessed. The presented approach can be applied to different linear landscape elements. For instance, along roads (e.g. for safety-relevant vegetation mapping) or watercourses (e.g. for assessing amounts of dead- and driftwood).

4. Conclusion

This study has confirmed that remote sensing technologies have great potential for providing data for large-scale lineside vegetation assessments. Through the combination of airborne laser scanning (ALS) data and high-resolution orthophotos, accurate models of safety-

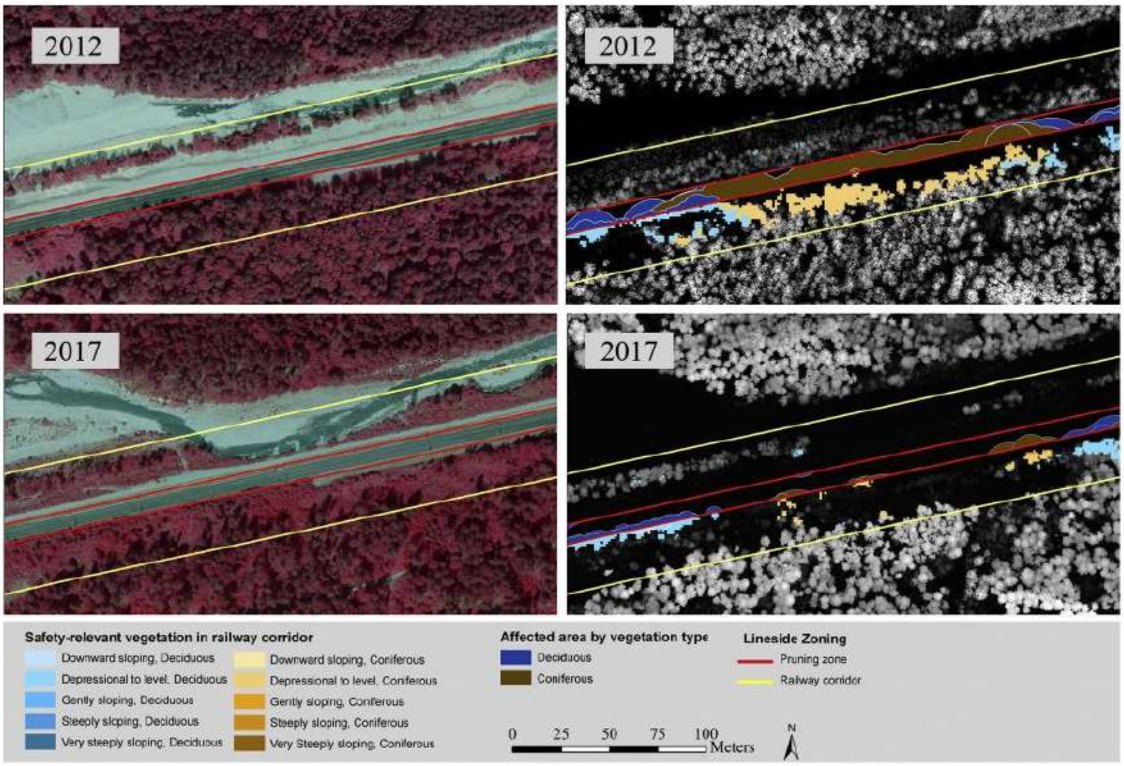

Fig. 6. Changes between 2012 and 2017: Orthophotos (colour infrared CIR composition) of the respective year (left). Canopy height model (CHM) with both the identified safety-relevant vegetation structures and the pruning zone within the falling curves (right).

relevant woody vegetation in a railway corridor were generated. Despite differences between the remote sensing data from the years 2012 and 2017 respectively, the results are comparable. This is shown by the similar total values related to the affected railway track in the studied years. The presented approach can support tree care management and contribute to maintaining safe and functional lineside vegetation. Railway segments, where many tall vegetation elements are present, can be subjected to more comprehensive monitoring practices. The presented study is based on widely available geo-data and can be expanded by further lineside vegetation mapping approaches. In this way, it supports the practice-oriented application of the green infrastructure concept on a large-scale.

Credit author statement

Stephan Hoerbinger: Conceptualization, Methodology, Investigation, Software, Visualization Writing- Original draft preparation Michael Obriejetan: Visualization, Investigation, Conceptualization, Writing- Reviewing Hans Peter Rauch: Visualization, Writing- Reviewing, Supervision Markus Immitzer: Conceptualization, Methodology, Investigation, Software, Visualization, Writing- Reviewing, Supervision.

Declaration of Competing Interest

None.

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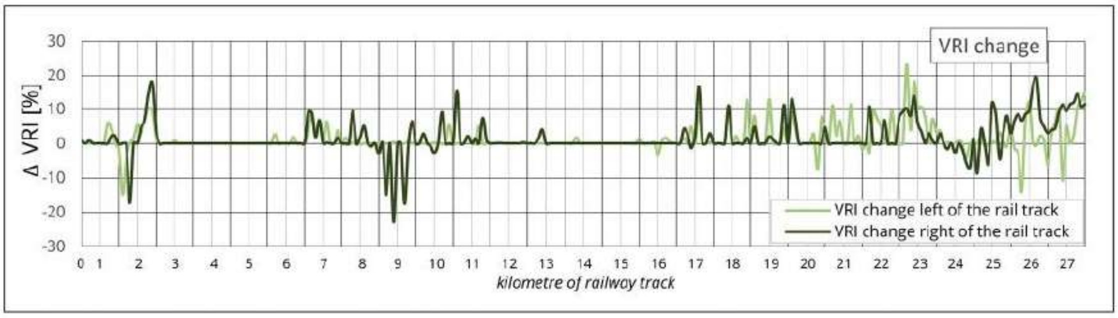

Fig. 7. Change in the vegetation risk index (VRI) along the railway corridor between 2012 and 2017.

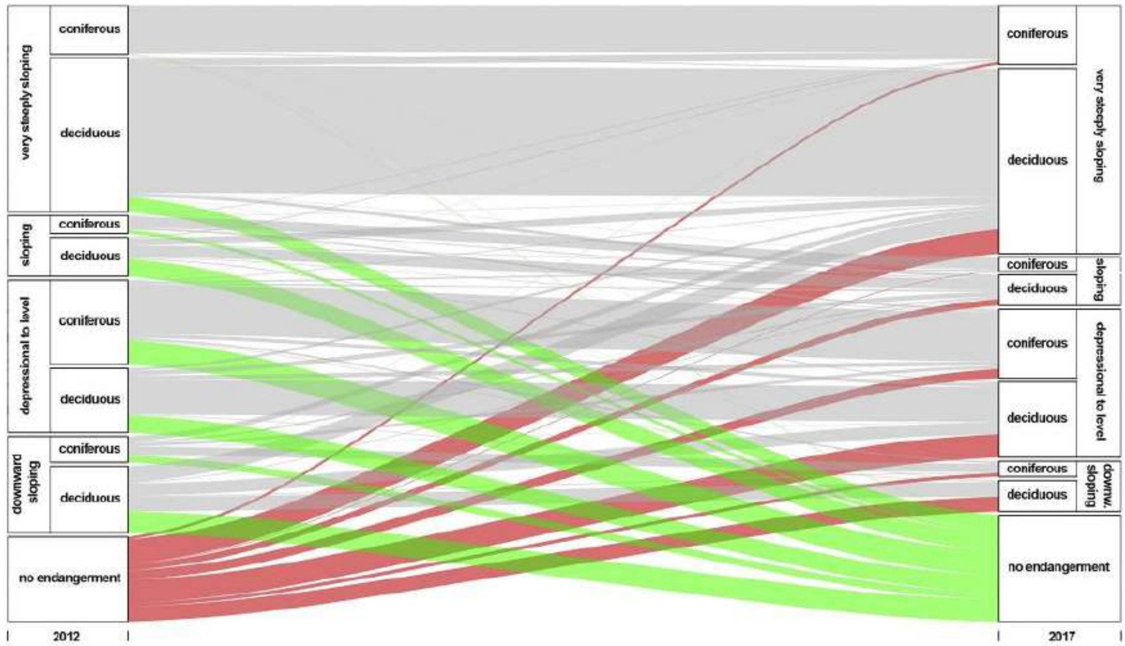

Fig. 8. Development of safety-relevant vegetation at the study site between the years 2012 and 2017.

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9.2 Article 2

GIS-based assessment of ecosystem service demand concerning green infrastructure line-side vegetation

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GIS-based assessment of ecosystem service demand concerning green infrastructure line-side vegetation

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ABSTRACT

A module-based Green Infrastructure (GI) and Ecosystem Service (ES) approach, adapted to the specific requirements and conditions for railway line-side vegetation management, is presented in this paper. The multi-functionality of line-side vegetation is addressed by an integration of the GI and ES concepts. The use of widely available geo-data enables its applicability, both in terms of large-scale and other infrastructure networks. In this way it can serve as a feature for emphasizing the creation of a productive, attractive and cost effective landscape resource. A methodological approach for the Ecosystem Service Demand Assessment (ESDA) of GI line-side elements was developed and applied at a study site. An ESDA was performed concerning "Structural landscape diversity" and "Water and climate regulation". The results represent the composition of landscape types, the demand for structural landscape features, the distribution of GI line-side elements and hotspots of land consumption. Additionally, potential capacity of GI line-side vegetation to provide ecosystem services was addressed. Maps created provide basic information for the railway operator to consider ecosystem service demand in construction and maintenance works. In this way, the presented GIS approach can support decision-making-sovereignty in implementing holistic line-side vegetation management strategies. The use of high resolution geo-data proved to provide a good basis for the accurate mapping of GI line-side elements. The study has confirmed that high resolution geo-data and GIS technologies have great potentials regarding spatial data provision and as analytical frameworks for line-side vegetation management.

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1. Introduction

Green Infrastructure (GI) and Ecosystem Service (ES) concepts are being increasingly applied for anthropogenic characterized landscapes. These concepts are promoted in order to improve environmental planning, based on a more holistic understanding of the complex interrelations and dynamics of social-ecological systems (Hansen and Pauleit, 2014). The European Commission has defined GI as a "strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services" (European Commission, 2013). This concept is typically used in the context of the "planned" open space which exists on public land including green urban spaces as well as right of way zones (Lovell and Taylor, 2013). The concept of multi-functionality is integrated within GI planning. This means that ecological, social, and also economic functions are taken into consideration. The aim of integrating the multi-functionality approach in management strategies for line-side vegetation is to emphasize the creation of a more productive, attractive, and cost effective landscape resource. Due to the extent of the area, railway managers need to balance many competing demands for resources (Below et al., 2003). There is a mitigation of risks through falling trees, abatement of invasive species, and consideration of the prevention of damage to technical facilities, which could be caused by overgrowth or increasing risks brought about through by climate change (Felderer et al., 2012). Additionally, the negative impact of linear infrastructure on landscapes, through habitat fragmentation and habitat loss, aesthetic impairments, disturbances and pollution, have been documented in several studies (Seiler, 2001; Hansen and Clevenger, 2005; Kumares and Samuel, 2007; Morelli et al., 2014; Nilsson et al., 2015). In terms of maintenance, line-side vegetation is regarded with ambivalence. On the one hand,

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there are the aforementioned risks, challenges and resource expenditures caused by vegetation. On the other hand, the functions of line-side vegetation are associated with an improvement of the stability and resilience of embankments and cuttings documented and proved by several soil bioengineering studies (Barker et al., 2004; Stokes et al., 2004; Obriejetan, 2013; EFIB, 2015). Additionally, line-side vegetation can supply multiple ecosystem services, which are not linked to the operational performance of rail traffic. The potential capacity of ES by line-side vegetation is documented in the literature, as well as the strong link between the demand on these services and the surrounding environment. Against this background, a method for an Ecosystem Service Demand Assessment (ESDA) was developed, which relates the line-side vegetation and the surrounding land use. Exemplarily, the demand for ecosystem services related to "Structural landscape diversity" and "Water and climate regulation" was assessed in a study site. Although line-side vegetation systems are disturbed or semi-natural ecosystems, they can provide important structural landscape elements, of contrasting characteristics to its surroundings. Passing through a wide range of landscapes, the demand for line-side vegetation as structural landscape elements is in direct relation to the surrounding environment. Particularly in cleared or featureless landscape types, line-side vegetation has great ecosystem service potentials to enhance "Structural landscape diversity". In order to assess the demand for ecosystem services related to "Water and climate regulation" the degree of sealing was assessed in the study site. The proportion of sealed soil and abstracted soil can be taken to measure regional regulation demand e.g. regarding flooding risk, infiltration or micro climate regulation (Helbron, 2008; Syrbe and Walz, 2012; EEA, 2011). A large amount of the spatial ecosystem service studies currently available, focus on ecosystem service supply, whereas the demand side has not been sufficiently considered (Burkhard et al., 2014). However, demand is crucial in ES approaches because per definition ES do not exist without human demand (Fisher et al., 2009). In terms of sustainable vegetation management, knowledge about the demand for specific functions is crucial when it comes to the implementation of measures and the use of resources. It has to be considered that the development of line-side ecosystems, and consequently their capacity to supply ES, is highly affected by human intervention. Due to this, the definition of Burkhard et al. (2012) was used as the basis of the concept in this study: "Ecosystem services are the contributions of ecosystem structure and function – in combination with other inputs – to human well-being". This definition incorporates anthropogenic inputs within the ES concept. Concerning GI line-side vegetation, the capacity of providing ES is highly influenced and controlled by these inputs (e.g. construction and maintenance). "Structural landscape diversity" and "Water and climate regulation" belong to the natural properties and form a basis for ecosystem functions and ecosystem processes. The anthropogenic influence on the development of GI line-side elements can affect the ecosystem functions and ideally contribute to the human well-being. Through the example of two specific groups of ES demands, a case study was implemented. This article presents a methodological approach for a GIS-based line-side vegetation management system, and shows the results of a case study. It is based on widely available geo-data and was designed to enable the application of the GI-concept on a larger scale. There are a number of GIS-based methodologies for hazard and risk assessments along railways. This article presents a new methodological approach for a GIS-based line-side vegetation management system including the Ecosystem Service Demand Assessment (ESDA) and shows the results of a case study. Through the combination of different GIS systems, comprehensive information including technical, ecological and economic aspects can be provided for the railway operator. The presented approach is based on widely available geo-data and was designed to enable the application of the GI-concept on a larger scale.

2. Material and methods

The workflow in Fig. 1 spans over different levels. The first level is the geo-database, which compromises of all data necessary to perform the working-steps. Along with high resolution geo-data, it includes shapefiles of the linear-infrastructure network at the trial site. A detailed land cover map was created as a basis for all further analysis. The application of multiple GIS-analyses resulted in the creation of specific thematic maps. By means of a methodically adjusted evaluation approach, which is based on a segmentation process, the thematic maps were merged together, and following on from this, the demand of selected ecosystem services were assessed.

2.1. Study site

The analysis was implemented at a 2.7 kilometer-long test site located in the western federal state of Austria, Vorarlberg (Fig. 2). The site is composed of the A14 highway, the S16 trunk road, ten national roads and including a number of major highway embankments. The trial site was defined based on the single track Innsbruck – Bludenz line (Arlbergbahn) and the double track Lindau – Bludenz line (Vorarlbergbahn). Vegetation conditions within the test site are representative of those found on the Austrian road and rail network, and across the alpine regions in particular. The study site covers a heterogeneous landscape including the densely populated region of the district capital "Bludenz" and less populated mountainous areas in the eastern part of the study site. The site is located in the alpine climatic zone. The topography in the area is variable exposed, flat and undulating.

2.2. GIS-based system analyses

2.2.1. Land cover map

The data-base comprised of a four-band orthophoto (NIR + RGB) with 12 cm spatial resolution, a DTM (0.5 m spatial resolution) and a nDSM (0.5 m spatial resolution, calculated by subtracting the DTM from the DSM). Spatial data was analyzed by means of ArcGIS 10.2 (ESRI). Information about the railway line was available as a polyline running through the track axis. A 1000 m buffer was created from this line. The buffer was used to crop the utilized geo-data. In terms of the object-based analysis, the segmentation process was performed by means of the eCognition Developer 8 software. For the classification metrics (mean, standard deviation, quantiles) based on the four spectral bands, nDSM and Haralick texture were used. Also shape features based on ratios between the area and the perimeter of the objects were computed. The features applied for the purpose of further land cover classification, were compactness and shape index. The Random Forest (RF) classifier, developed by Breiman (2001) was applied by using the statistic software R Version 3.3.2 (R Core Team, 2016). RF is a machine learning algorithm which consists of an ensemble of decision trees, and is currently widely used for land cover classification (Belgiu and Drăguţ, 2016; Gislason et al., 2006; Immitzer et al., 2016). The advantages of RF are the integrated bootstrapping which achieves relatively unbiased 'out-of-bag' (OOB) results, and that it can deal with minimal training data, multi-modal classes and non-normal data distributions (Hastie et al., 2009; Immitzer et al., 2012). The following classes were considered: railway facilities, streets, buildings, arable land, green land, coniferous tree, deciduous tree, shrub, bare ground, water and shadow. Subsequently the land cover map was adjusted from shadow by reclassification through vicinity analysis.

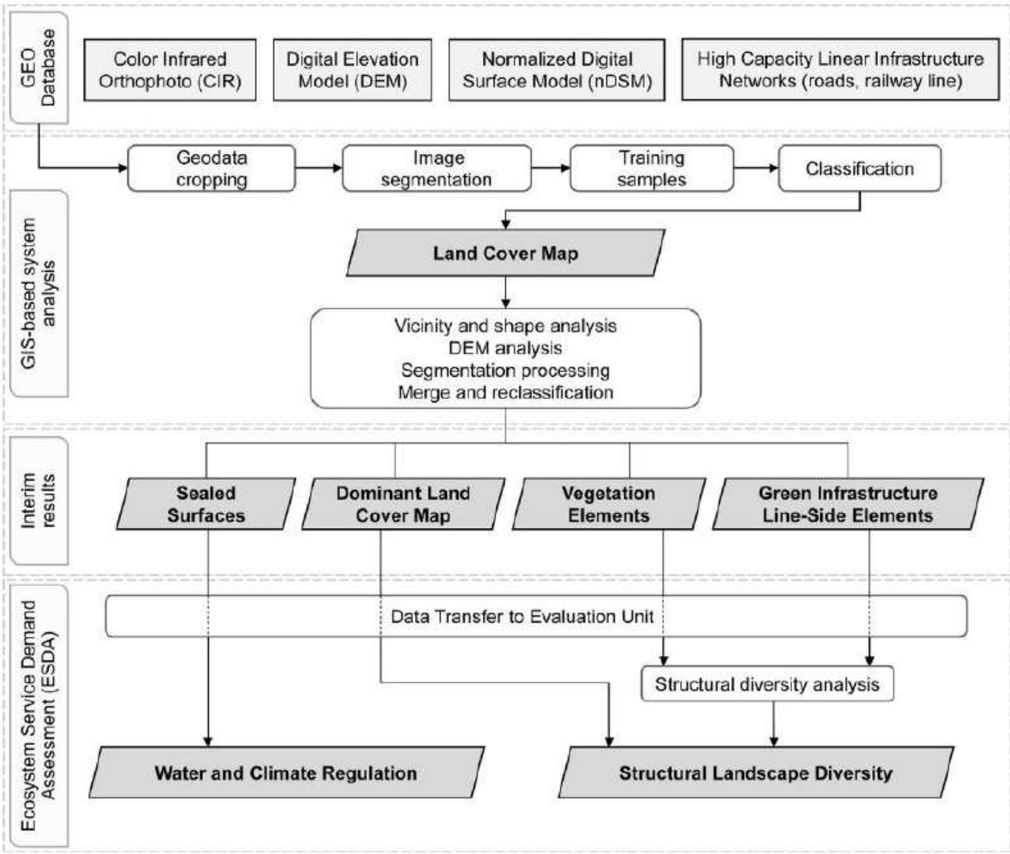

Fig. 1. Geoprocessing workflow including input data, analysis steps, preliminary results and Ecosystem Service Demand Assessment (ESDA).

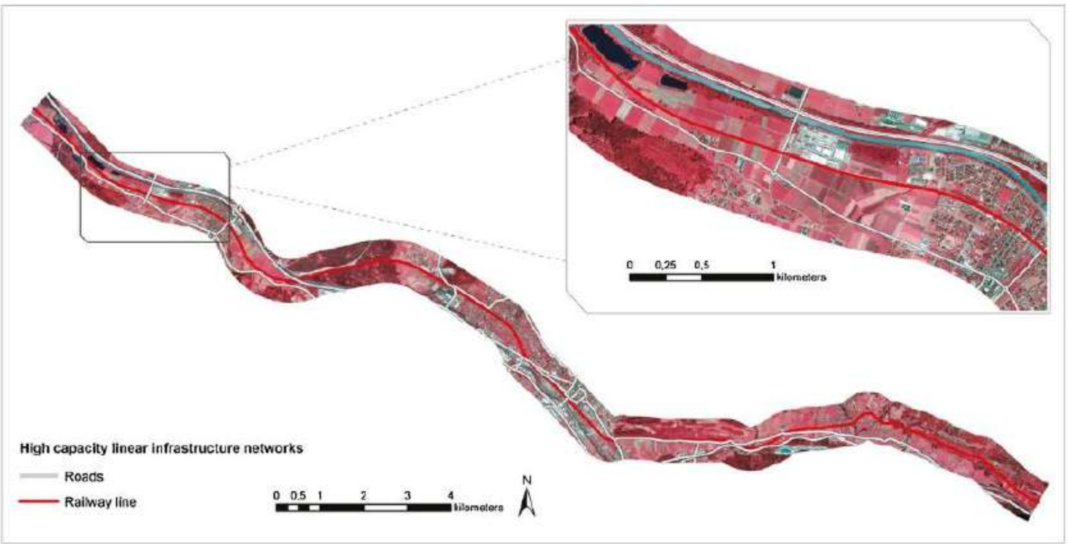

Fig. 2. CIR orthophoto of the study site.

2.2.2. Dominant land cover map

In order to characterize the landscape, within the context of GI elements along higher infrastructure system networks, the land cover polygons were aggregated to the dominant land cover. The classification was set in order to describe the formative landscape entities. The class traffic area consisted of polygons with the attributes "railway facilities" and "streets". All polygons containing classes of woody vegetation were analyzed in terms of their vicinity to water bodies. When found to be adjoining, they were attributed, along with water bodies, the class "water bodies with adjacent vegetation". The area of polygons with the attributes "deciduous trees" and "coniferous trees" was calculated. Based on Austrian forestry law, the threshold for the class forest was set at an area of >1000 m^2. Adjoining shrubs were added to the class forest. The classes urban area and rural area were compiled by means of vicinity analyses. The query for urban areas was set from polygons, which were classified as buildings in the land cover map. Concerning rural area, the query was based on green land and arable land.

2.2.3. Assessment of sealed surfaces

The composition of the landscape was measured in terms of the degree of sealing. All polygons, which were mapped in the land cover map as sealed, or partly sealed surfaces, were merged together. This comprises of polygons, which have the attributes streets, buildings and railway facilities. The calculated degree of sealing was adapted to the specification of the federal environment agency of Austria. The degree of sealing of railway facilities was defined at 50%, whereas buildings and streets were considered to be 100% sealed.

2.2.4. Mapping of vegetation elements and green infrastructure (GI) line-side elements

The following vegetation structures and GI line-side elements were mapped by reclassification of the land cover map: forest (mixed forest, deciduous forest and coniferous forest), copse high (tree group and single tree), copse low (shrub group and single shrub) and herbaceous vegetation (grass verge, grass on infrastructure embankments and sparse vegetation). The same threshold (area >1000 m^2) was applied for the classification of forest types. The class "mixed forest" was generated by using vicinity analyses. For the remaining polygons, shape features shape index, compactness and area, were calculated. Again, an RF classification was applied for differentiation between single wooden structures and wooden structures in groups. The remaining polygons which had been attributed woody vegetation were classified as "tree groups" or "shrub groups". Herbaceous line-side elements were generated by a reclassification of the classes "green land" and "bare soil". The slope was calculated from the DTM. Surfaces with a slope higher than 18° were intersected with polygons of herbaceous vegetation. A further RF process was applied to separate sparse vegetation from bare soil. The objective was to map herbaceous elements along high-ranking infrastructure. Thus, vicinity analysis on the basis of high-ranking roads and the railway line were applied in order to extract herbaceous GI-elements. The same classification criteria were applied for GI line-side vegetation and for the vegetation in the surrounding. In this way, the potential of GI line-side vegetation to enhance the amenities of the landscape could be analyzed. If similar vegetation structures are absent in the surrounding environment, a greater potential for providing ecosystem services, related to "Structural landscape diversity", are assumed.

2.2.5. Classification of green infrastructure (GI) line-side elements

GI line-side element types were defined regarding certain functions and requirements, consisting of the specific site conditions along the railway infrastructure. The vegetation categories were set following international maintenance practices (Luegger and Buser, 2009; Below et al., 2003; SBB, 2001), and take into consideration technical, economic, and ecological aspects. The line-side management zone was limited to 30 m from the edge of the railway ballast, on each side. This limitation was based on the maximum tree height, which was approximated to be 30m for the region. Trees can affect the operational performance by fouling the structure gauge, or can cause severe risks when falling onto railway facilities. For this reason, line-side vegetation management has to take into consideration an area extending up to the limits of the maximum falling curve of tree stocks. Agricultural vegetation structures or urban green spaces, which were inside of the line-side management zone, were not considered, because these structures are subject of different management practices.

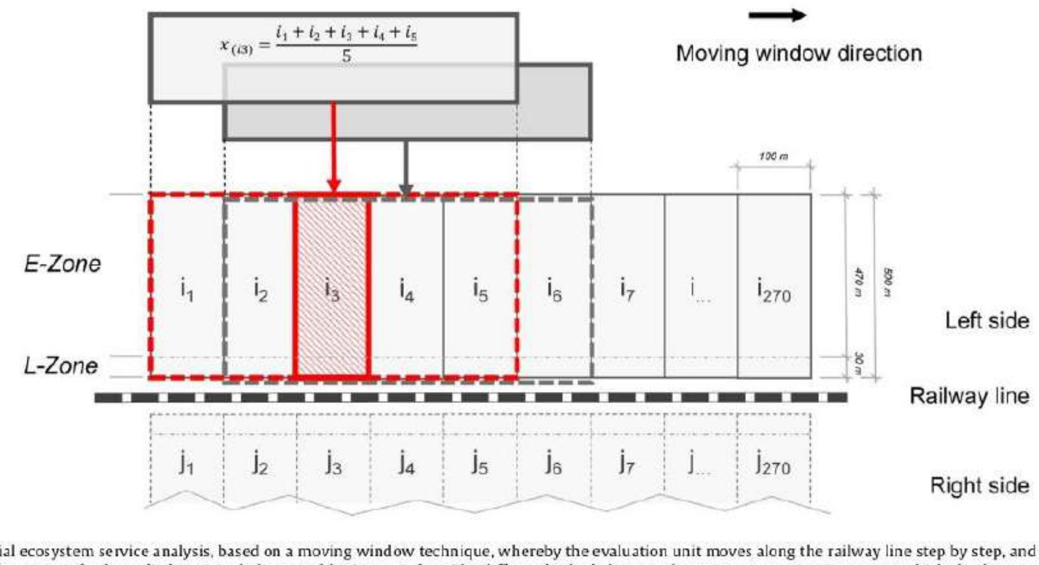

Fig. 3. Spatial ecosystem service analysis, based on a moving window technique, whereby the evaluation unit moves along the railway line step by step, and segment data is assigned by means of value calculation, including neighboring unit data. The differently shaded rectangles represent two sections, over which the data was calculated. X (i_3) = the moving average, calculated for the respective evaluation unit of the first section. It is the average value of the five neighboring units i_1, i_2, i_3, i_4, i_5. The evaluation units are subdivided into the Line-Side Management Zone (L-Zone) and the Environmental Zone (E-Zone).

Table 1
Confusion matrix based on OOB results of the RF model for land cover classification. (Abbreviations: UA: User's Accuracy, PA: Producer's Accuracy, OA: Overall Accuracy).

	Reference										Shadow	Σ	UA
Classified as	Coniferous	Deciduous	Shrub	Arable land	Green land	Bare ground	Building	Railway facilities	Street	Water bodies			
Coniferous	42	2	0	0	0	0	0	0	0	0	1	45	0.933
Deciduous	2	39	4	0	0	1	0	0	0	0	0	46	0.848
Shrub	0	4	40	1	4	0	0	0	0	0	0	49	0.816
Arable land	0	0	0	25	3	5	0	0	0	0	0	33	0.758
Green land	0	0	3	3	41	1	0	0	0	0	0	48	0.854
Bare ground	0	0	1	4	0	20	1	0	5	1	0	32	0.625
Building	0	0	0	0	0	1	45	1	1	0	0	48	0.938
Railway facilities	0	0	0	0	0	0	0	31	0	2	0	33	0.939
Street	0	0	0	0	0	4	1	0	29	0	0	34	0.853
Water bodies	0	0	0	0	0	0	0	1	0	18	1	20	0.900
Shadow	1	0	0	0	1	0	0	0	0	1	35	38	0.921
Σ	45	45	48	33	49	32	47	33	35	22	37	426	
PA	0.933	0.867	0.833	0.758	0.837	0.625	0.957	0.939	0.829	0.818	0.946	OA	0.857
												Kappa	**0.842**

2.3. Ecosystem service demand assessment (ESDA)

The limited lateral extension of GI line-side elements narrows their effective area, in terms of ES supply and demand. Consequently, the benefiting areas are concentrated along the railway line. Evaluation units were created along the railway line as a basis for further ES analysis. For this purpose, the railway line was divided into 270 segments, with a length of 100 m each. The edge points of the split railway line were snapped to the outline of the trial site. Subsequently, the points were connected by lines, which were used to split the buffer into segments of 100 m × 500 m. Since the land cover clearly differed, between the two sides of the railway line, all analyses for the right and left side was done separately. The evaluation units comprise of the Line-side management zone (L-Zone) and the Environmental Zone (E-Zone). To avoid sharp boundaries, similar to a moving window approach, the data of the two neighboring segments, on each side, was used for an analysis of the respective segment. Within the "moving window", the average of the segment values was computed and used as the value of the aggregated segments (Fig. 3).

The surrounding environment was analyzed in terms of the extent and presence of vegetation structures in order to assess the demand on ES, related to structural landscape diversity. Initially, the main characteristics of the landscape were examined. For this purpose, the dominant land cover map was transferred to the evaluation units. A land cover class was considered to be dominant if it covered more than double the area of the second largest class. If none of the dominant land cover types reached such extend, the respective evaluation unit was assigned the attribute "Mixed landscape". As a next step, the coverage of environmental zone vegetation structures and separately the coverage of GI line-side elements, was assessed within the evaluation units. Specifically, the composition of vegetation elements and GI-line-side elements, with regard to their coverage area within the evaluation units, were examined. The data was summarized qualitatively in boxplots. Subsequently, the results were interpreted on basis of literature review. In terms of the ESDA of water and climate regulating services, the degree of sealed surfaces was calculated for each evaluation unit, by applying the "moving window" approach. According to Wende et al. (2014), the degree of sealing was specified in six classes at 20% intervals. Class 0 indicates unsealed surfaces, while class 5 covers the division of 80% to completely sealed surfaces.

3. Results and discussion

3.1. Land cover map

The confusion matrix based on the OOB results of all reference data is shown in Table 1. In total 426 training samples were col-

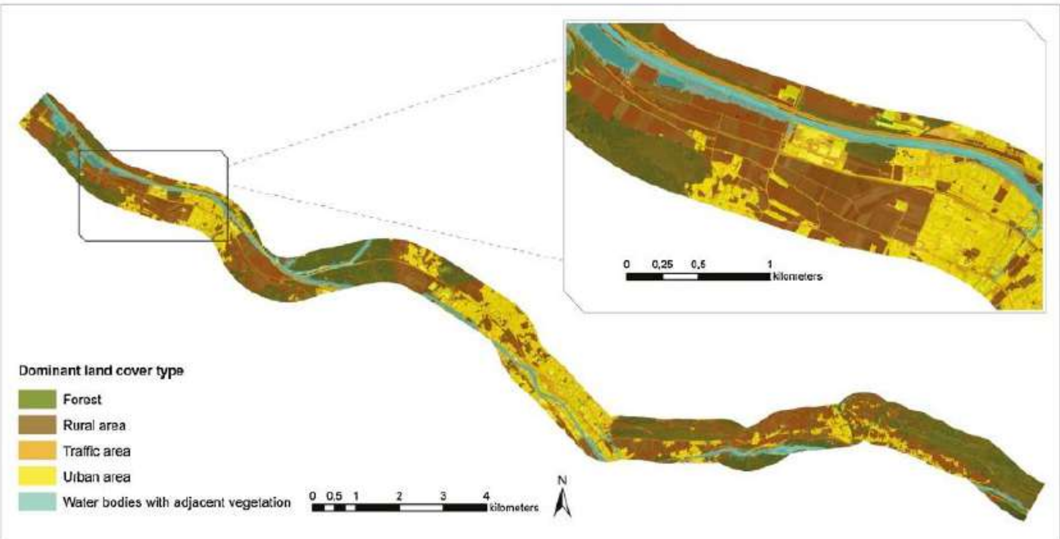

Fig. 4. Dominant land cover map of the study site and a detailed section of the map.

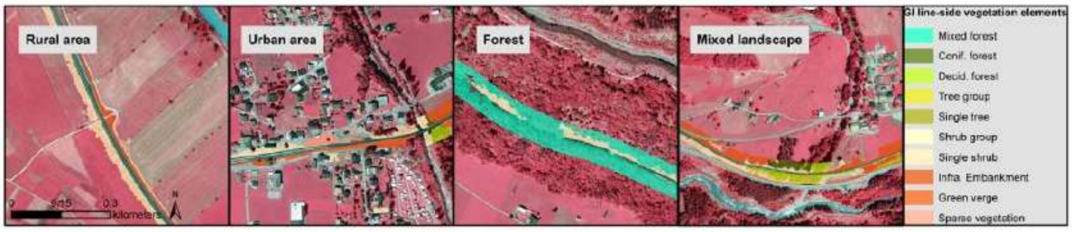

Fig. 5. Dominant land cover map of the study site and mapped GI line-side elements.

lected (20–45 per class), for the purpose of the classification of the land cover. The achieved overall accuracy was 85.7% which is sufficient for these types of classification problems based on monotemporal data sets. The class specific results are seen to be very uniform, and all classes reached the satisfactory user's and producer's accuracies. The user's accuracy ranged between 62.5% (bare ground), and 93.3% (coniferous). Similar results can be observed for the producer's accuracy, which ranged from between 62.5% (bare ground) and 94.6% (Shadow). The majority of misclassification was found within the classes bare ground and arable land. Therefore a combination with multi-temporal data (e.g. Sentinel-2 satellite data) could be helpful.

3.2. Dominant land cover map

The objective of the dominant land cover map was to characterize the landscape in coarser entities. The approach, which involved the use of vicinity based analysis for reclassification of the land cover map, showed good results (Fig. 4). However, in cases where the elements, from which the vicinity was queried, were detached, small units of classes sometimes resulted. Although small units were not the aim of this level of mapping, these units did not have any significant effect on further analysis. Another approach could be the application of a coarser land cover map segmentation process. This process may prove to be less time consuming, but it will also result in lower accuracy. All further landscape analyses carried out was based on the dominant land cover map.

3.3. Classification and mapping of GI line-side elements

The comprehensive requirements of an applied vegetation management were considered in the classification of GI line-side elements. Through accurate mapping, information about safety, ecological, societal and ecological aspects can be derived, and subsequently form the basis for a holistic management system. The use of metric shape features for the classification of vegetation elements showed good results. Single trees and single shrubs showed high correlation with the shape index compactness and the area. The class "green verge" could be classified by applying the shape index. The total area of around 78 ha highlights the importance, as well as the challenges, of maintenance at line-side management zones. At 47.3%, forest represents the largest amount of all categories. However, it must be noted, that larger forest stands extend, in many cases, over the whole line-side management zone. In rural or urban dominated landscapes, fields or settlements often almost reach up to the railway ballast, and railway verges are very narrow. The amount of single copse is at 0.1%, very small. At 29.8%, shrub groups are covering a large amount of the total area. This might the result of short rotation coppice practices. At 20.9%, herbaceous vegetation cover as well a large area (Table 2). In Fig. 5, mapped GI line-side elements within the dominant land cover types are illustrated.

Table 2
Categories of GI line-side elements, its coverage area and proportional distribution at the study site.

Category	GI line-side elements	Area in m^2	Area in%
Forest	Mixed forest	266,394	34.0
	Deciduous forest	97,455	12.5
	Coniferous forest	5885	0.8
Copse high	Tree group	15,214	1.9
	Single tree	739	0.1
Copse low	Shrub group	233,313	29.8
	Single shrub	124	0.0
Herbaceous	Infrastructure embankment	99,976	12.8
	Green verge	37,310	4.8
	Sparse vegetation	26,071	3.3

3.4. Ecosystem service demand assessment (ESDA) "structural landscape diversity"

Ecosystem Service Demand Assessment (ESDA) of "Structural landscape diversity" is based on the evaluation of the statistical distribution of the coverage area of vegetation elements in the environmental zone, and the line-side management zone (see Figs. 6 and 7). Firstly, the results of the coverage analysis in the environmental zone are presented. Subsequently, the demand for each dominant landscape class is assessed. The composition of forest dominated landscapes shows the highest proportion of vegetation covered area. Significantly, the highest proportion is presented by mixed forests. Shrubs present the second highest rate, but at a considerably lower level. Deciduous forest is less represented in this landscape composition. Other vegetation structures which were investigated are scarce, or not present. A similar trend was observable in mixed landscapes. However, the overall coverage of vegetation elements is considerably lower in this landscape type class. Deciduous forests are more frequent in this landscape type than they are in forest dominated areas. This presumably results from a high amount of riparian vegetation within this land cover class. In rural dominated landscapes, the percentage of vegetation covered area is significantly lower. However, a more varied composition of vegetation elements can be noted. A balanced presence of mixed and deciduous forests can be observed, albeit on a rather small scale. The total surface cover rates of vegetation elements in urban dominated landscapes are significantly the lowest of all reference groups.

3.4.1. Evaluation of demand "Structural landscape diversity"

The analysis shows that in landscapes with a high percentage of forest (forest dominated and mixed landscapes), the herbaceous vegetation elements which were investigated are only represented at a low level. A potential demand on herbaceous GI line-side elements can be assumed for these landscape types. This also conforms to Helldin and Seiler (2003), who mentioned that, in terms of woodland, open grassy verges may introduce more diversity into the surrounding habitat than they would do in open landscapes. Regarding the line-side management zone, a variety of

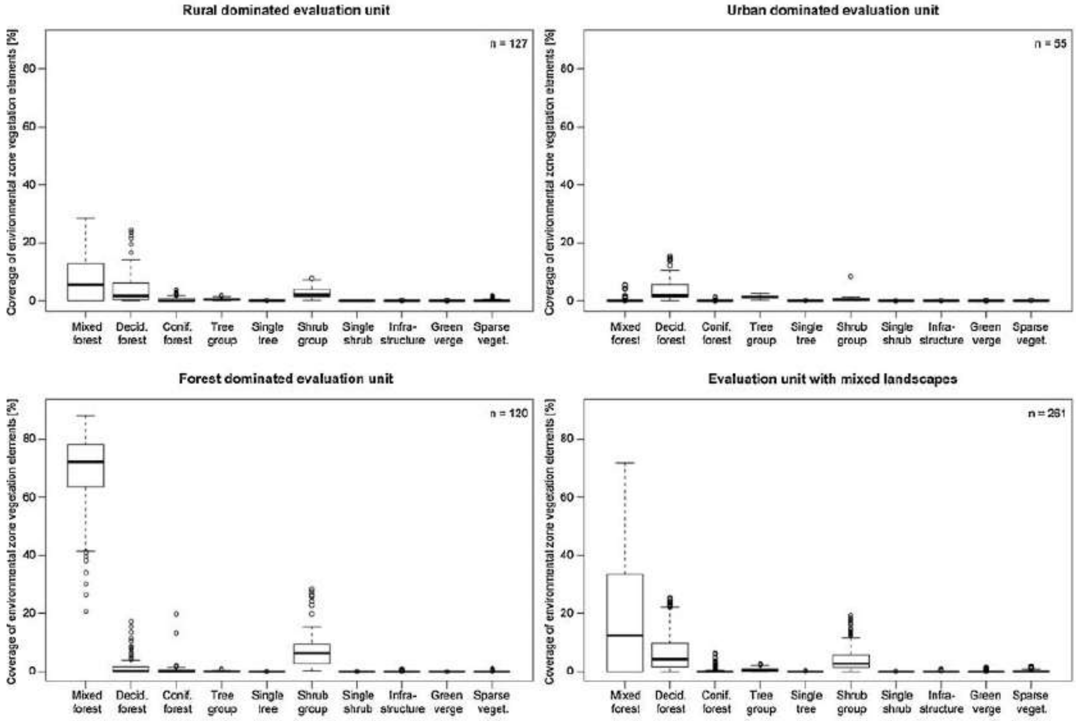

Fig. 6. Distribution of the coverage of environmental zone vegetation elements in the evaluation unit, in the respective dominant land cover type, and the number of evaluation units attributed to this land cover type.

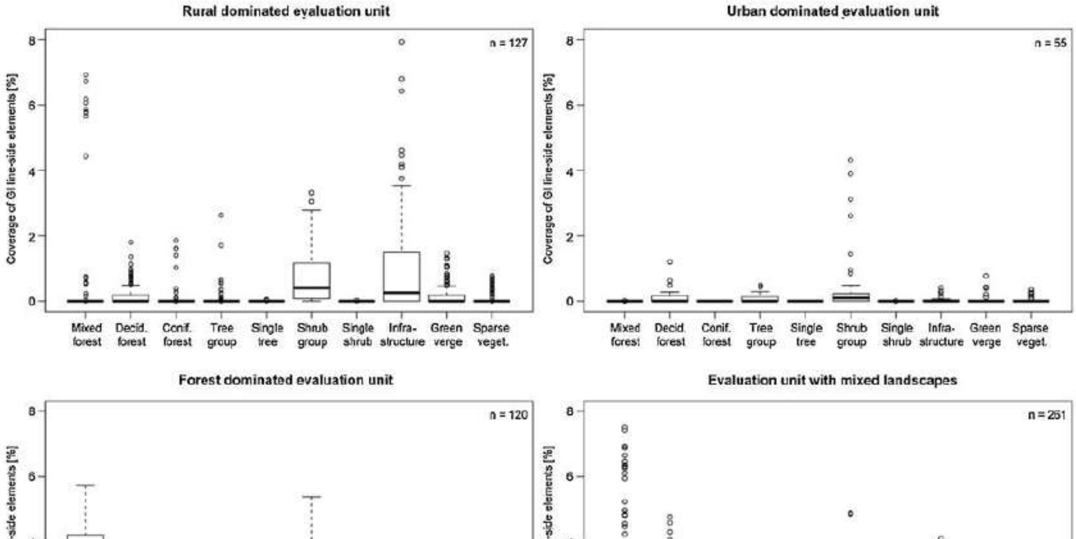

Fig. 7. Distribution of the coverage of GI line-side elements in the evaluation unit, in the respective dominant land cover type, and the number of evaluation units attributed to this land cover type.

herbaceous vegetation structures is noticeable. This highlights the potential capacity of GI line-side vegetation to enhance structural diversity in this type of landscape. In urban and rural dominated landscapes, the variability of vegetation structures is higher. The total coverage of vegetation elements is significantly lower in these types of landscapes. According to Penone et al. (2012), railway edges provide a potential function as corridors for common grassland species in urban landscapes. However, in urban landscapes the proportion of GI line-side elements is rather low within the study site. In contrast to mixed landscapes, the coverage area of woody vegetation is lower in rural and urban dominated landscapes. However, tree- and shrub groups are present in both landscape types. In fact, hedges and field coppice, in particular, can supply high ecological values (Bastian and Schreiber, 1994). Hedges and tree groups may provide habitats for bats (Vandevelde et al., 2014) and bird species (Morelli, 2013; Wiacek et al., 2015) whereas a dense shrub cover can lead to a deterioration in habitat of pollinators (Moron et al., 2014). In agricultural landscapes, a demand for tree structures, such as tree groups or single coppices, can be assessed. Dense shrub populations, within the line-side management zone, might have a lower value in terms of habitat provision in agricultural landscapes. Railway embankments are important habitats for pollinators in agricultural dominated landscapes. Bare ground and sparse vegetated verges can affect bee populations in a positive way. However, butterfly populations positively depend upon native flowering (Moron et al., 2014). Herbaceous infrastructure vegetation is presented at a relatively low level in rurally dominated landscapes within the environmental zone. Hence, a demand for these structures can be assessed. However, within the line-side management zone, these structures are not significantly present. The results of the dominant land cover types within the evaluation units provide an overview of the characteristics of the surrounding environment and display an overall description of the landscape composition (see Fig. 8). This enables an evaluation of the characteristics of the surrounding environment, in terms of the extent of the vegetation structures investigated. In this way a rapid overview of the status of the structural landscape diversity is provided, and demand tendencies can be assessed.

3.5. Ecosystem demand assessment (ESDA) "water and climate regulation"

The results of the analysis show clearly that highly sealed areas are concentrated in evaluation units in urban dominated or mixed landscapes. Not surprisingly, in the area of the district capital "Bludenz", a high concentration of evaluation units attributed to the class 4 is noticeable. Partially a high degree of sealing was observed within the class mixed landscapes. This may be a result of a high presence of large road systems and scattered settlements.

3.5.1. Evaluation of demand – "water and climate regulation"

Surface sealing degree and built area are crucial factors in terms of regulation demand within service benefitting areas (Syrbe and Walz, 2012, based on Helbron et al., 2009). Since soil sealing is a key indicator of the impact on soil, water, and climate, in urban areas, it is possible to derive conclusions about the tendencies of the microclimatic situation in urban subspaces by means of the degree of sealing (Wende et al., 2014). In urban environments, line-side vegetation can provide a significant supply of climate and water regulating services. Forests and Trees can increase the air humidity through absorption of rainwater and evaporation, bind dust, lower the air temperature and reduce the wind speed. Herbaceous and low copse vegetation can have a cooling effect on the surrounding built-up area in the evening and night hours and prevent extreme temperatures (Arlt et al., 2005). With a high degree of sealing a demand on water and climate regulating services can be assumed for the respective evaluation units (see Fig. 9). This means that GI line-side elements can provide benefits as a service providing unit.

4. Conclusion

GI line-side elements are a specific type of landscape component. Characteristically, they are disturbed or semi-natural ecosystems with specific properties and capacities for delivering ES. In particular, if similar structures are absent in the surrounding environment (environmental zone), there is an increasing demand on services provided by line-side vegetation. The evaluation of the ES demand and supply balance is complex, but the detailed map-

Fig. 8. Dominant land cover within the evaluation units, providing basic information for the Ecosystem Service Demand Assessment (ESDA) concerning "Structural landscape diversity".

Fig. 9. Degree of sealing within the evaluation units, providing basic information for the Ecosystem Service Demand Assessment (ESDA) concerning "Water and climate regulation".

ping of GI line-side elements allows the user a coarse evaluation. For this reason, no specific balance maps have been presented for the study site, rather the analyses are intended to provide guidance regarding ES in GI-line-side management. It has to be noted, that only if the technical requirements are fulfilled and thus it is ensured that the vegetation presents no risks and provides the desired regulating function further ecosystem services can be provided. Otherwise the risks outbalance all benefits. In fact, vegetation management is complex in terms of linear infrastructures, due to the extensive area, different site conditions and a wide range of technical as well as societal and ecological demands. Current management strategies are designed to minimize risks, and to ensure the operational performance of rail traffic. Detailed mapping of GI line-side vegetation can provide crucial information for resource efficient and sustainable maintenance works. In this way, the presented GIS approach can support decision-making-sovereignty in implementing holistic line-side vegetation management strategies. The selected railway section is located in a typical alpine region, characterized by a high degree of heterogeneity and different surrounding land use types. Therefore, it was suitable to develop and test the methodology. The presented results have to be considered as regional and specific for this landscape zone but it was taken care that the methodology is easily applicable over lengthier sections. By means of creating the dominant land cover map the landscape was characterized. The intersection of the present vegetation elements with each landscape type showed the landscape composition in the evaluation units. Knowledge about the present vegetation types in the surrounding environment provides basic information for the railway operator to define target vegetation systems. The analysis of the distribution of GI line-side elements showed their significant potential to enhance "Structural landscape diversity". Furthermore, basic information for the ESDA concerning "Water and climate regulation" was provided. It could be identified hotspots of regulation demand, which concentrate on areas of high land consumption. The study has confirmed that high resolution geo-data and GIS technologies have great potentials regarding spatial data provision and as analytical frameworks for line-side vegetation management. The standard geo-data such as orthophotos, together with state-of-the-art analyses tools, proved to be an appropriate method for landscape analyzing. Through the transfer of the data to common evaluation units, multiple issues can be considered collectively. In this way, the presented approach can be applied for further ecosystem service assessments, and to map hotspots of multi-functionality.

Acknowledgements

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9.3 Article 3

River restoration challenges with a specific view on hydromorphology

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FOREFRONT PERSPECTIVE

River restoration challenges with a specific view on hydromorphology

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1 Introduction

1.1 River ecosystem degradation

Over the past century, almost throughout the whole world, streams and rivers have been heavily polluted and morphologically degraded due to industrial, household and agricultural sources, leading to significant declines in biodiversity, water quality and ultimately water supply [1–5]. In the last decades, river system design has been practiced from an engineering viewpoint that focuses on water abstraction, sanitation, generation of energy, transportation and safety, rather than from a socio-ecological perspective. The technical management altered the understanding of a functioning river system itself and its social context. This strongly modified the physical and cultural nexus between rivers and the nearby human population [6]. Individual or combined effects of stressors usually lead to a reduction in biodiversity due to reduced water quality, habitat degradation, dispersal barriers, unsuitable biological flow regimes, changes in the input of organic matter or sunlight, etc.[7]. Given the importance of freshwater systems in providing ecological services and diverse habitats for many species, it is clear that restoration is needed to maintain sustainable ecological services while restoring ecosystem function and habitat scope [8].

1.2 Hydromorphology came into being

The insight that a restored river ecosystem can deliver multiple interconnected benefits to society has led to a change in the perception of functional river systems and to an expansion of river restoration [9]. The Water Framework Directive (200/60/EC, WFD) and the US Clean Water Act (US CWA) emerged as a formalized demand for healthy freshwater ecosystems and acts as a catalyst for river restoration projects, consequently meeting the implementation of upcoming directives like the UN' sustainable development goals (SDGs). A universal river restoration approach includes a wide range of possible target issues. In a first step the solution of a water pollution problem is a key issue of river restoration projects. Also, human activities. Besides that, human activities have a huge impact on the hydromorphlogical conditions of rivers. Therefore, hydromorphology is one key discipline in river restoration projects. Hydromorphology combines the disciplines of hydrology and geomorphology in order to classify both jointly for stream conditions [10].

Over the past 40 years, the destruction of the physical habitat of river ecosystem is especially serious due to the rapid urbanization speed in China, however, due to the huge pressure to face the increasing water pollution and frequent floods at the same time, river management still mainly concentrated in the flood control and water conservancy infrastructure construction and water environmental pollution control, and even many river regulation and flood control projects themselves have exacerbated the river ecosystem physical habitat destruction. It is necessary to learn from the lessons of developed countries and formulate the physical river habitat protection policy as early as possible, to reverse the declining physical habitat quality of river ecosystem, examine and develop hydromorphology, an emerging discipline in river ecosystem restoration practice.

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2 Application in river restoration

River hydromorphology represents physical structures and dynamics of rivers which is useful for establishing links between physical and biological conditions [11]. Within the WFD hydromorphology plays an important role to assess and support an integrated management of river systems. By means of hydromorphological assessments, large-scale processes and channel dynamics can be integrated in the planning of restoration projects. Furthermore, it provides the foundation for the evaluation of ecological responses to restoration measures. In this context the WFD is acting as a catalyst for hydromorphological assessment methods in countries of the European Union. With the implementation of the WFD in national law each member state developed one or more approaches to assess hydromorphological parameters. Belletti et al. [12] mentions in their review on existing hydromorphological methods a shift from approaches focusing mainly on occurrence and spatial configuration of habitats in the end of the 20th century to broader river condition assessments including pressure and response variables focusing more on dynamics and processes.

2.1 Hydromorphological assessment method

Current hydromorphological assessment methods can be distinguished in 4 main approaches: 1) physical habitat assessment, 2) riparian habitat assessment, 3) morphological assessment, 4) hydrological stream alteration [13]. All 4 approaches have different backgrounds and have been developed with certain aims. Physical habitat assessment methods are the most common approach and focus mainly on the presence and characteristics of physical habitats [12]. From a spatial context, they are applied in site to reach scale, laterally some methods are confined by the channel width most of them include riverbanks and some methods are extended to the whole floodplain [14]. However, historical evolution of the assessed river is seldom taken into account in this method [12]. It is important to understand biological-physical feedbacks in rivers. This applies to physical changes on microhabitat scale where, i.e., the properties of substrate and the pool/riffle system due to the variations of runoff and sediment transport is a relatively fast response of hydromorphology in a smaller spatial and temporal scale. And this applies to geomorphological change in a larger spatial and temporal scale, which can give more mechanism explanations, i.e., the cause-effect relationship. Riparian habitat methods focus mainly on the riparian zone and vegetation, some of these methods include also channel features. The integration of vegetation in the assessment of the river status links physical features with biota. Structures of the riparian zone represent main hydromorphological elements supporting the biological communities at different scales [15]. Both methods (physical and riparian habitat method) are focusing mainly on the actual state on a small scale and are highly time consuming due to extended field work. A lack of both methods is a poor consideration of the involved processes and the causes of the alteration at a larger scale [13]. The morphological assessment method is strongly based on a geomorphological approach [12]. The focus of this approach is not pointing on providing information on the current status of a river but on measuring both "pressure" and "response" variables and provide the means to develop a clear understanding of cause-effect relationship that regulate the system response [16]. The approach is including a larger time scale approach and is applied mostly on a reach scale. This would imply repeated assessments at different times of the year and further which is unlikely to handle within a rapid hydromorphological assessment. Thus, recorded indicators are often generated from a static visual assessment of the presence of processes [12]. The same authors mention that morphological assessment methods have the limitation that generally physical processes are hard to assess properly and that parameters as the vertical connection to the groundwater or the consideration of habitats are not explicitly included within these methods. Methods for the assessment of hydrological regime alteration are based on producing hydrological assessment data, especially focusing on hydrologic alterations [17]. Hughes et al. [18] suggests that reference system need to be carefully used with six reasons: 1) there is usually no proper reference system to use, 2) since the selection of the historical reference system, many watershed parameters have changed, 3) climate change has been continuous throughout the Holocene, 4) projected climate change is of uncertain magnitude, 5) alien species cannot be avoided, 6) landscape changes in the environment. The need of long time series which not always are available are a downside of these methods. Furthermore, the definition of reference conditions is critical if not enough long-time scales are present. However, reference conditions can support the understanding of pristine ecosystem states and guide our management that to what extent the river system should be restored, i.e., a balance of the restoration efforts and the societal and ecological functions.

2.2 The development of hydromorphological assessment

There has been an evident trend over the past few years to increase the scientific development of geomorphology-based approaches to attempt to understand the function and evolution of rivers as a basis for interpreting the current conditions [19]. A new approach was developed by Rinaldi et al. [19] first for application in Italy and then adapted to the European framework. This approach (Morphological Quality Index) can be classified as a "process-based" method, which is embedded in an overall hierarchical open-ended framework [20]. The hydromorphological assessment proposed by Rinaldi et al. [19,21] provides a flexible set of procedures, with four main stages:

1) catchment-wide delineation and spatial characterization;

2) assessment of temporal changes and current conditions;

3) assessment of scenario based future trends;

4) identification of management actions.

The approach described by Rinaldi et al. [19,21] was developed and tested within a research project and is embedded in a wider hydromorphological framework [22]. The framework incorporates the morphological characteristics of the channel and its corridors into a larger spatial and temporal assessment of the dynamic control of the reach, as well as a process-based interpretation of the current status, historical dynamics and possible future trajectory of the reach [21]. Stage 2 of the approach (assessment of temporal changes and current conditions) is focusing on the hydromorphological assessment of the river reaches which is assessed by the Morphological Quality Index. It is based on three main components: artificiality, geomorphic functionality and channel adjustment, whereby indicators of artificiality can be seen as "pressure" and indicators of geomorphic functionality and channel adjustment can be seen as "response" indicators [13]. The MQI approach is based on an expert's judgement, expecting from the user specific knowledge and experience. It is designed to be relatively simple and not excessively time consuming. The approach is based on the consideration of processes and is aiming to assess morphological quality, including explicitly temporal components by specific indicators. Reference conditions are defined within the approach on dynamic processes and functions that are expected to normally occur in a given physical context. The key scale of the approach is the river reach, which can be delineated as follows: general identification and setting of landscape units as well as fragments; confinement typologies definition; scope of identification of morphological types and consideration of other factors. The Morphological Quality Index consists of 28 indicators, divided into three main components: geomorphologic function, channel and artificiality adjustment. This approach seeks to provide a comprehensive and overall assessment of river condition to facilitate an understanding of stress and response conditions (i.e., cause and effect), thus supporting the identification of possible management operations [19].

River restoration focuses on a reestablishment of specific river-type conditions, where different processes are induced to a state of dynamic equilibrium, reflecting the characteristic structure, processes and functions of similar river/river types with only slight human influence, at least in accordance with the "good ecological and chemical state" required by the WFD. River restoration therefore refers to measures that incorporate river morphology and hydrology as key components, as well as measures linked to land-use practices and spatial planning [4].

Restoration of rivers must be undertaken within the context of the suite of local and landscape factors that drive instream conditions. Loss of habitat for fishes, invertebrates and macrophytes and morphology sediment regime are strongly influenced by urbanisation and climate changes. Within the scope of a river restoration project, all of the above-mentioned modified conditions have to be taken into account. The Society for Ecological Restoration (SER 2004) identified key attributes of successful restoration that fall into four main categories: 1) ecosystem stability, 2) ecosystem function, 3) species composition, 4) landscape context. It further defined potential indicators for each category that could be used to assess the outcome of projects in the field [23]. Several studies have proven that river restoration projects can lead to an improvement of the morphological river condition but not from a biotic point of view [7]. Various reasons where found, e.g., still polluted rivers by the surroundings, or too little time has passed since the restoration, so there exist still open research questions why certain restoration activities didn't reach their goals. Deffner and Haase [24] also highlight the need to include social aspects in restoration projects in order to create acceptance and understand societal relation to the nature and to include this relation in the planning process.

Gurnell et al. [20] propose a broader view of urban river restoration by evaluating possible ecosystem service potentials and highlight the need of internalising the ecosystem service approach in a readily-used planning tool. For urban rivers, Francis suggests enhancing ecological function alongside novel conditions, rather than by trying to return urbanized rivers to their previous state [25]. This fundamental change in state is extremely difficult to reverse while maintaining the societal function of the system. The concept of "reference conditions" as expressed by the WFD is static and does not fully recognize the dynamic nature of river systems at multiple spatial and temporal scales [26]. This is particularly true for urban river systems, demanding a novel ecological modeling approach that is based on a sound scientific understanding of the effects of combination of stressors.

2.3 Practical application in East Tiaoxi River and Nanxi River

Experts from Tongji University (Water Ecology Laboratory) and Kyushu University (Japan, river research laboratory) conducted ecological health assessment of inflowing rivers in the Taihu Lake Basin (Fig. 3), sino-Japanese joint research team identified 84 species of fish through the comprehensive evaluation of the biggest into-lake river East Tiaoxi River in Taihu Lake Basin [27], the evaluation results show that in the natural reach with less human intervention, the hydrogeomorphic diversity was significantly positively correlated with the habitat and fish diversity. The habitat diversity index increased with the increase of the river width-depth ratio (Fig. 1), and the fish diversity increased with the increase of the habitat diversity index (Fig. 2).

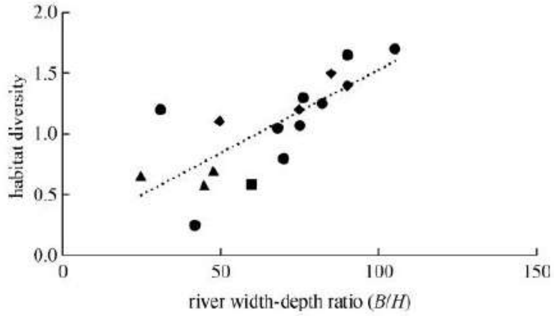

Fig. 1 Correlations between river width-depth ratio and habitat diversity.

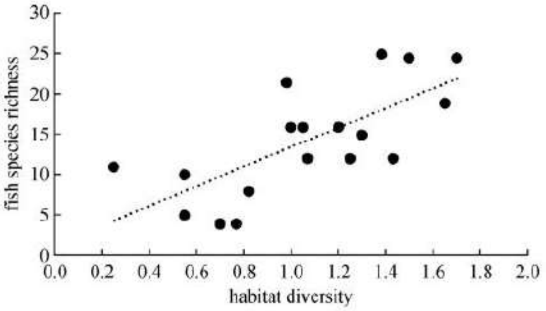

Fig. 2 Correlations between habitat diversity and fish species richness.

The Nanxi River is located in the river basin along the south-east coast of China, the basin area is 2436 km^2 (including 2223 km^2 in Yongjia county, accounting for 91.2%), and the mainstream river length is 142 km, with an average gradient of 6.0 ‰. The sino-European team carried out a joint survey on the Nanxi River since 2018 (Fig. 3), using 5 specific indicators from the MQI to assess the rivers morphological quality, which include Cross-section Configuration, Bed structure and substrate, vegetation and Interventions of maintenance and removal, and found that the hydrogeomorphic diversity played an important role in maintaining the river ecosystem function and protecting the aquatic biodiversity of the river. Benthic fauna and fish were in good condition.

3 Discussions

Despite much research on river systems over the last decade, critical questions remain to be resolved [25,28]. We lack an understanding of the mechanisms involved in linking rivers to the larger landscape and fundamental knowledge of urban aquatic ecology [25]. Knowledge gaps exist in aquatic habitat restoration in particular. The field of engineering disciplines can support the environmental restoration work in different ways. For example, at present China mainly focuses on pollution control of surface and groundwater. A high developed information technology and artificial intelligence technology provide automatic measurements, automatic sample collection, automatic water-quality-monitoring systems, automatic algae filtering and cleaning systems, and autonomous navigation for surface garbage cleaning and surface cleaning robots [29]. The results are most important first steps for river restoration and they provide a large-scale data basis for a sustainable integration of the ecological improvements. Further research should provide a clearer view of the outcomes of restoration measures based on pre- and post-project analysis [28]. Hydromorphological restoration that

(a) (b)

Fig. 3 Hydromorphological assessment in (a) Nanxi River and (b) East Tiaoxi River.

aims to improve the ecological status of river systems is often rather limited in scope and scale.

The socio-ecological approach we propose for urban rivers is based on the dynamic structure of river systems and incorporates societal, physical, chemical, biotic factors as well as their cumulative, antagonistic and synergistic effects. It also needs to be explored in future practice.

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9.4 Article 4

Installation of a Riparian Forest by Means of Soil Bio Engineering Techniques—Monitoring Results from a River Restoration Work in Southern Brazil

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Installation of a Riparian Forest by Means of Soil Bio Engineering Techniques—Monitoring Results from a River Restoration Work in Southern Brazil

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Soil bioengineering has been applied more and more in different regions of Brazil in recent years. The study in hand presents the installation of "new" riparian forest based on soil bioengineering techniques. This riverbank restoration work was implemented in the year 2010 and two onsite vegetation surveys, one shortly after the construction, and one in 2013. Besides that, the structures of reinforcement work, and its effectiveness were evaluated. By means of the vegetation survey, the applied species were examined for their ability to establish the riverbank in an environmentally sustainable way. Most notably, the species *Calliandra brevipes* Benth. (Fabaceae, Mimosoideae), *Phyllanthus sellowianus* Müller Arg. (Euphorbiaceae), *Salix humboldtiana* Willd. (Salicaceae), *Bauhinia forficate* Link (Leguminosae), *Inga marginata* Willd. (Mimosoideae) and *Ateleia glazioveana* Baill. (Leguminosae, Papilionoideae) showed a good growth development. The proportion of spontaneous vegetation increased significantly, with *Pennisetum purpureum* Schumach. becoming a dominating species. Resulting from that, the intervention can be assessed as functional and safe, but the strong increase of spontaneous vegetation is undesirable due to less flood resistance. The vegetated riprap could be the best to meet the expectations of the construction elements. Partly, the anchored willows showed as well a good growth development whereas the species used for the hedge brush layer could not develop as expected in large parts of the construction.

Keywords: Soil Bioengineering; Riverbank Restoration; Riparian Forest; Rio Grande do Sul

Introduction

In the recent past, soil bioengineering projects carried out in Brazil were done in the region of Rio Grande do Sul within river stabilization works, to protect agricultural land of small regional farmers. The soil bioengineering techniques, which are the use of living plant material for civil engineering structures, can be a helpful instrument for civil engineers taking into account not only technical but also ecological, sustainable and socio-economical aspects. These methods have meanwhile regained worldwide recognition for their use in river and civil engineering projects (Howell, 1999; Acharya et al., 2005; Durlo et al., 2005; Li et al., 2002; Lammeranner et al., 2005; Wu et al., 2006; Petrone et al., 2008; Petrone et al., 2010). The principle of biological engineering constructions is based on the combination of dead and living materials and the emerging positive synergistic effects. The dead auxiliaries (stone, wood, etc.) protect the living plants until they undertake technical functions. After several years, a part of the auxiliary material rots and the stabilization of the bank is secured by the plants (Gerstgasser, 2000; Schiechtl, 1980; Howell, 1999; Florineth, 2002; Durlo et al., 2005; Zeh, 2007; AMEC Environment & Infrastructure, 2012; Sutili et al., 2012; Acharya et al., 2008).The riparian vegetation has a major role in the river-bank's protection, through the roots system and the plant cover, improving the soil particles aggregation in a low cohesion situation, reducing the runoff and resulting in a lower erosion rate and sedimentation of the river channel (Holanda & Pinheiro da Rocha, 2010). Previous research already assessed some potentially useful plants for soil bioengineering works. Several studies have already been performed to investigate native, riparian species, their biological and technical properties, and soil bioengineering structures for their applicability in restoration works in Rio Grande do Sul (Altreiter & Plunger, 2004; Sutili et al., 2004; Durlo & Sutili, 2005; Florineth et al., 2006; Denardi, 2007; Vargas, 2007; Monteiro, 2009; Rauch, & Sutili, 2009). The acquired knowledge can be applied to the spreading area of the plants and in this way, it can be useful in various regions. This case study presents an intervention applied at the end of 2010, at the River Pardinho in the state of Rio Grande do Sul. The riverbank restoration became essential due to a combination of hydraulic induced erosion and bank mass failure. Bank mass failure resulted from fluvial erosion at the toe of the bank with a continuous removal of bank material, affecting a change in the bank slope by over deepening the bank and altering its angle. Additionally to the forces of the running water, surcharge from the weight of trees on the top of the slope accelerated the erosion process. Surcharge and near-surface moisture are, according to Simon and Collison (2002), destabilization effects that can affect slope stability. The objective of this study was 1) to document the implementation of soil bioengineering techniques and 2) to perform a comprehensive vegetation survey in combination with an assessment of the slope stability, examining the midterm effect and functionality of dense vegetation on slope reinforcement and the durability of soil bioengineering constructions. It is of high interest to analyze the vegetation after a certain period and evaluate the used species in order to be able to draft up efficient plant strategies for future riparian restoration works on degraded river embankments. Only in recent years, soil bioengineering has become more applied in Brazil. The research process in this field of study has been highlighting clear uncertainties in developing soil bioengineering standards from an engineering as well as from an environmental point of view.

Materials and Methods

Location

The River Pardinho, a tributary to the River Jacuí, is located in the watershed of the River Pardo, in the central region of the state of Rio Grande do Sul. The section where the intervention was realized is situated downstream of a reservoir dam which provides the water supply for the municipality of Santa Cruz do Sul with 119.057 inhabitants (Heuser, 2013).The Pardo River basin is comprised of areas with a difference in altitude of up to 500 m. Approximately 40% of its total area applied to the middle portion of the basin, where the municipal seat of Sinimbu is located, with altitudes ranging from 200 m to 500 m. The downstream (lower part) of the basin, where Santa Cruz do Sul is located, is characterized through flat areas with a slightly undulating relief (Commitê Pardo, 2011). According to Moreno (1961), the local climate is subtropical, with humid climatic conditions, hot summers and rainfall during all seasons. However, in months of high temperatures, hydrological deficits can occur. During the rainy season, the area is sometimes prone to extreme flash flood conditions. The slope reinforcement construction was implemented at an actively eroding bank section at the left side of the river with more than 80 m in length (see Figure 1).

The Causing of the Eroding Process

The instability of the bank resulted from a continuous process of erosion, landslide, collapse and remove a lot material due to the action of the watercourse (see Figure 2).

The latter has shifted its axes outwards on this slightly curving river section. The instability of the embankment was exacerbated by the steep angle of the embankment, preventing the vegetation from spontaneous establishment. Additionally, the vegetation that was planted initially along the river at the top of the margin (trees of *Enterolobium contortisiliquum* (Vell.) Morong) did not have any stabilization effect on the site. Actually quite the reverse occurred. This vegetation formed an overhead

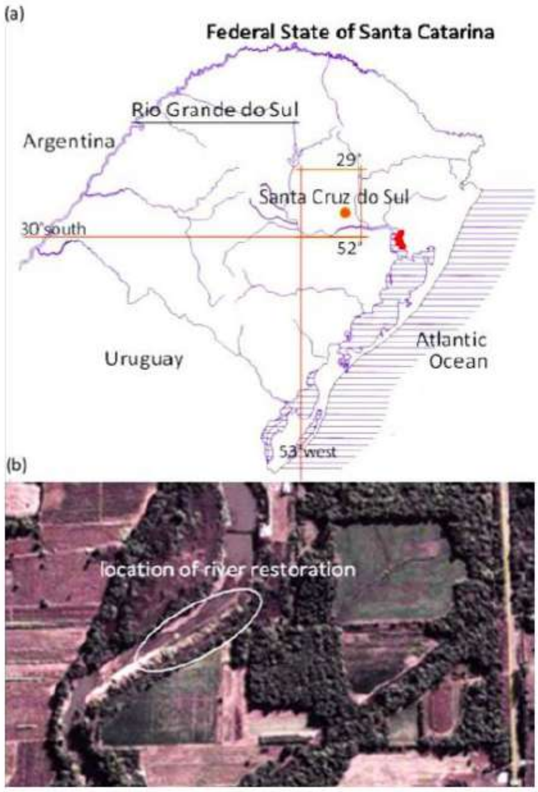

Figure 1.
(a) The location of Santa Cruz do Sul in the state of Rio Grande do Sul and the states big watercourses; (b) The location where the river restoration work was implemented.

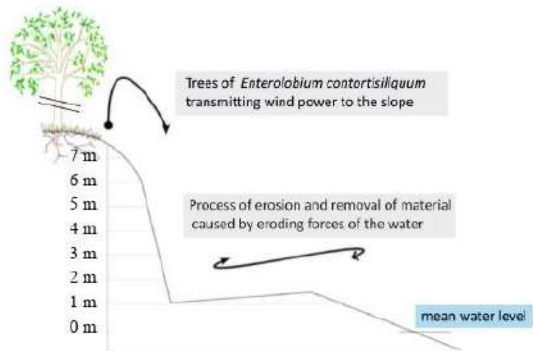

Figure 2.
Sectional view, illustrating the eroding process.

in the vertical axes, shifting its center of gravity in a less stable position. It captures and transmits wind power to the slope, creating a lever that certainly amplifies the dynamics of landslides, triggered by the current of the stream (Durlo & Sutili, 2005).

Methodology of Vegetation Survey and Evaluation of Construction

In the end of November 2010, two months after the last interventions had been completed; a vegetation survey was carried out in order to analyze the growth pattern of the plant stand. Therefore, 10 stripe-shaped transects where staked out along the riverbank. Each parcel had an area of 2 m in width and 15 m in length, extending from the water level to the highest point of the slope. By dividing the transects into sub-sampled portions of 1 m × 2 m, it was possible to recognize the variation along each parcel. In this way, it facilitated the interpretation of the data according to their variation along the gradient of the slope and individualize their analysis in accordance to the construction. Additionally to the classification of the plant individuals, the stem diameter at base and the plant height were measured.

At the end of January 2013, a second vegetation survey was carried out in order to examine the long term effects of the riverbank restoration and the development of species with their actual distribution. For this survey, the same methodology as for the first one was used in order to be able to compare the results of each parcel and sub parcel with the previous data. Supplementary, in the second survey the crown diameter and the number of shoots were measured, the coverage rate by using the method of "Braun Blanquet" was estimated and a classification of the plant's vitality, in four classes, was performed. An integral assessment method was developed to evaluate the status and the effectiveness of the constructions four classification classes were each defined (see **Table 1**).

Results

Intervention-Application of Soil Bioengineering Methods

The presented intervention was composed of two complementary and inseparable parts: the physical actions and the implementation of vegetation. The physical constructions and first vegetative interventions were done from January to February in 2010. The intervention was executed in the following sequence: Firstly, the vegetated riprap was realized by using *Calliandra brevipes* Benth. and hardwood cuttings of *Salix humboldtiana* Willd. Above, hedge brush layers of the species *Terminalia australis* Cambess. *Schinus molle* L., *Schinus terebentifolia* Raddi. and *Pouteria salicifolia* (Spreng.) Radlk. were installed. In the upper portion, trees of *Salix humboldtiana* were anchored to the slope, using wooden poles and steel wires. Even further up, in the same way, trees of *Enterolobium contortisiliquum* were anchored to the slope but without the expectation of sprouting. As a final measure, the top angle of the slope was corrected and seedlings and hardwood cuttings of *Phyllanthus sellowianus* Müll. Arg. were fielded on its middle portion. After heavy rainfalls, a second vegetative intervention was implemented to ensure the physical integrity of the margin. Its purpose was to support the vegetated riprap, the hedge brush layer and the anchored willows. Particularly as the anchored trees of *Enterolobium contortisiliquum* had been removed during the heavy-rainfalls, an additional action became necessary. The aim is to enhance the biodiversity on site, but also for testing various species in terms of their applicability for soil bioengineering interventions a wide range of species was used. **Figure 3** shows a technical sketch with all the applied soil bioengineering techniques and the used plants. The plant material consisted of 1550 seedlings of 32 native species.

Species Observed in Each Section of the Construction

The vegetation surveys were conducted in 2010 and 2013 as described in the methodology chapter. **Figure 4** shows an overview of all sections.

Section 1—Vegetated Riprap

In the segment of the vegetated riprap, three kinds of species were observed in the first survey, namely: *Calliandra brevipes*

Table 1.
Integral assessment method to evaluate the status and effectivity of structures and the vitality of species.

Classification	Status Class	Effectiveness Class	Vitality Class
1	**Good:** Both the supporting, technical structure (inert materials) as well as the used plant material is in a visible good state. There is no visible external damage indicating an imminent failure of the structure and the used plants are well established.	**Good:** The resulting effect to the respective intervention is highly achieved and is clearly visible.	**Exceedingly strong developed:** leaves lush green in color, high leaf mass, strong shoots development and growth in length
2	**Slight damage of construction or little dominance of invasive vegetation:** Slight damage of the technical structure or plants is observable. The living material will be able to compensate for the harmful effect by its growth and mechanical skills and it will not result in failure of the structure. The used plant material is well established and less or no invasive vegetation is present.	**Sufficient:** The ascribed effect to the respective intervention is largely achieved and is clearly visible, but not quite as remarkable as in the rating "good".	**Well developed:** leaves lush green in colour, little less leaf mass, weaker shoots development and growth in length
3	**Severe damage of construction or strong dominance of invasive vegetation:** Both, the technical structure (inert materials) as well as the used plants show external damage or are largely suppressed by invasive plants which became predominant. In the case that the invasive species can not compensate the stability of the used vegetation it can be assumed that an utter failure is imminent	**Still sufficient but obvious deficiencies:** The ascribed effect to the respective intervention is barely achieved but still visible.	**Poorly developed:** leaves yellow-green in colour, little leaf mass, very weak shoots development and growth in length.
4	**Destructed:** The structure is only rudimentarily observable or not existing anymore and is to be classified as ineffective.	**Insufficient:** The ascribed effect to the respective intervention is not achieved.	Plant already dead or dying.

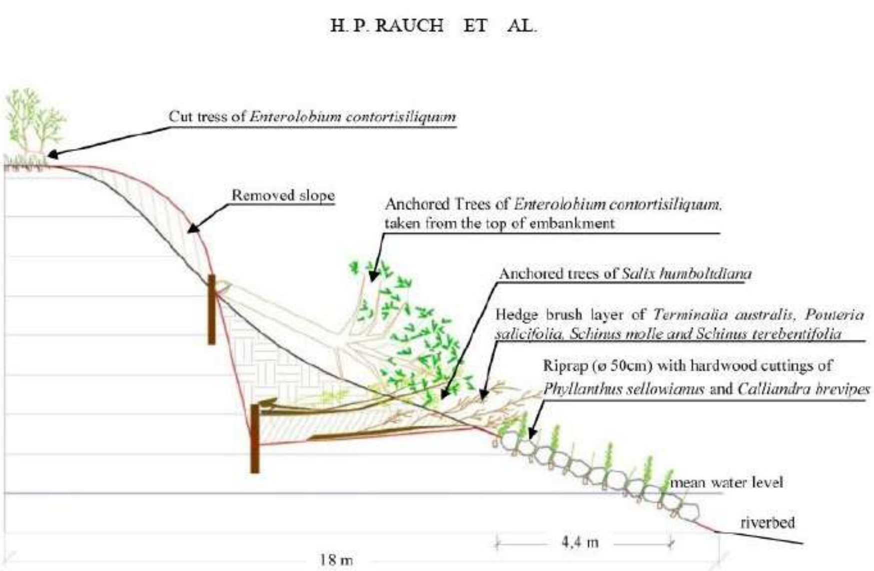

Figure 3.
Sectional view, illustrating the interventions taken at the embankment.

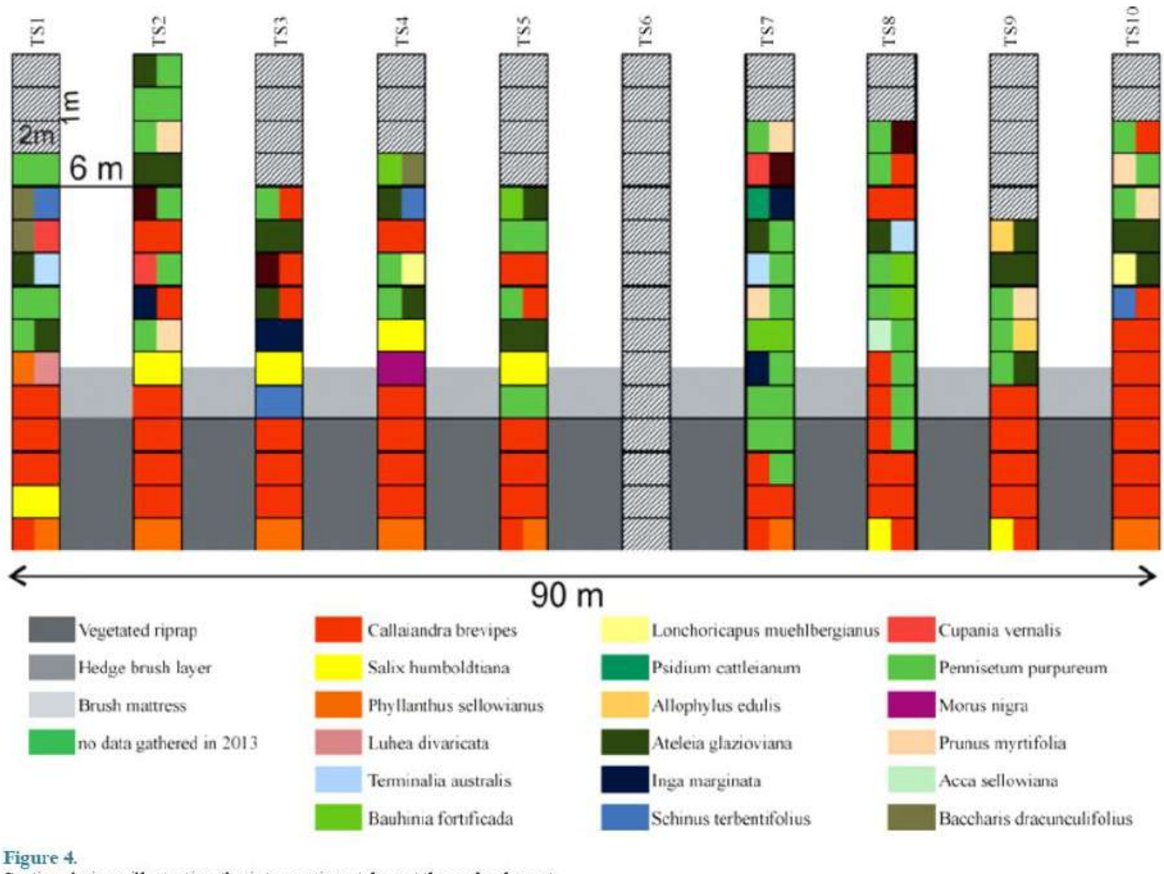

Figure 4.
Sectional view, illustrating the interventions taken at the embankment.

(51% of specimens), *Salix humboldtiana* (43% of specimens) and some plants which had emerged from the cuttings of *Phyllanthus sellowianus* (6% of specimens). These species have an average density of 2.6 plants per square meter. Compared to an initial density of 3.5 plants per square meter planted during the first intervention, 28% of seedlings had been lost in the first 8 months. These losses had occurred mainly in the segment closest to the mean water level, caused by long periods of submersion or by the flow. In the second plant survey the presence of the species was as follows; *Calliandra brevipes* (82% of specimens), *Phyllanthus sellowianus* (10% of specimens), *Salix humboldtiana* (5% of specimens) and *Terminalia australis* (5% of specimens). The density, now being 3.3 plants per square meter, shows that the plants could reproduce distinctly, in between the first- and second survey. In the lower part of the riprap, the dominating species were *Calliandra brevipes* (coverage rate [cr] of 39%) and *Phyllanthus sellowianus* ([cr] 11%) with some presence of *Salix humboldtiana* ([cr] 5%). It can be assumed that these species can best support the hydraulic shear stress. With a coverage rate of 55%, the uncovered area was extensive. Spontaneous vegetation was scarcely observed in this part. In the upper portion of the riprap, a strong dominance of *Calliandra brevipes* ([cr] 91%) was noticeable. Just a few other individuals had been able to emerge in this section. Namely; *Salix humboldtiana*, *Terminalia australis* and some spontaneous vegetation, like *Pennisetum purpureum* Schumach., *Sida* sp. and *Xanthium strumarium* L. Only [cr] 2% of the area was uncovered.

Section 2—Hedge Brush Layer and Brush Mattress

In the first vegetative survey, the following plants were observed in the sections of the hedge brush layer and anchored willows; the sprouting of *Salix humboldtiana* was prevalent, accounting for 59%, and concentrated on the central portion. *Terminalia australis*, *Morus nigra* L. and *Schinus terebentifolia* were only found point wise. There was no sprouting of the hedge brush layer or the brush mattress in the transects 7, 8 and 9. In this portion, mainly the shrubs *Schinus molle*, *Schinus terebentifolia* and *Pouteria salicifolia*, which did not produce any shoots, had been used. The vegetation survey in 2013 showed the following situation in this section; *Salix humboldtiana* had diminished to a proportion of 31%, still concentrating more in the central portion ([cr] 34%). *Terminalia australis* completely disappeared. *Morus nigra* and *Schinus terebentifolia* still were observed only point wise. *Calliandra brevipes* ([cr] 10%) had been able to spread in each part of the construction. Spontaneous vegetation had emerged over the whole length of the intervention and was partly dominant. Frequently, *Poaceae* sp. was found besides *Pennisetum purpureum* ([cr] 29%) and constituted the second most prevalent group of spontaneous vegetation. The uncovered area was [cr] 9%.

Section 3—Plantations in the Upper Parts of the Slope

The plants fielded in the second vegetative intervention in October 2010 showed mortality rate of only 2.6% two months after being fielded. In total, 273 plants were observed in the first survey. This number had decreased to 127 plant individuals in 2013. In the upper portion of the embankment, the greatest variety of species was found, although it had diminished distinctly from the first to the second survey. The diameter, as well as the plant height, had increased noticeably in this period of time. The vitality analysis showed that most of the species had developed very well. The amount of spontaneous vegetation was very high in this portion. As can be seen in Figure 4 and from the high coverage rate of 41%, *Pennisetum purpureum* was dominant in several parts of the section. Other species with a considerable coverage rate are *Ateleia glazioveana* ([cr] 26%), *Calliandra brevipes* ([cr] 9%) and *Bauhinia forficata* ([cr] 4%). The uncovered area was [cr] 7%.

Development of Species

In Table 2, the species, which were found in the plant survey in 2011 but disappeared until 2013, are listed. Particularly strong losses were seen with the species *Machaerium paraguariense* Hassl., *Eugenia myrcianthes* Nied. and *Myrcianthes pungens* Berg. Legr. In Figure 5, the species, which were found in both vegetation surveys plus their mean plant height are shown. The species which developed best are *Calliandra brevipes*, *Phyllanthus sellowianus*, *Ateleia glazioveana*, *Salix humboldtiana*, *Bauhinia forficata* Link and *Inga marginata* Willd. In Figure 6, the growth development of these species is illustrated. *Salix humboldtiana*, showed great losses in the number of individuals. However, it grew very strong and highest of all species in the plant stand. The second highest grown species is *Ateleia glazioveana*. Its mean vitality was classified as 1 and only a few losses of plant individuals occurred. During the period of the monitoring, the plant individuals of *Phyllanthus sellowianus* increased and showed significantly the best growth along the mean water level. The plant individuals of *Bauhinia forficata* showed a good development. The same applies to *Inga marginata*, which could even increase the number of plant individuals. As well, *Luehea divaricata* Mart. and *Inga marginata* showed to be able to emerge on river embankments, as its number of individuals increased. *Pouteria salicifolia*, which was used in the hedge brush layer completely disappeared. Further species of the hedge brush layer are *Morus nigra* and *Terminalia australis*.

They were observed in the second survey but only in small number. *Calliandra brevipes* had the most significant increase of all applied species. The habitus is a small grown shrub, which produces many shoots. It can be assessed as a very dominating species, with the ability to grow on extreme conditions. Species which showed a good development but occurred only in a small number of individuals are *Schinus terebentifolia*, *Schinus molle*, *Cupania vernalis* Cambess. and *Psidium catileyanum* Sabine.

Evaluation of Structures

In Figure 6, the evaluation of the structures in terms of effectiveness and status is shown. As a whole, the intervention can be assessed as functional and safe. The effectiveness of the structures in conjunction with the present vegetation is rated in the classification classes 1 or 2. This means that the embankment is well protected and no imminent failure should be expected. Analyzing the structures separately showed some issues with the intervention. Only the vegetated riprap developed as it was supposed should have. In several spots, the implemented vegetation material did not or just sparsely emerge. Especially in the hedge brush layer and in the upper portion, where a wide range of species was fielded, the desired development was only partly achieved. The anchored willows showed a good development in half of the intervention, where high, vital brushes developed, making a major contribution to slope reinforce. In the other half, from transect 6 on, the brush mattresses could not develop at all. In the parts where the implemented vegetation did not develop as desired, spontaneous vegetation overtook the role of erosion protection, and therefore erosion just occurred point wise. Since the anchored trees of *Enterolobium contortisiliquum* were swept away shortly after planting, that intervention was classified with the category "destructed". Figure 7 shows the embankment before the restoration work in 2010 and after the monitoring in 2013.

Table 2.
Species which disappeared between first and second survey.

Name	Number specimens	Name	Number specimens
Machaerium paraguariense Hassl.	18	Eugenia rostrifolia D. Legrand	3
Eugenia myrcianthes Nied.	14	Matayba eleagnoides Radlk.	3
Myrcianthes pungens Berg. Legr.	8	Tibouchina mutabilis (Vell.) Cogn.	3
Eugenia involucrata DC.	5	Aiouea saligna Meisn.	2

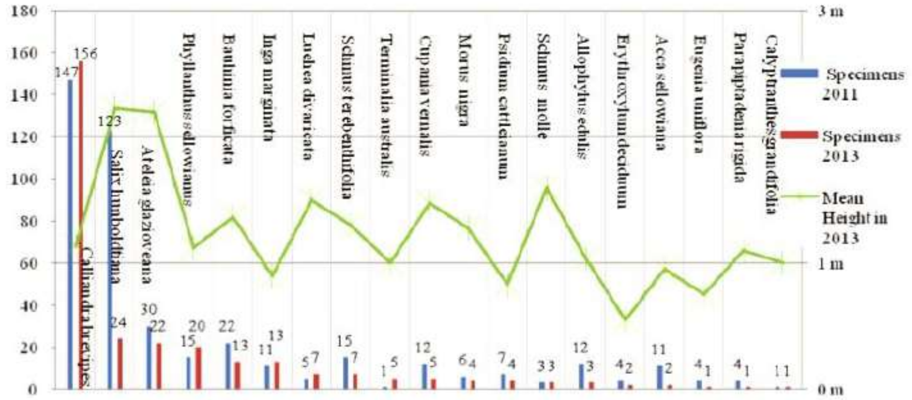

Figure 5.
Growth development of the species after 3 years of intervention.

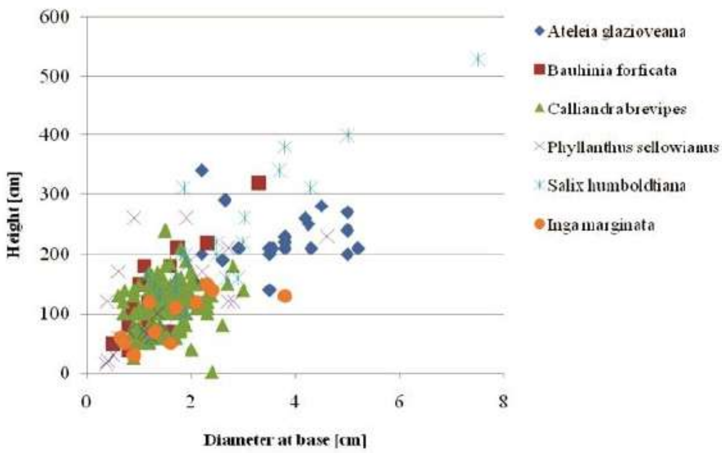

Figure 6.
Growth development of the species after 3 years of intervention.

Discussion on the Applicability of Most Remarkable Species for Riverbank Restoration Works

The installation of "new" riparian forest depends on the technique of soil bioengineering method as well as on the used plants. Furthermore, the applied structures and some of the species, which are most decisive for the development of the embankment are discussed.

Discussion of Applied Structures

The installed **vegetated riprap**, was the most effective and stable construction applied. Realized by using relatively big basalt blocks, it is the less natural related construction of the applied structures. However, it provides considerably more habitats then in case of solid bank constructions. As the study shows, several species could emerge in the interstices of the basalt blocks. Through the changing of the temperature conditions and the position along the mean water level, it is a habitat for plants, tolerating extreme growth conditions. Moreover, its major contribution to the protection of the embankment enables an establishment of the plant stand above. In the **hedge brush layer**, it was observed that many species had diminished or disappeared.

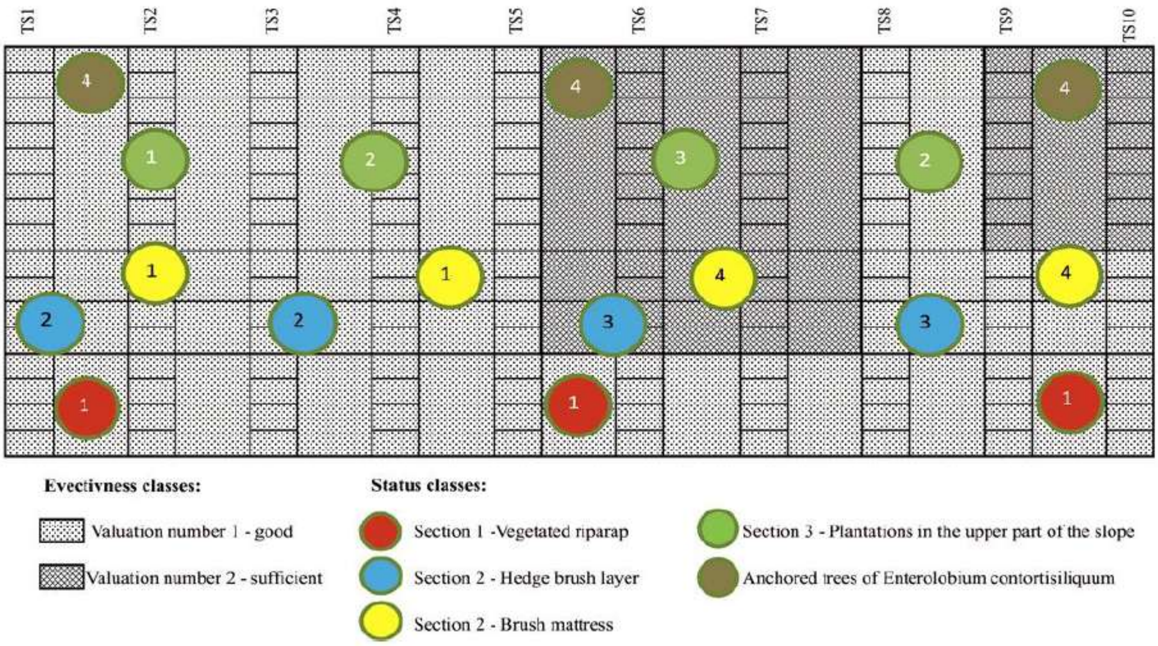

Figure 7.
Evaluation of structures.

Although slope reinforcement was obtained, the high proportion of spontaneous vegetation plus uncovered areas might endanger the stability in the long term. Implemented species which significantly diminished or disappeared completely are not recommendable for further slope reinforcement constructions. The **brush mattress** showed in half of the construction very good development and seems therefore to be an appropriate construction for the use in soil bioengineering works. However, in view of its large application along the whole construction, the assertiveness against other species seems to be relatively low due to the partial occurrence of *Salix humboldtiana*, This fact should be considered in further applications of brush mattresses using *Salix humboldtiana*. In the **upper part of the slope**, which is only prone to extreme flow conditions in case of flooding, the increase of spontaneous vegetation was partly very high and several fielded species could not develop as expected. This provides important information about the assertiveness of the species used. The sweeping away of the **anchored trees of *Enterolobium contortisiliquum*** might be a result of the one-sided anchoring to the slope. A double-sided anchoring might prevent floating in case of flooding.

Discussion of Species

The strong dominance of ***Calliandra brevipes*** shows that it has very good properties to resist against hydraulic shear stress and is applicable to locations with extreme growth conditions like ripraps. Through its very dense growth and production of many shoots, its contribution to soil coverage and consequently to erosion protection is very high. It could also prevail in the upper section of the embankment and is the only species which was present in all portions. Due to its dense growth pattern, no other plants could develop, which is a major reason for its dominance. It proved to be very appropriate for slope reinforcement interventions projects, but its dominant characteristics should be considered for further works. As it is both an ornamental brush and a very robust species, it has great potential to be applied at different riverine landscapes.

Phyllanthus sellowianus established best along the mean water level and is compatible with extreme growth conditions, for example temporary submersions. Rauch and Sutili, 2009, already ascertained *Phyllanthus sellowianus* as a very flexible plant because of a high percentage of gelatinous fibers. By bending, it protects the margin of the river and is very rapture resistant. Moreover, Hörbinger (2013) showed by means of a pull-out test its high pullout resistance and favorable root architecture in terms of root anchorage ability. In the present study, it was confirmed that *Phyllanthus sellowianus* can deal with hydraulic shear stress and shows very good properties for soil anchorage. It was hardly present above the riprap and it can therefore be assumed that it is a specialist on extreme growth conditions and not very dominating.

Salix humboldtiana proved to be very appropriate to be used in embankment restoration works since it showed a good growth on extreme site conditions. It was, along with *Phyllanthus sellowianus*, the only species which established at the mean water level. However, the small number of individuals in the riprap shows that *Salix humboldtiana* could not prevail against the highly dominating *Calliandra brevipes*. In the upper portion, where *Salix humboldtiana* could prevail and form shoots, high brushes developed which contributed strongly to the slope reinforcement. The fact that it could not emerge in half of the construction points to a minor assertiveness of the species. Florineth et al. 2006 investigated, among others, *Salix humboldtiana*, *Phyllanthus sellowianus*, *Calliandra brevipes*, *Morus nigra*, *Terminalia australis* and *Pouteria salicifolia* for their ability to sprout from shoots and to produce adventitious roots.

The best properties showed *Phyllanthus sellowianus* and *Sa-*

lix humboldtiana with a satisfying production of adventitious roots and sprouting from shoots. The other mentioned species have not shown the desired results. In the present study, ***Terminalia australis*** and ***Pouteria salicifolia*** where used in the hedge brush layer and did not show any, or just weak sprouting. *Pouteria salicifolia* had already completely disappeared at the first performed survey and seems to be ineligible for the use in river restoration works. The number of plant individuals of *Terminalia australis* increased until the second performed survey, however for the use in a hedge brush layer this species seem to be inapplicable.

Ateleia glazioveana was, in the upper portion of the embankment, the species which had the strongest increase in the plant stand. It can become a tall tree which might be the reason for the strongest increase of the stem diameter of all species. A big stem diameter can be unfavorable in terms of embankment protection because these plants rather break than bend in case of flooding. In the early stage, the plant continues to contribute to the protection of the slope because it is still flexible. However, maintenance work is necessary to prevent an overly strong growth of that species. If maintenance work is neglected, *Ateleia glazioveana* will become a high grown tree and put shade pressure onto other plant individuals. Moreover, it can cause slope instabilities by its own weight. *Morus nigra*, not a native species in Brazil, could establish in the section of the hedge brush layer. However, because of the small number of individuals it was not a suppressing species. The spontaneous grass which emerged widely in the hedge brush layer and in the section of the brush mattress constituted of not native species.

Pennisetum purpureum was noticeably the most assertive species of the spontaneous vegetation. The question arises if *Pennisetum purpureum* with less flood resistance will provide long term slope reinforcement. It seems that some of the implemented vegetation was pushed back by the highly dominating *P. purpureum*. Once the established vegetation has reached a certain height, no further pushing back by *P. purpureum* has to be expected. It is, however possible that *P. purpureum* will be pushed back again in further succession of the plant stand. This, as well as the long term slope reinforcement effect, should be a task for further surveys on site.

Conclusion

Figure 8 shows an overview of the situation before the intervention (2010) and after 3 years of plant development (2013). The "new" riparian forest based on the application of soil bioengineering techniques fulfills technical as well as ecological functions. The generated forest provides bank protection against erosion and creates new ecological habitats. Furthermore, the project shows that soil bioengineering techniques are suitable for engineering purposes supposing that both the technique and the local plants are taking into account in the planning and implementation procedure.

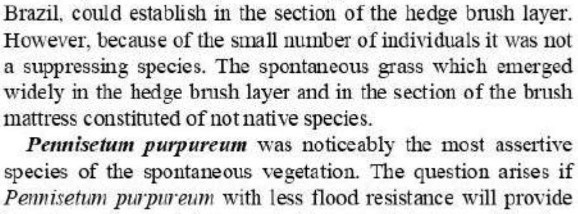

Figure 8.
(a) Embankment before implementation of reinforcement works (Sutili, 2010); and (b) two years after its completion (Hörbinger, 2013).

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9.5 Article 5

A Case Study: The Implementation of a Nature-Based Engineering Solution to Restore a Fallopia japonica-Dominated Brook Embankment

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A Case Study: The Implementation of a Nature-Based Engineering Solution to Restore a *Fallopia japonica*-Dominated Brook Embankment

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Abstract

Considering the high abundance of knotweeds along river courses, the expected increase of invasion and the consequent negative impacts on riparian ecosystems, there is a high demand for innovative approaches and management strategies. While a primary aim of weed management is to reduce the population of an invasive plant species, the goal of the presented nature-based engineering solution (NABES) is to reinstall native riparian forests and to restore ecosystem functioning. The concept of NABES is to support the implemented species by frequent removal of the knotweed shoots until the native vegetation represses the knotweeds by root competition and shadow pressure. In order to be able to develop adaptive knotweed management strategies, knowledge concerning seasonal biomass development and the most effective maintenance intervals must be improved. Additionally, greater understanding of the interaction between invasive and native species is essential. In the present study, the effectiveness of a willow brush mattress (a frequent technique for controlling riverbank erosion) in combination with adapted management strategies was tested on a *Fallopia japonica*-dominated brook embankment. Due to its high ecological amplitude and excellent soil bioengineering properties the species *S. purpurea* was used. In the upper part of the embankment, *F. japonica* shoot production was by far the strongest, while it was low in the sections next to the water. The strongest biomass production was observed in the months April and May. Even though the temporal interval between shoot removal was increased, shoot production decreased strongly and nearly ceased in August. Branches of *S. purpurea* with contact to the water of the brook showed good development. In contrast to *F. japonica*, which suffered a rapid decrease in biomass production after the third survey, the coverage ratio of *S. purpurea* decreased gradually over the vegetation period.

Keywords

Fallopia japonica, Soil Bioengineering, Ecosystem Restoration, Riparian Vegetation

1. Introduction

According to the European Commission, the invasion of alien biota is the second-largest threat to biodiversity after habitat loss. The spread of invasive alien plants (IAPs) has significant implications for agriculture, forestry, aquaculture, ecosystem services, and human health (Commission of the European Communities, 2013). Compared to other pressures on protected areas (e.g. land-use change), the impacts of IAPs are frequently less well understood (Hulme et al., 2014). Riparian habitats are among the most prone to invasion, as these habitats are strongly affected by both natural and human-driven disturbances. Further spread of IAPs into riparian habitats is facilitated by hydrological alterations (Stromberg et al., 2007), climate change (e.g. Dudgeon et al., 2006; Settele et al., 2014), or human interventions within the riparian zone (Haag & Krüsi, 2014). These disturbances tend to alter environmental conditions in a manner that increases the potential for invasion by IAPs (Santoro et al., 2011) and, therefore, losses of natural riparian habitats have to be expected alongside running waters (IUCN, 2000). Out of all the potential plant invaders, the complex of species *Fallopia spp.* (Asian knotweeds) is of particular concern for conservationists and land managers. The species is currently listed in Europe's top 100 most invasive plant species by DAISIE (2008) and is highly invasive within riparian zones. In the literature, there is inconsistent information about the applicability and efficacy of non-chemical control measures. Various methods have been tested for Asian knotweeds but they are often largely inefficient and expensive. One of the most efficient methods is early uprooting and disposal, combined with constant monitoring of areas at risk (Dommanget et al., 2016). Additionally, repeatedly mowing is a solution, which is commonly used for eradicating or at least reducing Asian knotweeds in conservation areas. However, these procedures are labor-intensive and require repeated treatment, and thus become quickly expensive (Delbart et al., 2012; UBA, 2015). The presented case study pursues a different approach, by developing nature-based engineering solutions (NABES). These are built on the principles of soil bioengineering, with specific adaptations to effectively support the natural riparian plants against dominating IAPs. Soil bioengineering is a construction technique that uses biological components for hydraulic and civil engineering solutions. Nowadays, soil bioengineering is of increasing importance as there is a high demand for engineering solutions which take into consideration not only technical issues but also ecological and socio-economic values (e.g. Durlo & Sutili, 2005; Lammeranner, Rauch, & Laaha, 2005; Rauch, Sutili, & Hoerbinger, 2014). In order to achieve these ambitions, soil bioengineering makes use of different materials. First and foremost, living materials, such as seeds, plants, plant parts and so forth, are applied. This means that soil bioengineering structures are dependent on the properties and development of plants. In revitalization projects, the techniques of soil bioengineering can provide an effective means of treating sites where steep slopes and soil instability result in revegetation problems. Recently revitalized areas are often scarcely covered by vegetation. Since the majority of IAPs have a high light requirement and grow on nutrient-rich soils, the promotion of competitive native vegetation in combination with the creation of nutrient-poor locations is a promising approach. Open niches, e.g. on eroded river banks, are particularly vulnerable to recolonization by IAPs. Soil bioengineering is an appropriate technique for the stabilization of erosion-prone areas as it helps to eliminate flood damage, and consequently to prevent the spread of unwanted species in the locality. In areas already colonized by IAPs, the invaders are effectively pushed back through shading and rooting competition by the installed native vegetation. In experimental tests, Dommanget et al. (2015) planted the cuttings of fast-growing *Salix viminalis* on previously mowed knotweed patches in order to stimulate the regeneration of a competitive canopy. After two or three years of repeated cuts, the Asian knotweeds present were dominated by willows, and their biomass had significantly decreased. Similarly, Delbart et al. (2012) showed that mowing associated with transplanting of native trees was the most efficient mechanical control method. However, little is known about the effectiveness of different native riparian species when competing with IAPs. Dommanget et al. (2013) found that the allelopathic effect of *Fallopia japonica* influenced the growth of Salicaceae species to a different degree and that the choice of resistant species could prove crucial for restoration success. In the present study, the effectiveness of a willow brush mattress (a frequent technique for controlling riverbank erosion) in combination with adapted management strategies was tested. The concept of NABES is to support the implemented species by frequent removal of the knotweed shoots until the native vegetation represses the knotweeds by root competition and shadow pressure. Through immediate erosion control by the auxiliaries, further downstream colonization should be prevented by uprooting of knotweed rhizomes. Over the course of the present study the development of both the installed vegetation and the invasive knotweeds was examined during the first vegetation period.

2. Materials and Methods

2.1. Location and Site Conditions

This case study involves a nature-based engineering solution on a *F. Japonica*-dominated embankment at the Steinbach Brook, located in the west of Vienna, Austria (see **Figure 1**) (48°14'11.4"N 16°11'34.7"E). The experiment started with the implementation of the intervention in March 2018 and extended over the whole vegetation period until September 2018. The site of intervention is within the Wienerwald Biosphere Reservoir. Due to the dominance and rapid spread of invasive alien plants within the Biosphere Reservoir, the diversity of plant species and thus the resilience of the native ecosystems is reduced (UNESCO, 2013). The numerous rivers and small brooks are particularly affected by knotweed invasion. The broad range of climatic and geological conditions in the Wienerwald is the reason for its great diversity in vegetation types. During the term of the experiment the mean temperature was high compared to the normal long-term value (see **Figure 2**). Dry conditions in the beginning of the vegetation period affected the initial growth of vegetation. In July, the sum of precipitation clearly exceeded the long-term value. However, this higher value resulted mainly from heavy rainfall events, which reached a high of 49 mm of total precipitation in one day (ZAMG, 2019). The soil in the Wienerwald is underlain by sandstone. As a result, during heavy rain the soil quickly saturates, resulting in substantial runoff. Thus, the flow of the Steinbach Brook can quickly increase, and affect the dispersal dynamics along the brook. As flooding favors the spread of invasive alien knotweeds along rivers (Truscott et al., 2006), an increased frequency of high flows has the potential to intensify this effect. For instance, a riverine patch of *F. japonica* could gradually colonize downstream banks with every flooding event (Duquette et al., 2015). In the lower reach of the Steinbach Brook the surrounding land is characterized by both the Wienerwald and housing structures. In a field survey it was observed that, downstream of the experiment, where the brook flows into the Mauerbach Brook, frequent *F. Japonica* populations were present and formed monospecific stands. Against this

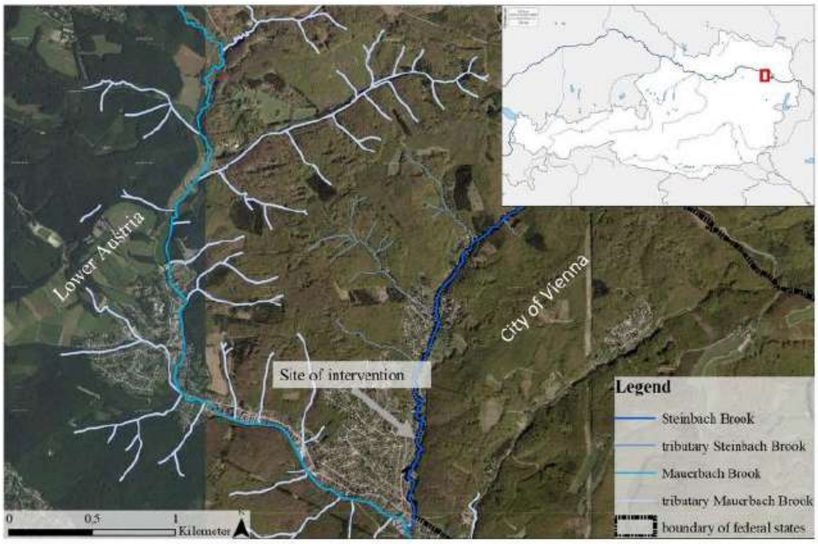

Figure 1. Map of Austria showing the site of intervention, marked in the northeast (d-maps, 2018), and the location of the site of intervention at local level (basemap.at).

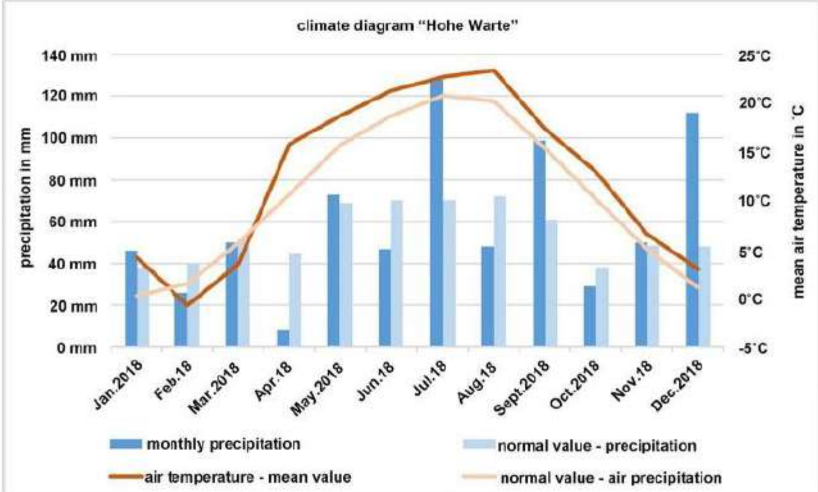

Figure 2. Climate diagram illustrating the monthly sum of precipitation and the monthly mean air temperature for the year 2018. Additionally, the normal values, calculated from the long-term monthly mean of the years 1981-2010 are shown. Data was recorded nearby the site of intervention by the meteorological measuring station "Hohe Warte" (ZAMG, 2019).

background, a nature-based engineering solution was designed with the aims of the immediate prevention of further spread originating from this *F. japonica* patch, the reinstallation of site-specific riparian vegetation, and the re-establishment of ecosystem service provision. At the same time the intervention has to serve to secure bank stability and resist high hydrological pressure.

2.2. Intervention-Application of a Willow Brush Mattress

The site of the intervention is located on a very steep embankment of difficult accessibility. Hence, it was decided to execute the structure by hand without the aid of any machines. The intervention was executed in the following sequence: firstly, the embankment was raked and cleaned of above-ground plant material and stones. Only large rhizome parts of *F. japonica*, which could easily be pulled out, were removed. At the toe of the embankment a trench was dredged into the bed of the brook. Subsequently, branches of *Salix purpurea* were placed densely on the embankment in a way that the thicker ends of the branches were positioned within the trench (see Figure 3). Due to the height of the embankment, a second layer of willow branches was installed. The upper branches did not have access to the water. In the next step, a willow fascine was installed in the trench and fixed with wooden poles. The willow branches were fastened to the embankment by the use of wire and wooden laths. The whole structure was covered by a thin layer of soil. It was decided to use *S. purpurea* due to its high ecological amplitude. It is a deciduous medium-sized to large-sized shrub that adapts equally well to wet or dry sites and exhibits great vegetative reproducibility (Hörandl et al., 2002). A small segment (3 m^2) of the willow brush mattress was

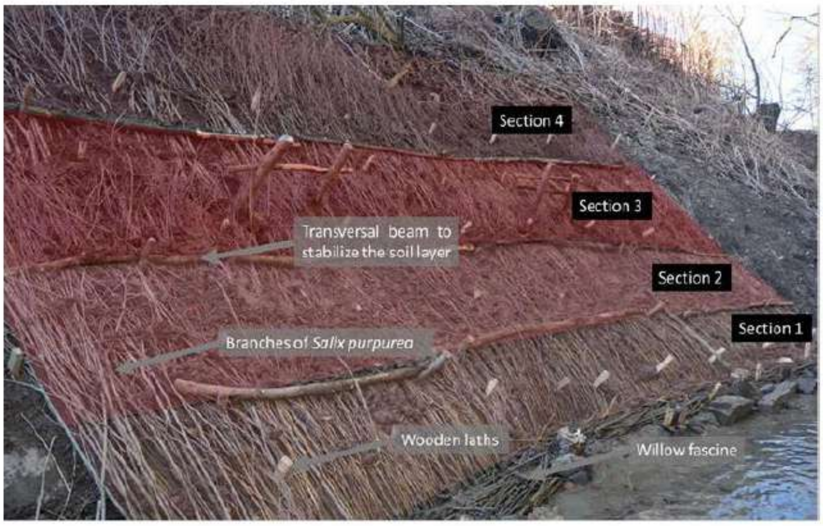

Figure 3. Illustration of the intervention after its construction, including descriptions of the constructive elements and allocations of the sections.

built by using *Salix fragilis*. This segment was not considered in the analysis below but will be addressed in the discussion.

2.3. Maintenance and Monitoring

Intensive maintenance work was carried out in order to support the implemented *S. purpurea* in competing with Asian knotweeds. Shoots of *F. japonica* were removed in very high frequency (three-week cycle). Over the course of the vegetation period, the shoot production of *F. japonica* decreased significantly and almost ceased. Therefore, the frequency of shoot removal was reduced. In order to evaluate the above-ground biomass production of *F. japonica*, the harvested shoots were dried and the dry biomass was measured in the laboratory. The ground coverage ratio of the vegetation was determined by image analysis. In order to determine the total coverage ratio, photographs were taken before shoot removal. A second image, taken after shoot removal, shows the ground coverage ratio of the implemented willows (see **Figure 4**). The data gained from this non-destructive analysis is used to monitor the development of the willows and their above-ground competitiveness. The analyses were performed by using the script "HORST" (Obriejetan, 2015) which is based on ImageJ, a Java-based image-processing program. "HORST" is an automated method for effective and accurate evaluation of the ground-coverage ratio from images. It analyzes the green tones of an image and calculates their relative area percentage. The color space used for the image analysis is the L* a* b* color system, which reflects the human perception of colors in a three-dimensional coordinate system. The green component or red component is expressed via the a* axis, while the b* axis defines the blue or yellow component of a picture. The luminance or brightness of the color values is displayed on the L* axis. After selection of the green values,

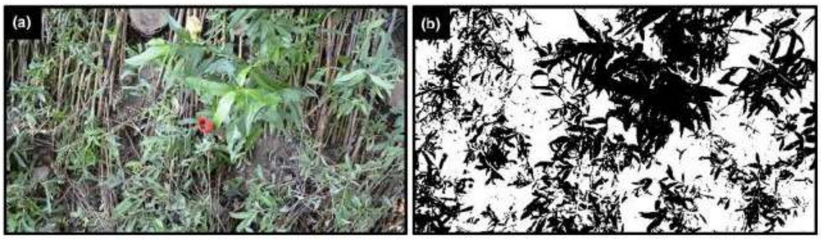

Figure 4. Coverage ratio analysis of the 4th survey (21. June 2018). (a) Image taken after the removal of knotweed shoots and (b) The analyzed image with the extracted vegetation in black.

the marked portions are converted to a binary image characterized by the presence of black and white pixels. In order to reduce any image noise, the median filter is used, which recalculates all pixel values based on their own value and the neighboring pixels. Finally, the proportion of black pixels is calculated relative to the number of total pixels and the result is output in percent.

3. Results

Plant Development

The development of *S. purpurea* differed significantly between the four sections of the intervention (see Figure 5). Within the section at the toe of the embankment, *S. purpurea* showed the strongest shoot production. In other sections, the development decreased with distance to the brook. Especially in the third and fourth sections, where branches of *S. purpurea* were implemented without water contact, the production of leaf mass decreased more strongly across the vegetation period than in the lower sections. At the first survey, on the 12th of April, the first leaves of *S. purpurea* had already developed, while *F. japonica* had not produced any above-ground biomass yet (see Figure 6). The pattern of spatial distribution of *F. japonica* shoot production was inverted compared to that of *S. purpurea*. Within the upper section, *F. japonica* shoot production was by far the strongest, while it was relatively low in the sections next to the water. Over the vegetation period the biomass production decreased significantly. The strongest biomass production was observed in the months April and May. Even though the temporal interval between shoot removal was increased, shoot production decreased strongly and nearly ceased in August. The photographs in Figure 7, taken at different surveys, illustrate the development of the intervention over the vegetation period.

4. Discussion

Invasive knotweeds impact multiple ecosystem functions provided by riparian vegetation and jeopardize river systems. They are pressure on the riparian system by themselves and often have a major impact if they act in combination with other pressures. Considering the high abundance of knotweeds along river courses, the expected increase of invasion and the consequent negative impacts

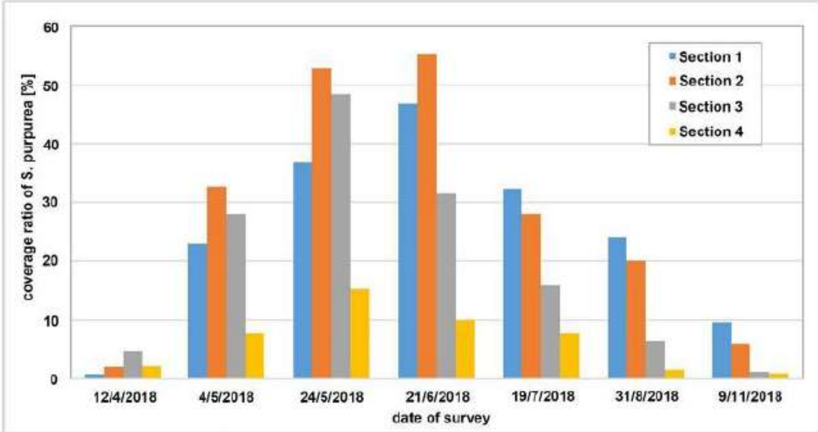

Figure 5. Development of the coverage ratio of *Salix purpurea* in the four sections over the vegetation period.

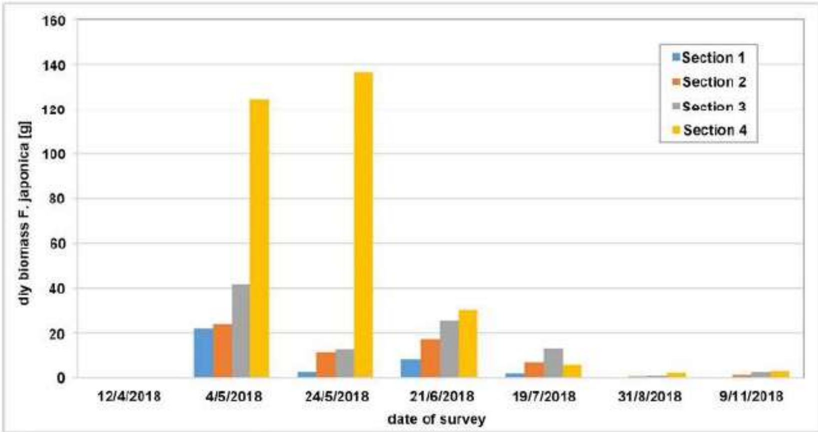

Figure 6. Development of the dry biomass production of *Fallopia japonica* in the four sections over the vegetation period.

on riparian ecosystems, there is a high demand for innovative approaches and management strategies. Conventional management efforts are ongoing and long-term, and will hardly reach a state of "eradication". In order to be able to develop adaptive knotweed management strategies, knowledge concerning seasonal biomass development and the most effective maintenance intervals must be improved. Additionally, greater understanding of the interaction between invasive and native species is essential.

4.1. Analyses of *F. japonica's* Biomass Production Reveals Its Response to Competition and Frequent Shoot Removal

F. japonica developed distinctly in the four defined sections on the brook embankment. In particular, within the two sections next to the brook it developed hardly any shoots. By far the strongest biomass development was observed in the uppermost section. At each of the seven surveys, all present shoots of *F. japonica*

Figure 7. Photographs from selected surveys to illustrate the development of the intervention along the course of the first vegetation period after construction.

were removed. Although the interval of shoot removal was shortest in the months of May and April, the amount of removed biomass was by far the greatest. Due to weak shoot production in the subsequent months, the intervals between surveys were gradually extended. With each session of shoot removal the natural development of *F. japonica* was set back and it seems that it could not recover efficiently after the second cutback. The hot and partly dry climate conditions might have additionally restrained regeneration. *F. japonica* developed significantly less above-ground biomass where the competitive vegetation could establish itself. This indicates a negative impact of the installed *S. purpurea* on the knotweed population. This could be observed particularly within the lower sections, where *S. purpurea* formed a high ground coverage.

4.2. Analyses of *S. purpurea's* Cover Ratio Reveals Its Development on *F. japonica*-Dominated Embankments

Branches of *S. purpurea* with contact to the water of the brook showed good development and could withstand the hot and dry climate conditions during the term of the experiment. Additionally, *S. purpurea* could successfully compete with *F. japonica*. The second layer of willow branches, without contact to the brook, showed significantly less shoot production and shoots partially died back throughout the summer months. In contrast to *F. japonica*, which suffered a rapid decrease in biomass production after the third survey, the coverage ratio of *S. purpurea* decreased gradually over the vegetation period. Noticeable was the good performance of the small implemented patch of *S. fragilis*. Although the branches had no water contact, very strong shoot development was observed. *S. fragilis* is a willow tree, which is characterized by very strong growth and competitive strength. The stronger performance of *S. fragilis* compared to *S. purpurea* was unexpected. The botanical habitat of *S. fragilis* is on moist locations while *S. purpurea* has the greatest ecological amplitude of native willow species in Austria and naturally occurs also in dry locations (Hörandl et al., 2002). The strong growth of *S. fragilis* could be an indicator of competitive strength against *F. japonica*. However, the use of *S. fragilis* for water engineering purposes is limited due to its fast growth and low resistance against fraction. It is only applicable if waterways are sufficiently dimensioned.

4.3. Nature-Based Engineering Solutions (NABES) and Management Perspectives

While a primary aim of weed management is to reduce the population of an invasive plant species, the goal of the developed NABES is to reinstall native riparian forests and to restore ecosystem functioning. The presented study demonstrates that comprehensive monitoring is crucial in the initial phase of NABES. Through monitoring, the timing when maintenance activities are most efficient can be determined. By the removal of knotweed shoots, development of the desired natural vegetation can be effectively supported. It must be taken into account that both monitoring as well as maintenance activities involve considerable expenditures. Besides adapted maintenance practices, the selection of implemented species is also decisive in the success of the intervention. There is still little known about the interaction between riparian species and Asian knotweeds. Accordingly, further investigation into the competitiveness of soil bioengineering species against Asian knotweeds is needed. The concept of NABES encompasses the removal of knotweed shoots in order to support the implemented species until they effectively push the knotweeds back through shading and rooting competition. As soon as the natural vegetation is successfully established, monitoring and maintenance activities can be reduced. Especially in sensitive areas and small initial patches of *F. Japonica* NABES seems to be an appropriate technique for sustainable knotweed control.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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9.6 Article 6

Energy balance and global warming potential of soil bioengineering structures

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Conference Proceeding:
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Energy balance and global warming potential of soil bioengineering structures

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ABSTRACT: With regard to climate change, energy consumption and consequential Life Cycle Assessment (LCA) is becoming more important. This issue is also becoming relevant for soil bioengineering. It is a technique using plants for civil a hydraulic engineering purposes. It can be applied as standalone solutions or in combination with conventional engineering structures. So far, no LCA models exist for soil bioengineering constructions. Therefore a new systematic scheme with differentiation of the natural hazard processes for bioengineering constructions is developed. The most important output of the scheme is a list of needed materials for each construction type, because this information is necessary as input for LCA studies and working with OpenLCA (software). This is an important step, because the existing assessment schemes are based solely on economic feasibility studies. Furthermore, these innovative Environmental LCA models will provide a higher level of transparency for the responsible planners, by pointing out the effective costs – involving natural resources - of all construction phases and components.

1 INTRODUCTION

1.1 Background of the research project 'E-Protect'

Due to the ongoing climate change, the awareness for the use of energy became more important in the whole field of civil engineering. To assess the use of energy in different sectors, the concept of Life Cycle Assessment (LCA) has been developed. The model of a LCA is already in use for different products and processes, for example in the sector of civil engineering, agriculture and food industry. With the research project 'E-Protect', the implementation of an Environmental Life Cycle Assessment model in the field of natural hazards for the Austrian Service for Torrent and Avalanche Control (WLV) is first realised. Both, the Cumulative Energy Demand (CED) and the Global Warming Potential (GWP) will be considered in this LCA approach.

The well-organised system of Austria´s natural hazard protection has a long tradition and is based on comprehensive expert knowledge. Even though there is a strong commitment to a resource-friendly management of considering natural resource-saving strategies by the WLV, a tool for its application is completely missing. The existing assessment schemes are based solely on economic feasibility studies. In the course of the project, the effective life span of conventional and soil bioengineering approaches will be analysed, which is a key factor to contribute to effective climate change adaption strategies. This paper focuses on the implementation of soil bioengineering constructions in a Life Cycle Assessment model.

1.2 Soil Bioengineering

Nowadays there is a high demand on engineering solutions considering not only technical aspects but also ecological and aesthetic values. In this context soil bioengineering techniques are often used as standalone solutions or in combination with conventional engineering structures. Soil bioengineering is a construction technique that uses biological components for hydraulic and civil engineering solutions. In general, it pursues the same objectives as conventional civil engineering structures. To achieve these ambitions, bioengineering is primarily making use of living materials, such as seeds, plants, parts of plants and plant communities to employ them in near-natural constructions while exploiting the manifold abilities inherent in plants. In many cases, soil bioengineering is advantageous to create nature orientated protection measures, especially for rivers and watersides. Furthermore it is applied in all fields of soil and hydraulic engineering, especially for slope and embankment stabilisation and erosion control (Zeh, 2007).

Meanwhile, these methods have regained worldwide recognition for their use in river and civil engineering projects (Howell (1999); Acharya and Rauch (2008); Durlo and Sutili (2005); Li and

Eddleman (2002); Lammeranner et al. (2005); Petrone and Preti (2008); Petrone and Preti (2010); Rauch et al. (2014)). By applying biological engineering techniques, living building materials become an integral part of infrastructure objects and contribute substantially to their security and their integration into the landscape (Gerstgraser, 2000). Soil bioengineering structures should comply with the same requirements as classical building projects (Strauss and Bergmeister, 2009). In practice, civil and geotechnical engineers have several concerns about using soft engineering techniques. An integrated or combined use of vegetation and natural structures like wood, stones, or geotextiles can reinforce the soil deep (Gray and Sotir, 1996).

2 SCIENTIFIC RESEARCH QUESTION

Based on these considerations and the fact, that the main focus of the research project is related to energy (in terms of the Cumulative Energy Demand (CED) and the Global Warming Potential (GWP)), the following questions for soil bioengineering structures arise:

- How much CED and GWP are caused during construction, use and end of life phase?
- How can planning and implementation processes be improved by Environmental LCA Models (CED and GWP)?
- How much CED and GWP can be reduced by life cycle optimized constructions?
- How can soil bioengineering measures be assessed in terms of resistance and stability functioning as well as their changes over time, taking into account the whole lifespan? The required functioning depends on specific engineering demands and varies from case by case.

3 METHODOLOGY

3.1 Basic Concept of Life Cycle Assessment

Life Cycle Assessment (LCA) models are procedures for a better understanding of the environmental impact of products or services (both manufactured and consumed). The objective of an LCA is the compilation and evaluation of the inputs, the outputs and the potential environmental impacts of a product system throughout its life cycle. Because the awareness of the importance of environmental protection is increasing, it is very important to expand this technique for the field of soil bioengineering. Therefore, it is of utmost importance to refine models and also to extend the existing databases. LCA can help us to find opportunities to improve the environmental performance of a product or service, select the relevant indicators of environmental performance and also inform the decision-makers (ISO, 2009). All these tasks are also valid for the application of soil bioengineering structures. Within 'E-Protect', the standardised LCA method of ISO 14040 is used as basis for an Environmental LCA of the soil bioengineering measures.

As mentioned before LCA is a tool to address the environmental aspects and potential environmental impacts of a product or a service throughout the whole life cycle. It starts with the production and acquisition of raw materials, the construction of the measures, the use and the end-of-life treatment, as well as recycling and the final disposal (Fig. 1, ISO (2009)).

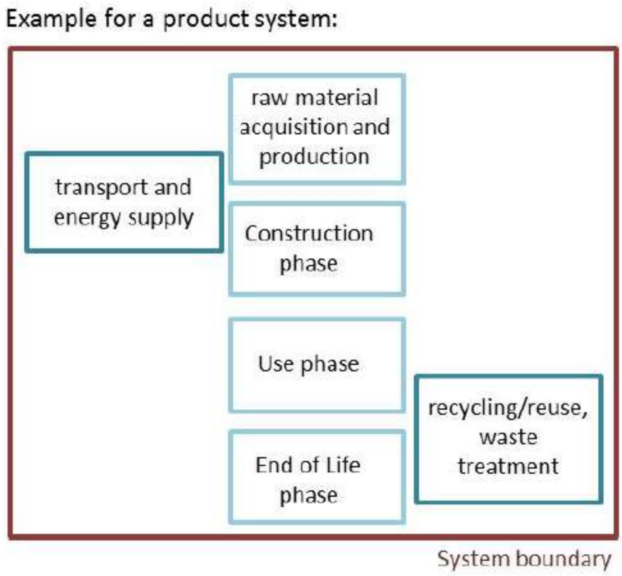

Figure 1. Example for a product system.

Four phases have to be considered to conduct a Life Cycle Assessment. As a first step the scope and the goal have to be defined. This step also includes the definition of the system boundaries determining, which parameters should be taken into account and which parameters can be neglected. The second step is an inventory analysis, where the compilation and the quantification of inputs and outputs for a product or service throughout its life cycle are involved. The impact assessment phase (third step) aims at understanding and evaluating the magnitude and significance of the potential environmental impacts. Within the last step, an interpretation of the results is necessary to evaluate the achievement of the goal and the compliance with the scope in order to reach conclusions and recommendations (Fig. 2, ISO (2009)).

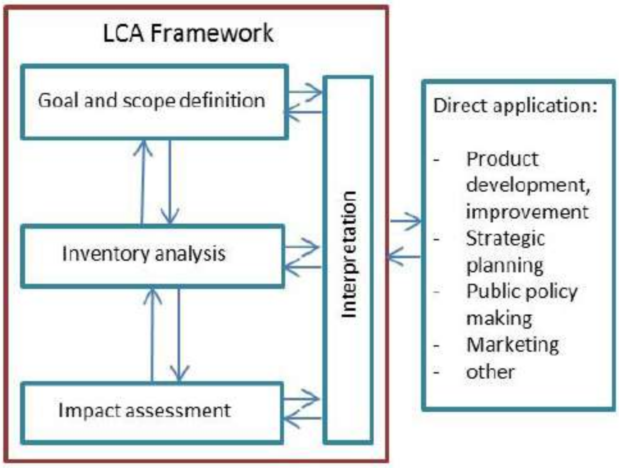

Figure 2. Stages of a Life Cycle Assessment.

3.2 Data acquisition (=Life Cycle Inventory, LCI)

For the data acquisition, reports and documentations from soil bioengineering construction sites will be collected. Additionally, the Austrian Service for Torrent and Avalanche Control provided construction reports for every region of Austria. Finally data bases of soil bioengineering construction sites from different regions all over Austria are available, providing information about applied techniques and materials (including transport) and about necessary work stages. As a result from this first working step, a so called Life Cycle Inventory (LCI) can be generated.

For non-specifically soil bioengineering work, existing databases, for example Ecoinvent, Agribalyse or Bioenergiedat, already contain a lot of useful information within the software OpenLCA. The materials and processes, that are not included in these databases, have to be detected and generated or adapted, so it is possible to create a database for relevant soil bioengineering structures. The overall goal is to apply Environmental LCAs for a wide range of soil bioengineering measures with OpenLCA. To produce the first case study with the software, all information about materials, product flows, and processes have to be entered into a database. By means of this input, a screening LCA is conducted, which means a first rough estimation (for the environmental impact of the structure). The screening LCA is the basis for the prospective LCA models.

4 FIRST RESULTS

In cost-benefit analysis, soil bioengineering measures perform worse than conventional technical measures in many ways. A critical factor is time. For technical design, the lifetime can be approximately estimated, what is much more difficult for a biological engineering design. Concerning the life time, different opinions are found in the literature and there is a lack of documented experience reports. In addition, the technical designs achieve their desired benefits immediately. The biological engineering design, however, requires a certain time to accomplish the desired benefit fully. This in turn affects the cost-benefit analysis in a negative way, since late accruing benefits are devalued in the balance sheet (Grossmann, 2010). However, especially in providing intangible benefits such as in aesthetic, ecological or ecosystem service aspects, soil bioengineering often has an advantage over technical designs. A great positive but still barely considered impact of soil bioengineering techniques is carbon sequestration by the used plants. Through revegetation, a great positive benefit for climate change mitigation is provided. Surfaces with a vegetation cover hold more carbon in their soils and biomass than surfaces that are sparsely vegetated or where vegetation is absent (Post and Kwon, 2000). The rate of carbon sequestration in slowly growing forests is low and the maintenance of the carbon pool by minimizing forest disturbances is important (Jandl and Schindlbacher, 2014). As trees reach maturity, their CO_2 sequestration potential decreases (in conjunction with a decrease in their growth rate). Willows, which are a key species for soil bioengineering implementations, produce high quantities of biomass and sequester carbon effectively. By continuously making the willow shrubs young, they keep their optimal sequestration capacity (Volk et al., 2004).

The biggest disadvantage of soil bioengineering is, that it is not possible to standardise living plants (Gerstgraser, 2000). Therefore, all relevant parameters for the plants at a construction site have to be considered and reviewed in order to provide a good basis for the growth of the plants and a good stabilisation effect of the measures.

The focus of this paper is the basis and conceptional considerations of an Environmental LCA model for soil bioengineering structures. In the field of soil bioengineering the procedure of implementing a measure is quite similar as in other disciplines. The process starts with the design, followed by its implementation and after that monitoring systems will be used to assess the performance during the phase of use. These individual life cycles are the fundamental building blocks of a soil bioengineering life cycle (Fig. 3).

The selection of the required construction material is essential for designing (first working step: design of a measure). Therefore, the acquisition and production of the raw material, as well as the further processing and the transports have to be considered.

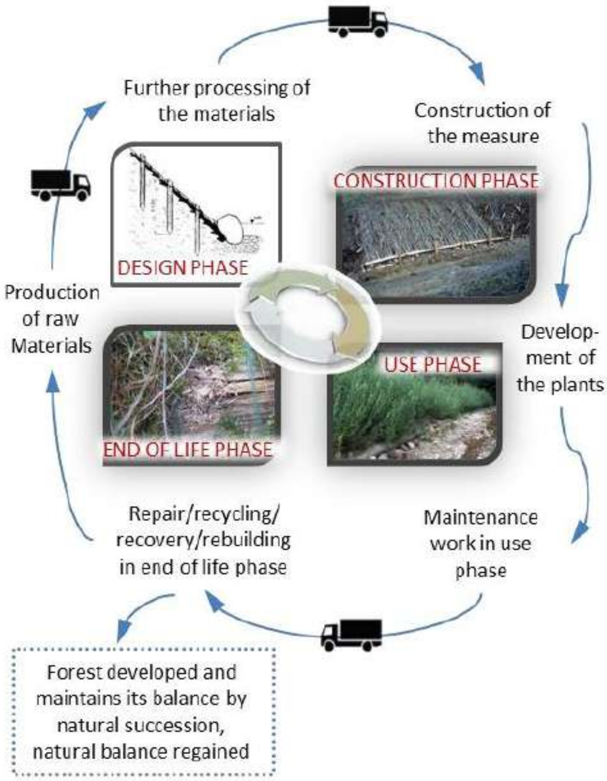

Figure 3. Soil bioengineering life cycle.

After the transport of the materials to the construction site, the construction phase is starting, followed by the use phase. Thereby the plants are developing until the measure reaches its full operational capability. At this succession stage some maintenance work can be necessary, thus again transports and machine use, etc. are required. Once the technical or environmental function can't be fulfilled any longer, the measure has reached the end of life phase. Arrived at this stage an assessment and following decision has to be made if some parts of the structure can be repaired or recycled, or if it's necessary to rebuild the soil bioengineering measure. Here again some transports and machine use, as well as new materials can be necessary. At this point the soil bioengineering life cycle is closed and it could start again. Another option would be to get out of the cycle, because the structure has already reached the full functional capability and the natural balance is regained.

Considering bioengineering structures, the majority of the energy input is required during the construction phase due to the cumulative energy demand of the inert materials used. Storesund et al. (2008) compared the life cycle impacts of a conventional concrete retaining wall vs. bioengineered slopes. Soil bioengineering interventions cause higher cost due to the active maintenance required, but significantly lower energy requirements and emitted only about half as much global warming relevant gases as the reinforced concrete retaining wall stabilization method. In this analysis, the effect of CO_2 emission credit as a result of photosynthesis from the used vegetation was not analysed and taken into account (Storesund et al., 2008). The principle of biological engineering constructions is based on the combination of dead and living materials and the emerging positive synergistic effects. The dead auxiliaries (stone, wood, etc.) protect the living plants until they undertake technical functions. After several years, a part of the auxiliary material rots and the stabilization of the bank is secured by the plants (Gerstgraser (2000); Schiechtl (1980); Howell (1999); Florineth (2002); Durlo and Sutili (2005); Zeh (2007); Sutili et al. (2012); Acharya and Rauch (2008)). During the operational phase of the structure, maintenance work has to be done in order to preserve the protective properties of the used plants. This is particularly necessary in the working field of water bioengineering considering the discharge capacity of certain river cross sections. In this case it is essential to keep the plants flexible and to prevent a too strong growth. Through actions like coppicing the vegetation back to the trunk, energy will be put into the system (through machine use etc.), but will also be put out in form of biomass. Additionally, carbon is sequestered by the biomass production of the plants. In contrast to conventional protective structures, soil bioengineering techniques are designed to have a subsequent use phase. That means in a best case scenario, that after the actual lifespan of the construction, a riparian forest should have developed, that keep its balance by natural succession (i.e. by dynamic self–control, without artificial input of energy) (Fig. 4, exit of life cycle).

To work with the soil bioengineering measures in OpenLCA, a classification was required. Therefore, all existing measures (Florineth (2004), Gerstgraser (2000), Zeh (2007)) were collected and ordered according to:

- process and application
- function of the measure
- technical or ecological function
- their containing materials (measures with only living materials used, measures with only dead materials used, and measures with combined materials (living plants and dead materials)).

At this point it gets obvious, that soil bioengineering is the English mistranslation of the German word 'Ingenieurbiologie'. But the addition of the word 'soil' seems necessary, to avoid any misunderstanding with other medical or genetic disciplines (Bischetti et al., 2014). As a consequence this paper distinguishes water bioengineering (as

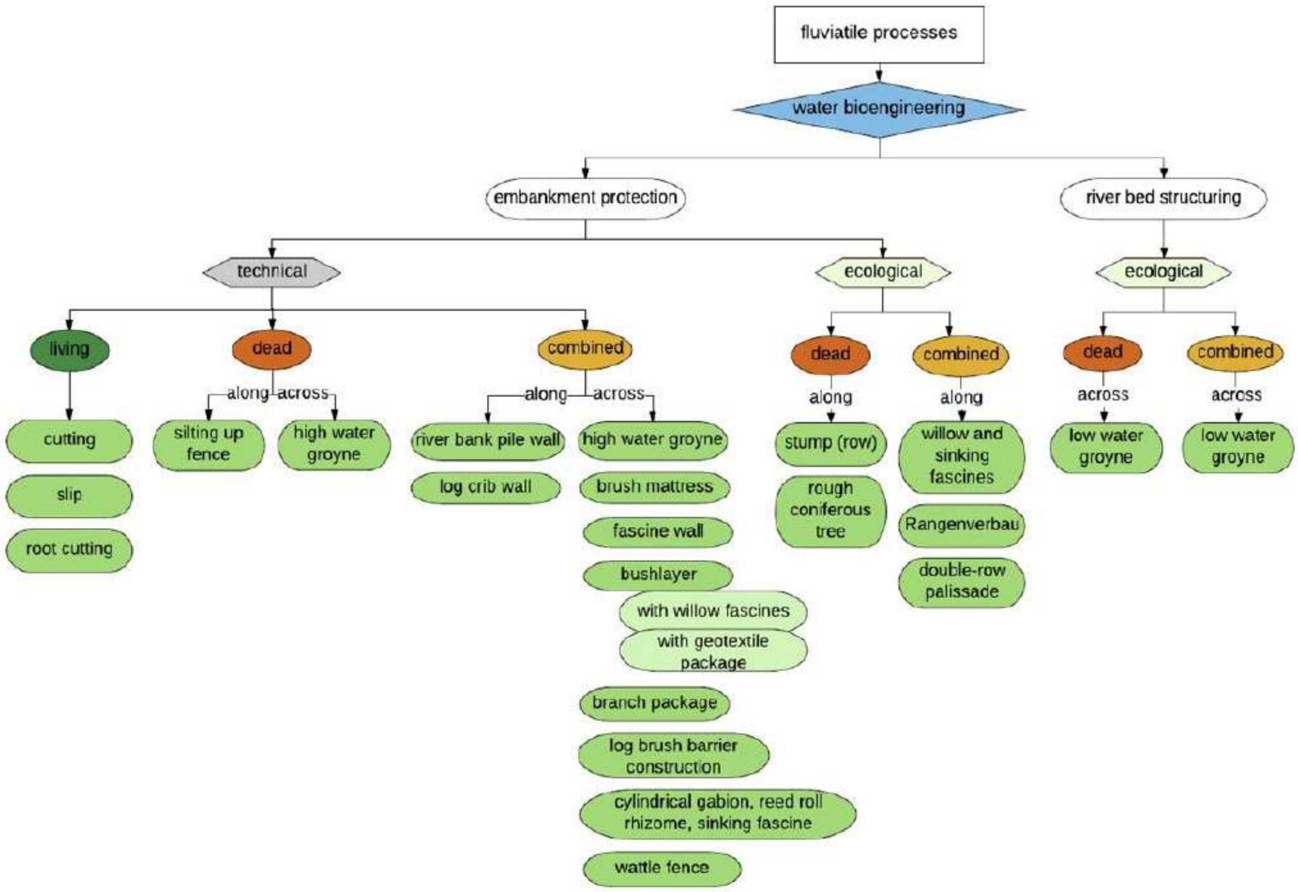

Figure 4. Systematic of the water bioengineering structures. Decision path from the process to the fitting structure.

mentioned before), containing riverine constructions, and soil bioengineering constructions, containing slope stabilisation and earth constructions, in the developed bioengineering systematic.

In Figure 4 the flowchart for fluviatile processes and water bioengineering measures is shown. The same scheme is done for erosion processes and soil bioengineering measures, but this diagram is not shown in the paper, due to lack of space. Other important processes are rock fall and avalanches. They are considered, but not as profound as the other processes mentioned before, because there are not as many possible bioengineering structures against this processes. For rock fall and avalanche processes, plants can be a possible alternative to conventional constructions as well, for example in form of protection forests.

By using the flowcharts, the first decision to make is about the processes. Should the soil bioengineering structure be effective against fluviatile or soil erosion processes? When answering the question, it is obvious whether it's a water- or a soil bioengineering structure. As shown in Figure 4 the next decision in water bioengineering is about the function. Should the structure provide embankment protection or river bed structuring? As a further subcategory, one can decide if a technical construction is necessary, or if the ecological demand is the focus. The last option is about the materials, used for the structures, with three possibilities: structures with only living materials used, structures with only dead materials used, or structures with living and dead materials combined. After working through this diagram a list of possible constructions is offered. Additionally all materials, needed to build the structure, are listed (Fig. 5).

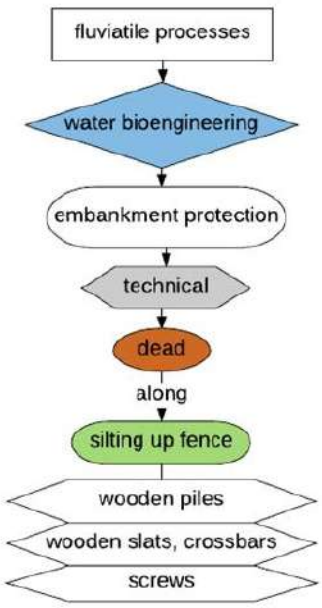

Figure 5. Decision path for the silting up fence, with listed materials.

Once the best fitting structure is chosen and all needed materials are defined, they can be found in the databases for OpenLCA. If not, they have to be produced with well documented background information. For the last step all the machines, that are used to build the structure, have to be listed in OpenLCA. As recently as all data exists in the databases the first screening LCA for soil bioengineering structures is possible.

5 OUTLOOK

The next important step is the identification of the processes which are relevant for a construction site and the demand of materials. In a further step a major integrated qualitative and quantitative comparative analysis is undertaken for the already existing databases and data which have to be generated in the field. Finally the OpenLCA software will be applied for soil bioengineering structures.

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9.7 Article 7

Development of an environmental life cycle assessment model for soil bioengineering constructions

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Development of an environmental life cycle assessment model for soil bioengineering constructions

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ABSTRACT

In recent times, a trend towards more climate-friendly and sustainable strategies and techniques in the field of civil engineering has arisen. For this reason, there is a high demand for engineering solutions which take into consideration not only technical issues but also ecological and aesthetic values. In this context, soil bioengineering constructions are gaining importance because the utilisation of living plants as construction material for conventional protective structures represents a preferred alternative. Different soil bioengineering techniques are used as stand-alone solutions or as complementary to conventional hydraulic and civil engineering solutions. Although the field of soil bioengineering has a long historical tradition, there is no assessment scheme that analyses energy consumption nor carbon footprint throughout the entire life cycle of soil bioengineering constructions. The following paper focuses on assessing three different soil bioengineering construction types. Through the use of an environmental life cycle assessment model, we show the possibilities and deficiencies of this method in the field of soil bioengineering. The analysis concentrates on the product stage and the construction phase. The results reveal that the hotspots of energy consumption for soil bioengineering constructions are the operating machines.

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Introduction

Soil bioengineering

Soil bioengineering is a construction technique that uses biological components for hydraulic and civil engineering solutions. In general, soil bioengineering pursues the same objectives as conventional civil engineering structures. Nowadays, soil bioengineering is of increasing importance as there is a high demand for engineering solutions which take into consideration not only technical issues but also ecological and socio-economic values (Acharya & Rauch, 2008; Durlo & Sutili, 2005; Howell, 1999; Lammeranner, Laaha, & Rauch, 2005; Petrone & Preti, 2008, 2010; Rauch, Sutili, & Hoerbinger, 2014). In order to achieve these ambitions, soil bioengineering makes use of different materials. First and foremost, living materials, such as seeds, plants, plant parts and so forth, are applied. This implies that

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soil bioengineering structures are dependent on the properties and development of plants. However, living materials are often used in combination with dead materials (e.g. stones and wooden logs) and different auxiliary materials (Florineth, 2012; Gerstgraser, 2000; Zeh, 2007). The fields of application for the discipline of soil bioengineering are soil- as well as water-related engineering. Whilst soil bioengineering deals with shallow landslide and gully stabilisation (also above the timber line), protection against superficial erosion and other earth constructions, water bioengineering concentrates on protecting and stabilising river banks as well as river restoration. This indicates that the English term 'soil bioengineering' is too specific and must be considered in a broader context that includes water bioengineering. At this point, it becomes obvious that soil bioengineering is an English mistranslation of the German word 'Ingenieurbiologie'. Yet, the addition of the word 'soil' appears to be necessary in order to avoid any misunderstanding concerning other medical or genetic disciplines (Bischetti, Di Fi Dio, & Florineth, 2014; Stokes, Sotir, Chen, & Ghestem, 2010). In terms of this paper, the term soil bioengineering is used for the sake of simplicity, but the meaning also incorporates water bioengineering. For an understanding of the definition of the term soil bioengineering, knowledge of the historical background and evolution of this working field is of the utmost importance.

Development of soil bioengineering and the application of the life cycle assessment (LCA) concept

The discipline of soil bioengineering has a long tradition. Bischetti et al. (2014), Schlüter (1984) and Florineth (2012) have given an overview of its history. Bischetti et al. (2014) positioned the origin of soil bioengineering '… within the process of the construction of German highways during the Nazi dictatorship, with the establishment of the Research Office for Bioengineering in 1936, …'. The earliest records in Europe go back to the Roman Imperial period. In the fifteenth century, Leonardo da Vinci documented his thoughts and knowledge about soil bioengineering techniques (Schlüter, 1984). Not only in Europe but also in Asian countries, for example in China, there are traces of the use of woven baskets made out of willows, bamboo or hemp for stabilising slopes. They were filled with rocks and used to repair dikes as long ago as 28 BC (Finney, 1993; Lewis, 2000). Stokes et al. (2010) found Chinese history books containing the earliest references, in which giant fascines used to control torrential floodwaters are mentioned, and which date back to 2000 BC. In Austria, the history of soil bioengineering was established with the foundation of the Austrian Service for Torrent and Avalanche Control in 1884. This particular institution deals with developing and improving constructions for protective measures, which illustrates the application-oriented basis of soil bioengineering. During industrialisation, the discipline of soil bioengineering disappeared in Austria until Schiechtl rediscovered it and was able to establish it again (Luzian, Kohl, Bichler, Kohl, & Bauer, 2002). What can be observed from historical hindsight is that the types of construction that are being used today are based on an empirical approach. Many practitioners experimented with and tested various different constructions. A strong argument for the application of soil bioengineering techniques, along with its technical functions, is also its ecological value. Therefore, the discipline has been established worldwide as an environmentally friendly and economically viable solution.

As a result of climate change, in particular, and its various consequences, interest in environmental issues is rapidly increasing and more attention is being paid to sustainable construction techniques (Buyle, Braet, & Audenaert, 2013). Soil bioengineering techniques use natural materials and can be a helpful instrument for civil engineers, as they take into account not only technical but also ecological and socio-economic aspects (Rauch et al., 2014). Biomass is produced with the development of plants, which subsequently leads to potential new habitats and additionally sequesters CO_2. Recently, Begemann and Schiechtl (1994); Florineth (2012); Gray and Sotir (1996); Schiechtl and Stern (1992, 1994) and Zeh (2007, 2010) have described the construction procedure and dimensioning of soil bioengineering techniques. However, a method for assessing the potential environmental impact has developed over the last 20 years. The Life Cycle Assessment (LCA) is a tool which provides the possibility of achieving a better understanding of the potential environmental impact of products or services. The overall objective of the LCA model is the compilation and evaluation of inputs and outputs and the assessment of the potential environmental impacts of a product system throughout its life cycle (EN ISO 14040, 2009). An LCA is organised in four phases. Initially, the goal and scope have to be defined. Following this, an inventory analysis is required, which involves the compilation and quantification of inputs and outputs for a given product. After this, an impact assessment phase must be undertaken and, finally, interpretation of the results is necessary (EN ISO 14040, 2009). System boundaries are defined in EN ISO 14040 (2009) as being 'a set of criteria specifying which unit processes are part of a product system'. According to EN 15978 (2012), the system boundary in the field of construction can be defined as cradle-to-grave (referring to the whole life cycle), cradle-to-gate (including raw material acquisition up to finalised building materials) or gate-to-gate (taking into consideration the construction process). The functional unit is used as a reference unit and defines the quantification of processes (EN ISO 14040, 2009).

The methodology for an environmental LCA in building construction has recently been developed (EN 15804, 2014; EN 15978, 2012). It is continuously being refined as awareness of the importance of environmental protection and the possible negative impacts associated with building projects are on the rise (EN ISO 14040, 2009). In contrast to the building sector, there is a lack of knowledge in the application of a Life Cycle Assessment Concept in the field of civil engineering. In terms of protective structures, only few and limited case studies, such as those undertaken by Gebauer et al. (2001); Noda, Kayo, Sasaki, and Takaoku (2014) and Storesund, Massey, and Kim (2008), are available. The methodology of LCA has not been considered so far in the field of soil bioengineering. One reason might be the static nature of LCA models for biological engineering building materials and constructions, which is in contrast to the dynamic development of the living plant materials used in the buildings.

The aim of this paper is to close this knowledge gap, and to present the application of an environmental LCA model for soil bioengineering techniques. Based on this aim, the two following scientific research questions have been devised: (1) How much energy [MJ] is used to build up a specific soil bioengineering structure? (2) Which processes are the most energy-intensive?

Methodology

A case study at the river Liesing

This case study involves a construction site at the river Liesing, located in the south-west of Vienna, Austria (Figure 1). Three different construction types were implemented at the construction site: a riprap (Figure 4), a log crib wall (Figure 6) and a brush mattress with willows (Figure 8). These construction types were chosen because they all fulfil the same function and pursue the same objective. However, they all differ with regard to the materials used. The riprap was built of dead and heavy materials such as limestone; the log crib wall combines wooden logs and stones, but is nevertheless a heavy construction; and the brush mattress was mainly built out of willow branches, supported by auxiliary material (such as wire and wooden piles). All measures were carried out in 2015.

Goal and scope definition

LCA was chosen as the method with which to assess the environmental impact of soil bioengineering. The focus of this paper is on displaying the construction phase of three soil bioengineering structures, including the acquisition of raw materials, the further processing of materials, transport, energy supply and all building processes. The main goal was to conduct a hotspot analysis in order to find out which processes consume the most energy. Opportunities for improving the environmental properties of soil bioengineering structures based on the LCA model can be shown. This LCA study is of relevance to planners, stakeholders and decision-makers who are interested in LCA case studies, especially those conducted for the purpose of soil bioengineering and protective structures. The scope includes the system boundary and the functional unit.

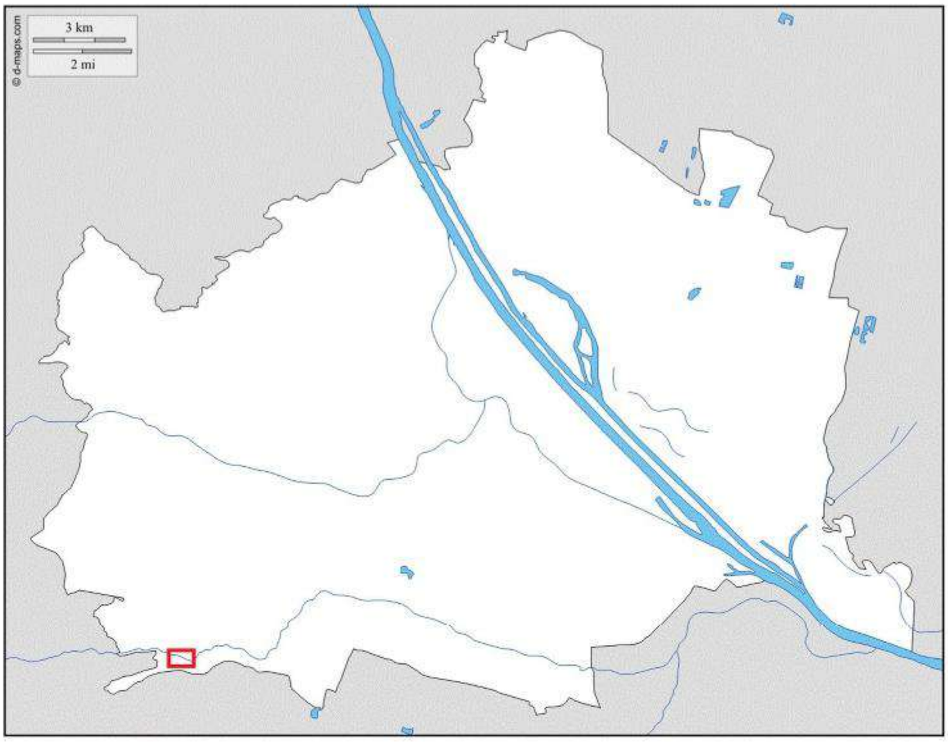

Figure 1. Map of Vienna showing the construction site at the river Liesing which is marked in the south-west.

System boundary

The focus of the present paper is on building materials and construction processes and, therefore, the cradle-to-gate system boundary (including construction phase) has been selected.

Considered in greater detail, the system boundary for the soil bioengineering LCA models presented excludes manpower (typical for the LCA method) and all smaller tools, for example drills (rechargeable battery operation), hammers, shovels and handsaws. For the tools mentioned, no fuel consumption is necessary and therefore they have been omitted.

Functional unit

Paratscha et al. (2017) and Noda et al. (2014) have described the difficulties in finding a functional unit for unique constructions in the field of alpine protective structures. This applies equally to soil bioengineering constructions. Each construction is unique and built in a different way and, therefore, fulfils a specific function. In this sense, it is difficult to find a consistent reference unit. In regard to the construction types presented in this paper, the functional unit is defined as '100 m of embankment protection of the river Liesing'. This functional unit does not take into account the service life time of the three different structures because there is a lack of data concerning the service life time of soil bioengineering structures. However, this will be an important aspect in further research.

Inventory analysis, software and database

Within the research project, the inputs of consideration are resources and energy consumption, including construction materials, machine use at the construction site and transport (on- and off-site). The summarised transport distances for each vehicle in Tables 1, 3 and 5 include the empty transport back

Table 1. Processes and machinery documented on the riprap construction site at the River Liesing.

Processes	Machine	Quantity	Unit
Preparation embankment/excavation	Excavator	20	h
On-site transportation of soil and stones	Dumper	60	h
Placing stones and backfill	Excavator	25	h
Off-site transports – material delivery	Truck >28t	432	km

to the production site. To detect these inputs, construction reports and documentation from the soil bioengineering construction site at the river Liesing, built in 2015, have been analysed.

The software OpenLCA version 1.4.2 has been used for the purpose of analysing this LCA case study. The Swiss Ecoinvent database version 2.2, released in 2007, was used for the purpose of conducting the first environmental LCA for soil bioengineering constructions. A large amount of important data for civil engineering has been collected in Ecoinvent, which is adaptable for soil bioengineering materials and processes. Some special soil bioengineering materials were added by creating new processes containing the existing Ecoinvent 2.2 flows. Mahler and Schneider (2017) recommend avoiding mixing data from different databases as they could involve different background calculations. Therefore, the use of data from other databases was intentionally avoided.

Impact categories

The Life Cycle Impact Assessment (LCIA) was conducted using the impact indicator Cumulative Energy Demand (CED). Regarding the construction types analysed in this paper, the non-renewable resource demand (fossil, nuclear and primary forest) has been considered as an impact category.

Results

In order to understand the life cycle of soil bioengineering structures, it was essential to analyse the processes which occur in all of the life cycle phases, including the construction, use and end-of-life phases (von der Thannen et al., 2017). Another important aspect was to identify the relevant construction materials because their production, as well as the supply of the raw materials, was considered in the upstream chain. The analysis of soil bioengineering construction types and the related materials are shown in a schematic diagram in Figure 2. The scheme shows a path with decision steps (◊, choose the next step) and confluence points (○, no matter which decision has been made previously, you end up here). Starting with an analysis of the predominant process, one is able to see if the system can be assigned to soil or water bioengineering. This is important to distinguish (as already mentioned in the introduction) because the associated construction types fulfil different functions. In the next step, the objective of the construction must be defined. Based on the definition of the objective, the main function of the structure is selected. However, soil bioengineering constructions are mainly implemented for technical purposes, whereas the objectives of water bioengineering constructions are, in many cases, a result of ecological and landscape functions. After determining the desired functionality, the construction type can either be chosen directly or following the definition of the category of materials. When choosing to define a predominant material, the following construction types are reduced to the preferred type of material. At the end of the path, the construction type and the materials attached to it are listed.

As a next step, the system diagram for the analysed product is compiled. In Figure 3, a simplified system diagram is shown. It includes the entire life cycle, from the acquisition of raw material at the product stage to further processing, up to the end-of-life stage. The construction phase is concerned with building the structure and consists of all building processes, including fuel for running the machines. Following implementation and the successful development and integration of the soil bioengineering structure in the use phase, periodic monitoring to check the defined attainment is recommended.

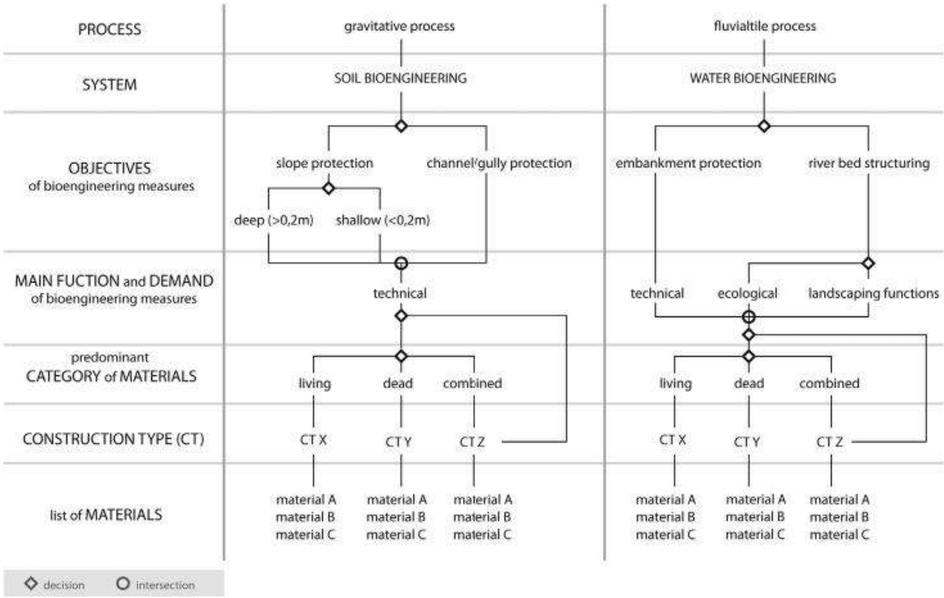

Figure 2. Scheme of decision path for soil/water bioengineering construction types.

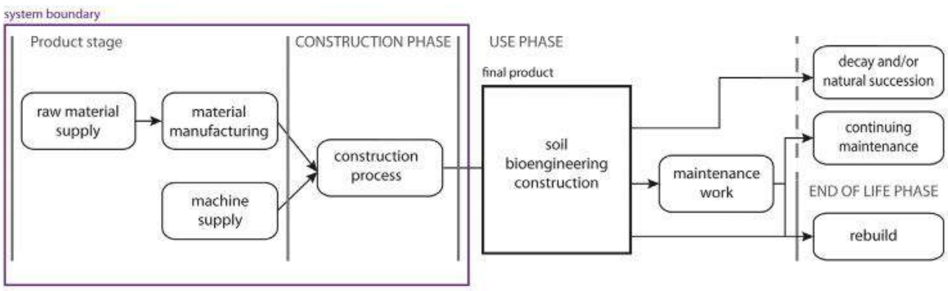

Figure 3. System diagram for the life cycle of a soil bioengineering construction.

Additionally, follow-up maintenance, development maintenance and conservation maintenance should be included in the monitoring process because there is no model for the development prediction of the structures. With regard to the end-of-life scenario, three different options for soil bioengineering structures arise. Rebuilding is the option which is most relevant for technical constructions. If the target state of the construction is to develop a natural riparian forest, an end-of-life scenario does not really exist as the forest is left to its own devices. Other structures require continuous maintenance in order to reach the defined target (Figure 3).

Construction type – riprap

A riprap is a technical construction used for riverbank protection. Riprap structures are made out of large stones or boulders that are carefully placed and matching up with each other. Using a riprap, it is possible to stabilise embankments with a larger angle of inclination than the natural one (Zeh, 2007). Additionally, a backfill can support the riprap in preventing the fine materials (soil, sand, gravel) from flushing out and thereby destabilising the structure. However, in order to protect very steep embankments and provide higher stability, the additional use of concrete or cement is indispensable.

Figure 4. Riprap, front view.

Table 2. Materials documented for the riprap construction site at the river Liesing.

Materials	Dimensions	Quantity	Unit
Lime stone boulders	$LMB_{10/60}$ (EN 13383, 2002)	225	t

In terms of this case study, the aim was to keep the riprap natural and ecologically friendly. Therefore, no cement or concrete was used and a backfill was not necessary. Figure 4 shows how the boulders are placed individually but interlocking with each other.

The model data input of the riprap for an embankment with a length of 100 m is given in Tables 1 (processes) and 2 (materials).

No information concerning transport distances is given in the construction report. Therefore, a transport distance of 9 km (from a local quarry in Gießhübl, Lower Austria, to the construction site in Liesing) for the delivery of the boulders was assumed. The transport distance summarised in Table 1 includes the transport route for 225t of limestone. As the capacity of one truck load stands at 9.68t (Ecoinvent Report), the truck is required to drive 24 times from the quarry to the construction site.

As can be seen in Figure 5, an analysis of energy consumption for the construction of the riprap reveals that operation of the hydraulic excavator during construction (13156 MJ) has the highest impact on energy consumption, followed by the dumper (9031 MJ). The transports show a relatively low influence on energy consumption due to the short transport distances.

The cumulative percentage curve, shown in Figure 5, illustrates the total energy input. It can be seen that nearly 40% of the whole energy consumption (35338 MJ) is consumed by the hydraulic excavator. Adding energy consumption from the dumper and the transportation, an input percentage of 80% can be seen on the cumulative percentage curve. The supply of limestone consumes about 20% of the total energy consumption.

Construction type – log crib wall

A log crib wall represents a transverse soil bioengineering structure that is used for bed consolidation in steep gullies or slope stabilisation works. The log crib wall is employed in hydraulic engineering as a

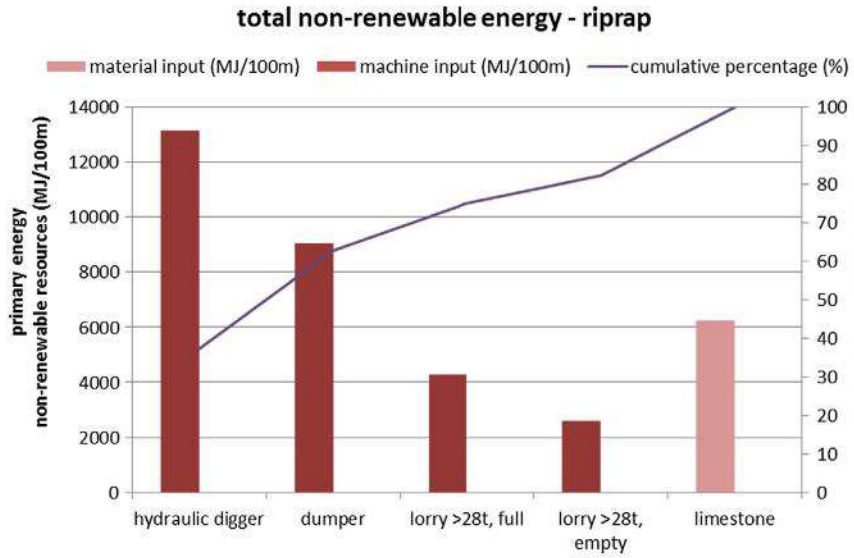

Figure 5. Consumption of non-renewable resources (primary energy) for building a riprap.

Figure 6. Log crib wall building process. (a) preparing earthworks, (b) placing the first layer of the wooden logs, (c) filling with boulders and soil and (d) log crib wall after 4 months.

longitudinal structure for river bank protection (Zeh, 2007). The visual appearance of this construction type can be described as inclined, extensive and rough (Florineth, 2012). As shown in Figure 6, the main materials used in the construction are wooden logs and stones (as drainable filling material).

Table 3. Processes and machinery documented on the log crib wall construction site at the river Liesing.

Processes	Machine	Quantity	Unit
Excavation	Excavator	15	h
Relocating rough deciduous trees	Excavator with a chain	0.5	h
Backfill	Excavator	9.5	h
Compressing	Vibrating plate/ compactor (90x50 cm, 383 kg, 7 kW)	6	h
Off-site transports – material delivery	Truck >28t	220	km
Off-site transport smaller items	Van <3.5t	20	km

Table 4. Materials documented for the log crib wall construction site at the river Liesing.

Materials	Dimensions	Quantity	Unit
Round wood pine (longitudinal)	400 × 20 cm	50	pcs
Round wood pine (transversal)	200 × 20 cm	37.5	pcs
Rough deciduous tree	–	2	pcs
Ground anchor	Cast iron, 2.1 kg per piece	4	pcs
Wire cable	Ø 6 mm, steel	32	m
Wood screw	8 × 300 mm, EFP coated	100	pcs
Iron bars	9 × 28 cm	14	pcs
Boulders*	Granite boulders 30 × 40 cm	117	pcs
Filling material/soil*	From excavation	–	m^3

*Available on-site due to construction → not separately modelled.

Additionally, the gaps in-between the logs can be filled with fascines (bundled willow branches), from which vegetation develops (vegetated log crib wall).

The process of building a log crib wall is schematically shown in the following Figure 6.

The data input for this example of a log crib wall is given in Tables 3 (processes) and 4 (materials).

The transport distances were not documented in the construction report. Therefore, the transport distance was assumed to be 30 km (Donau Auen – construction site Liesing) for the rough deciduous trees and to be 80 km (Hetzmannsdorf – construction site Liesing) for the wooden logs.

The processes and materials listed in Tables 3 and 4 serve as the input parameters for the analysis of the total energy consumption. Figure 7 illustrates that the hydraulic excavator (7309 MJ) has the highest impact on energy consumption. The production of the wooden logs (2222 MJ) and the summarised transport costs rank second and third, respectively. Additionally, a cumulative percentage curve is shown in Figure 7 in order to quantify the total energy input of the entire construction site. Comparing the cumulative percentage curve to the energy consumption of the hydraulic excavator, it can be seen that the excavator consumes 50% of the total energy input (14547 MJ). Furthermore, the cumulative percentage curve shows that the entire machinery input consumes approximately 75% of the total energy input. The remaining 25% is consumed by the production of the materials.

Construction type – brush mattress with willows

A brush mattress with willows consists of willow (*Salix spp.*) branches, which are tightly laid down on a riverbank transverse to the direction of flow. The branches are held down with wire that is tied around wooden piles to ensure ground contact (see Figure 8(c), the pile is on the right-hand side of the Figure). The basal endings of the willow branches must reach into the water in order to achieve optimal water supply and thus ensure development of the plants (Florineth, 2012; Zeh, 2007). The foot of the embankment corresponds to the foundation of the brush mattress and is, therefore, supported by rough deciduous trees (shown in Figure 8(d)). This construction type can be applied in versatile ways but it is mainly used to prevent erosion of river banks due to the impact of flowing water.

The process of building a brush mattress with willow branches is shown in Figure 8.

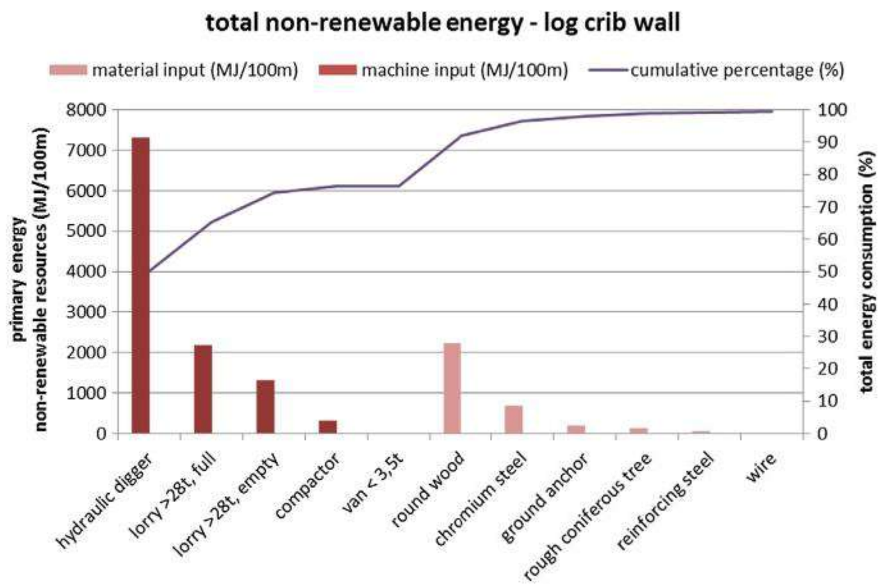

Figure 7. Consumption of non-renewable resources (primary energy) for building a log crib wall.

Figure 8. Building process of a brush mattress with willows. (a) preparation of the ground, (b) placing the willow branches, (c) branches fixed with wire and (d) brush mattress after 4 months.

Data input for the example of a brush mattress with willows for an embankment length of 100 m is given in Tables 5 (processes) and 6 (materials).

Table 5. Processes and machinery documented at the brush mattress construction site at the River Liesing.

Processes	Machine	Quantity	Unit
Preparation embankment	Excavator	6	h
Cutting willows	Power saw	9.4	h
Relocating rough deciduous trees	Excavator	0.5	h
Covering with soil, placing stones	Excavator	4	h
Off-site transports – material delivery	Truck >28t	60	km
Site-to-site transports – willow branches	Truck 3.5–20t	10	km
Off-site transport – smaller items	Van <3.5t	20	km

Table 6. Materials documented for the brush mattress construction site at the River Liesing.

Materials	Dimensions	Quantity	Unit
Willows (*S. caprea* und *S. trianrda*)	Ø 2 cm, 1.80 m long	40	pcs/m
Wooden piles (*R. pseudoacacia*)	4.5× 3.5 cm, 90 cm long	237.5	pcs
Iron wire	Ø 0.9 mm, steel	800	m
Soil*	–	7.5	m^3
Rough deciduous tree	–	6	pcs
Ground anchor	Cast iron, 2.1 kg per piece	12	pcs
Wire cable	Ø 6 mm, steel	96	m

*Available on-site due to construction → not separately modelled.

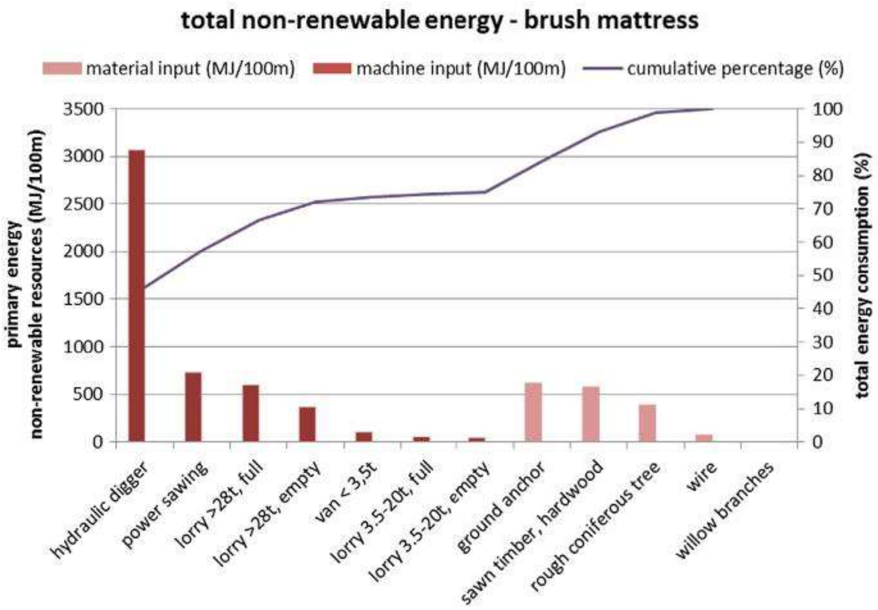

Figure 9. Consumption of non-renewable resources (primary energy) for building a brush mattress with willows.

The only documented transport distance for this construction site is the one concerning the willow branches, with a distance of 5 km (from Petersbach to the construction site Liesing). Therefore, the transport distance for the rough deciduous tree is assumed to be 30 km (Donau Auen – construction site Liesing) and 10 km for the smaller items.

The results for the brush mattress (Figure 9) point to a total energy consumption of 6603 MJ. The hydraulic excavator (3070 MJ) has the highest impact, whereas the power saw and the transports carry marginal weight. The cumulative percentage curve in Figure 9 shows the total energy input of the whole construction site. Additionally, it illustrates that the hydraulic excavator uses nearly 50% of the total energy consumed. Furthermore, it shows that the energy consumption of all the machines combined amounts to about 75% of the total energy input.

Discussion

Based on the hotspot analysis, we can see that the running of the machines had the highest impact on energy consumption within every single construction type (Figure 10). However, the materials used in these constructions show a rather low impact. When comparing the total energy consumption of the three construction types, it can be seen that the riprap shows the highest total energy consumption of 35338 MJ. This amounts to about 60% more than the total energy consumption of the log crib wall, which is 14547 MJ. At this point, it is worth mentioning that the log crib wall benefits from the reuse of boulders, which were available on-site. The brush mattress shows the least total energy consumption of 6603 MJ, which means 80% less total energy consumption than the riprap.

An analysis of the results of the three construction types shows that the machinery and the transport are the most energy-intensive processes on soil bioengineering construction sites. The reason for this is the predominant use of biological and natural building components. Soil bioengineering techniques can only be used when the technical specifications can be met by these structures. When using natural materials, soil and water bioengineering are climate-friendly building techniques that combine technical, ecological and aesthetic requirements. Additionally, they are cost-effective and economic because they require less heavy equipment and the materials can be obtained on-site in many cases. This consequently prevents long transport distances (Lewis, 2000; Zeh, 2007). Due to the lack of data for the transport distances in this case study, minimum transport distances were assumed. This procedure may have an influence on the results, depending on the construction type. However, the results of this study indicate that the transport is less energy intensive than the operating machines on-site. Exceptional cases could be soil bioengineering construction types built without heavy machinery.

Another approach for further analysis could be the differentiation of on- and off-site transportation. In this case, a comparison could be made between the energy input of the on-site processes, which would include on-site transportation and machinery operating time, and the energy input of the materials and the associated off-site transportation.

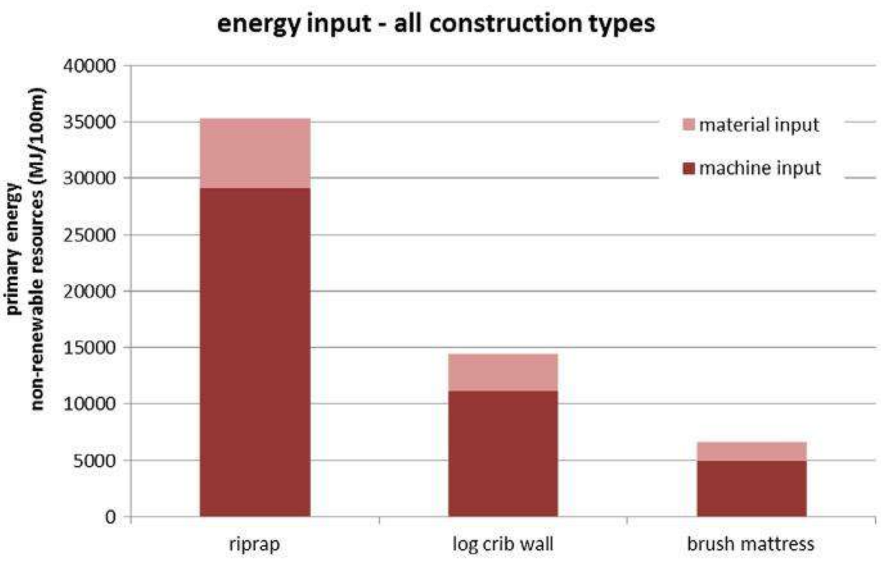

Figure 10. Overview of the energy consumption of all three construction types.

Conclusion and outlook

LCA for soil bioengineering constructions offers a great opportunity to assess structures by taking into consideration not only technical performance but, more importantly, aspects of ecology, for example, energy efficiency. The LCA method is definitely applicable to soil bioengineering structures because of its extensive data basis. However, there is need for a professional expansion of the database with specific soil bioengineering material data. The challenge for LCA regarding protection measures and, in particular, soil bioengineering constructions is the definition of the functional unit. Every single construction (type) has its own special function, and, therefore, a particular functional unit. This paper has presented a small selection of construction types and clearly demonstrates their variety. The riprap represents a hard construction type for steeper embankments and for providing a protective effect immediately. The log crib wall is a massive construction which offers strong protection for riverbanks and has an immediate effect. Additionally, the brush mattress, with its use of willows, represents a measure for the immediate protection of shallow surfaces and for the later development of a deeper protective effect due to the roots and branches of the willows, which continue to grow. This is a good example for illustrating how the system of soil bioengineering structures is not static, but evolving and flexible. Therefore, the claim that such a structure would call for a dynamic LCA model should be verified. A new approach could be a growth model that predicts the development of the plants. This growth model should be used as a basis for the LCA inventory during the use phase. Applying a growth model could help gain a better understanding of the growth behaviour of pioneer plants used in soil bioengineering structures and serve as a tool for predicting the frequency of maintenance work and the service lifetime of the structure.

LCA is a methodology that helps, *inter alia*, identify the highest energy consuming processes. This information can verify whether soil bioengineering construction is de facto the more sustainable solution under given circumstances. The method is helpful in the consideration of the real ecological benefits of soil bioengineering constructions and, additionally, reveals the hotspots of energy consumption and emissions. Being aware of the hotspots helps with locating environmental burdens and improving the processes concerned. The three construction types analysed in this paper show that the operation of machinery and transportation are more important factors compared to the energy input of the materials. Therefore, noting the effective operation time of the machines and the transport scenarios is certainly of the utmost interest because it makes a large difference whether stones are being transported from the most nearby quarry (as in the case in this case study) or if they are imported from foreign countries or even other continents. Furthermore, if the dimension of the excavation can be minimised, a lot of energy can be saved due to the hydraulic excavator subsequently having a shorter operation time. In effect, this shows that soil bioengineering is not per se an energy-effective construction technique but, rather, it depends on the chosen construction materials, the transport distances and, most essentially, the operation time of the machinery.

Having discussed the energy efficiency of soil bioengineering constructions, it should also be pointed out that the assessment presented has only considered the raw material production stage and the construction phase. The results could be different should the use phase and the end-of-life phase (including life time calculations) also be taken into account. At soil bioengineering construction sites specifically, intensive maintenance work can be necessary from an engineering point of view. Therefore, future analysis should consider the cradle-to-grave system boundary, whereby the entire life cycle of soil bioengineering constructions, including the use phase (maintenance) and end-of-life phase (recycling, reuse, and waste treatment), is analysed. In terms of considering the whole life cycle, the service lifetime of a construction is an important parameter. It helps define the functional unit in more detail and supports the comparability of different structures. Therefore, it will be considered and analysed in future research. Furthermore, the next assessment study (which will take into account the entire life cycle) will include other impact categories, such as the global warming potential (GWP) for a time horizon of 100 years (GWP_{100}) (according to the IPCC, [2007, 2013] specified in CO_2 equivalents ($CO_{2\text{-eq}}$)). The use phase and the service lifetime of soil bioengineering structures are expected to be highly relevant for the impact category GWP_{100}. This fact indicates the main reason for not taking GWP_{100} into account in this paper. Another reason is that the values of $CO_{2\text{-eq.}}$ would be negative (calculated as credits) when using wood as input material (including carbon uptake and storage) but excluding the end-of-life scenario, during which CO_2 is emitted again. This indicates that it makes sense to analyse GWP_{100} after having considered the entire life cycle of a soil bioengineering construction in order to take into consideration the varying service lifetime of different construction types. Additionally, the CO_2 emissions of wood would be balanced by including the end-of-life scenario.

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Disclosure statement

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9.8 Article 8

Development of a concept for a holistic LCA model for soil bioengineering structures

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Development of a concept for a holistic LCA model for soil bioengineering structures

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ABSTRACT: The consequences of climate change constitute, at the same time, a challenge and an opportunity for our future society. Climate change adaption and mitigation, as well as reduced availability of resources can only be met with substantial advances in technology and science. In view of these challenges it can be stated that climate change is having comprehensive effects on the entire field of civil engineering. To assess the use of energy, and detect potential environmental burdens, the concept of Life Cycle Assessment (LCA) has been developed. Different models of LCA have already been in use for specific products and processes. However, a model for application in soil bioengineering has still not been developed.
In the frame of a research project at the University of Natural Resources and Life Sciences, Vienna, Austria funded by the ACRP, a conceptual approach for an LCA model for the field of soil bioengineering has been developed. The focus, so far, has been on the product and the construction phase, but in this paper, the model will be extended for the purpose of simulating and analyzing the use phase of soil bioengineering constructions. Therefore, maintenance work has to be considered, as well as the service life time of the construction materials.
This paper presents the initial results of the assessment of the use phase and provides key elements to install a holistic LCA model for soil bioengineering structures.

1 INTRODUCTION

1.1 *Climate change and adaption strategies*

Due to the ongoing presence of the topic climate change, awareness about the use of energy has become more important in the entire field of civil engineering. To assess the use of energy in different sectors, the concept of Life Cycle Assessment (LCA) has been developed. The LCA model is already in use for different products and processes, for example in the sector of civil engineering, agriculture and the food industry. Optimizing the life cycles of different services and products is becoming increasingly popular. However, not only scientists, but also economists, are interested in the application of life cycle assessment models. LCA has become something of a certificate for more ecologically produced products and more sustainable services. In the field of building construction, this method has become an important tool for assessing the environmental burdens of any construction site and to be able to have another basis of argumentation for "greener" ways of building. Therefore, the LCA method is highly relevant for the field of soil bioengineering, which is considered to be a sustainable construction method in the field of civil engineering.

1.2 *Soil bioengineering and the development of a Life Cycle Assessment model*

Soil bioengineering is a traditional construction technique which was already applied by the Chinese as long ago as 28 BC (Finney, 1993), by the Romans in their imperial period, and by Leonardo da Vinci in the fifteenth century (Schlüter, 1984). In this technique, natural materials, such as wood, stones and living plants, are used to develop hydraulic and civil engineering solutions. This applies to nature oriented protection measures for rivers and watersides, but also for slope and embankment stabilization as well as erosion control (Zeh, 2007).

Over the last decades, soil bioengineering has been receiving more attention because the demand for engineering solutions, which take into consideration not only technical issues but also ecological and socio-economic values, is increasing (Lammeranner et al., 2005, Petrone and Preti, 2010, Rauch et al., 2014). Therefore, in specific cases, soil bioengineering can be seen as an ecological alternative to conventional civil engineering structures.

In specialist literature on this topic, descriptions for the construction procedure and dimensioning of soil bioengineering structures can be found (Begemann and Schiechtl, 1994, Florineth, 2012, Gray and Sotir, 1996, Schiechtl and Stern, 1992, Schiechtl and Stern, 1994, Zeh, 2010). Additionally, ecological values are evaluated for certain specific topics, such as the shading potential of riparian vegetation or the influence of soil bioengineering structures on aquatic habitats, and water-ecological improvements (Kalny et al., 2017, Melcher et al., 2016, Holzapfel et al., 2013). However, no study has yet analyzed and assessed the energy balance or carbon footprint of soil bioengineering constructions. Subsequently, the question arises as to wether a soil bioengineering structure is an ecological construction type *per se,* or if an LCA model could be of help in clarifying this statement from an energy balance perspective?

In the field of building construction, the method of Life Cycle Assessment has already been well established. Therefore, the idea is to adapt this method and develop an environmental LCA model for the field of soil bioengineering. For the development of such an innovative LCA model, a concept based on EN ISO 14040 (2009), EN 15978 (2012), EN 15804 (2014) has been created. In Figure 1 a system model for soil bioengineering constructions is presented.

Additionally, the model shows the sources of data and the working steps for the product stage and also the construction phase. In the use phase, it is necessary to carry out field measurements and monitoring in order to get an idea of how these structures will develop over time. Furthermore, the end of life (EoL) phase will be reached when technical requirements can no longer be fulfilled by the plants or the non-living materials used.

In a recently published paper by von der Thannen et al. (2017), an LCA case study for soil bioengineering structures has been presented. Three different construction types, with the same function (embankment stabilization) were assessed in relation to energy consumption, starting at the product stage and continuing up to the construction phase and the finalized product. For further analysis regarding the use phase, and the end of life phase, different scenarios need to be considered. Therefore, the paper at hand focuses on the development of a conceptual approach for determining maintenance processes for soil bioengineering structures in the use phase. Additionally, it aims at presenting a solution for dealing with the difficulty in calculating the use phase of soil bioengineering constructions, and for applying the LCA model in a specific working field.

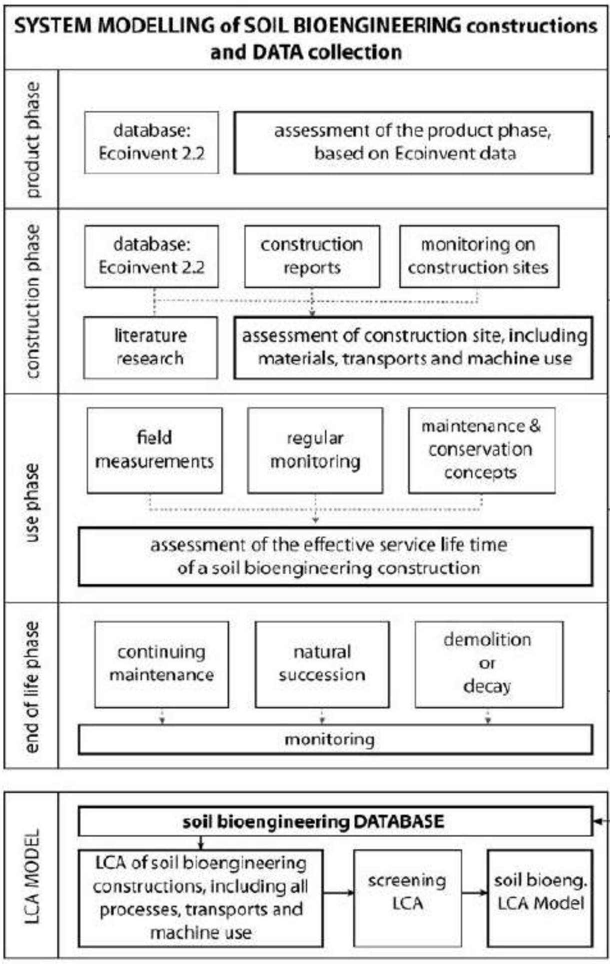

Figure 1. System model of soil bioengineering constructions, including data collection information.

2 RESEARCH QUESTIONS

The opportunity to assess soil bioengineering structures from the product stage up to the construction phase is an important achievement. Taking this approach as a basis for the use phase and the end of life phase should be considered. Therefore, the following scientific research questions arise:

- How can soil bioengineering structures be classified in terms of maintenance work during the use phase?
- How do the structures develop and alter over time, regarding the use phase? Do they appear to be the same for all structures?
- Are different maintenance scenarios necessary? What do they look like? Are they going to have and influencing the EoL Phase?
- What do the different EoL scenarios look like?

All of these questions are relevant in the use phase, and affect the end of life phase. Furthermore, it is essential to deal with these questions and find solutions to be able to further develop the LCA model for soil bioengineering systems.

3 USE PHASE ANALYSIS OF SOIL BIOENGINEERING STRUCTURES

The use phase of soil bioengineering structures is not easy to define, because every structure evolves individually, depending on construction type and built-in materials. In soil bioengineering structures, living materials such as seeds, plants, plant parts are mainly applied. But they are often used in combination with dead materials (e.g. stones and wooden logs) and with different auxiliary materials (Florineth, 2012, Zeh, 2007, Gerstgraser, 2000). This implies that soil bioengineering structures are dependent on the properties and development of the particular type of plant planted. Within the development of the plants biomass is produced, which subsequently leads to geotechnical stabilizing effects, potential new habitats, and additionally sequesters CO_2. These are some of the positive and ecologically friendly effects of soil bioengineering systems. Apart from this, the steady production of biomass could be a reason for the need for regular maintenance work, which would lead to additional energy consumption. However, when dealing with the use phase of soil bioengineering structures which contain living plant material, the application of different maintenance strategies must be considered. In soil bioengineering literature, follow-up maintenance, development maintenance and conservation maintenance are described as being the basic tending concepts (Zeh, 2007, Florineth, 2012). Follow-up maintenance is necessary within the growing-in phase of the plants, and should guarantee their further development. This method of maintenance is usually part of the construction phase, for supporting the process of growing-in and to present a working system (see Figure 2). For achieving the functional condition of soil bioengineering structures, the development maintenance (see Figure 3) is of utmost importance. Last but not least, conservation maintenance (see Figure 3) is necessary to ensure the long-term performance of the defined function. Furthermore, the harvested biomass could be used for energy or heat production, but these options have not been considered in the present paper.

To point out all relevant processes at all life stages a system diagram (originally developed for von der Thannen et al. (2017)) has been revised and is presented in two parts (Figure 2 and 3). The focus of the case study done by von der Thannen et al. (2017), was on building materials and construction processes, and therefore the "cradle-to-gate" system boundary (including construction phase) has been selected (see Figure 2). Within the analysis of the construction phase of soil bioengineering structures, the acquisition of raw materials, the further processing of materials, transport, energy supply and all building processes are included. Additionally, and considering the use phase within this study, the follow-up maintenance has been added in the construction phase. This type of maintenance is usually part of the construction phase, and is done to guarantee the process of growing-in before the structure is handed over. The other maintenance strategies, development and conservation maintenance, are already part of the use phase (see Figure 3). Additionally, Figure 2 and 3 demonstrate that a combination of all maintenance strategies is possible.

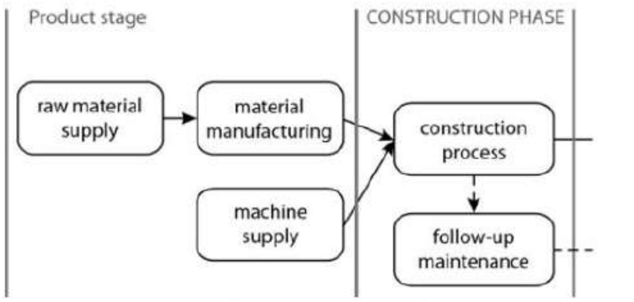

Figure 2. First part of the system diagram for the product stage and the construction phase of soil bioengineering structures.

By adding the second part of the system diagram, an extension of the "cradle-to-gate" system boundary into a "cradle-to-grave" system boundary was made possible. Due to this highly relevant enhancement, an important foundation for the realization of a holistic LCA model for soil bioengineering structures has been created.

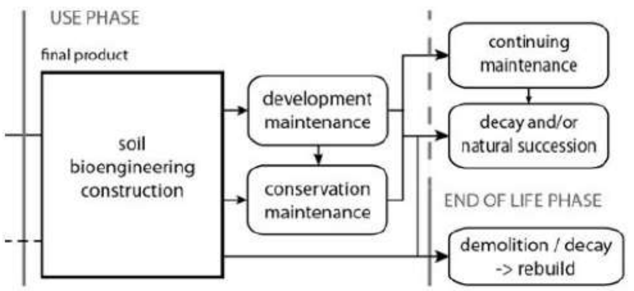

Figure 3. Second part of the system diagram for the use phase and the end of life phase of soil bioengineering structures.

To be able to define the use phase and the end of life scenario more precisely, it is necessary to assign them to different soil bioengineering structure types. Thereby, the main function and the objective of every structure type is relevant, and the maintenance concept has to be adjusted accordingly. In order to simplify this procedure, every construction type is assigned to a different category, according to the specified materials. In this context, all structures are not only assigned to the field of soil or water bioengineering, but, are additionally classified, according to their main building material.

Classification consists of three classes: plant based structures, combined structures, and non-living bioengineering structures. Plant based structures are -in this context- constructions whereby the main building material is the living plant, this includes, for example, brush mattresses, living fascines, brush layers, etc. Combined structures are structures whereby living and dead building materials are combined, such as, for example, in vegetated log crib walls or vegetated wooden gratings. Finally, non-living bioengineering structures represent constructions that are built with non-living but natural materials, for instance ripraps or log crib walls.

In line with this concept, a use phase scenario for each structure category will be presented in the next section of this paper. The intention of this is to assist in comprehending the complexity of these systems.

4 USE- AND END OF LIFE-PHASE CONCEPTS FOR THE DIFFERENT STRUCTURE CATEGORIES

In this section of the paper, use phase concepts present the function development of the different structure categories over time. Put simply, one diagram for each structure category is presented, although it includes the different maintenance or conservation options that can be applied.

4.1 Plant based bioengineering structure

Generally, plant based structures need regular maintenance, and they are aiming at fulfilling not only technical functions, but also ecological, socio-economic and aesthetic functions (Florineth, 2012).

Therefore, the use phase concept for plant based structures (see Figure 4) illustrates three relevant maintenance scenarios, including a zero alternative without any maintenance work (dashed, blue line). The first maintenance strategy, to be applied in the construction phase is follow-up maintenance (1). In this case, the growing-in of willows needs to be ensured, and additionally, the shoots should be kept small and flexible. Development (2) and conservation (3) maintenance are necessary in order to ensure the plants remain small and flexible throughout the entire life time. It must also be mentioned that all maintenance concepts can be either applied independently, or can be combined in different ways.

Additionally, Figure 4 shows the different end of life scenarios that are representative for plant based bioengineering structures. One option is the destruction or demolition of a structure, caused by external processes. Another option could be the progressive decay of a structure due to external and internal processes and advanced age. The third option could be a never ending phase of life, more specifically use phase, thus the attainment of the natural state. Therefore, it can be summarized that the service life time of the structure lasts as long as the objectives and the function of the structure are fulfilled. In the field of soil bioengineering and in technical literature, no data concerning the life time of soil bioengineering structures can be found.

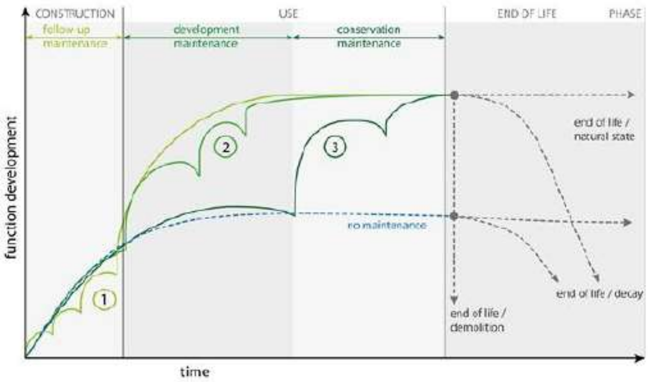

Figure 4. Maintenance concepts in the use phase of plant based bioengineering structures and possible end of life scenarios.

4.2 Combined bioengineering structure

Combined bioengineering structures consist of both living and non-living natural materials. The main function to be achieved by combined structures is mostly a technical one, but they are also able to fulfil ecological and aesthetic functions. The use phase of these structures is very complex, because maintenance and also conservation measures have to be taken into account, in terms of both the living and non-living materials used. The implementation of impermanent non-living materials (wooden logs) requires conservation measures that might be necessary at certain points, depending on the intensity and frequency of hazardous events and other external processes. The brown line in Figure 5 indicates the development of the use phase, combining maintenance measures for living and non-living materials. The zero alternative (dashed blue line) is added to illustrate the scenario without maintenance.

In end of life scenarios of combined bioengineering structures, demolition, caused by hazardous events or other external processes, and the decay of structures is considered. The third end of life option, the natural state, is in fact not an option for this structure category, because the non-living material is highly relevant for fulfilling the function of these structures.

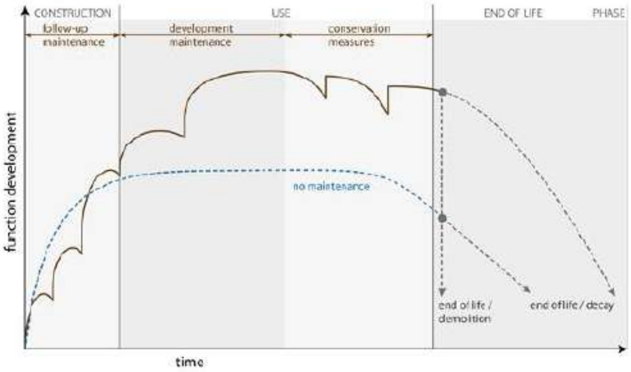

Figure 5. Maintenance/conservation concepts in the use phase of combined bioengineering structures and possible end of life scenarios.

4.3 *Non-living bioengineering structure*

The category type non-living bioengineering structure solely consists of non-living materials. Therefore, these materials are used in order to fulfil a technical function. Additionally, this structure category does not contain any living construction material, which therefore means that no maintenance work accrues. At a certain point, in the use phase (depending on the intensity of external processes), conservation measures should be undertaken in order to prolong the service life time of these structures (see Figure 6). End of life scenarios for non-living bioengineering structures are the same as those for combined bioengineering structures.

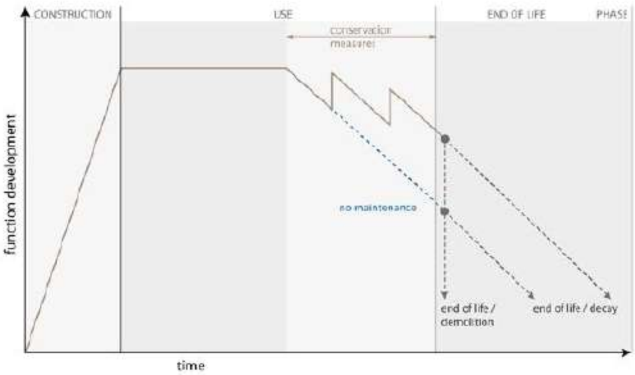

Figure 6. Maintenance/conservation concepts in the use phase of non-living bioengineering structures and possible end of life scenarios.

5 CONCLUSION

In summary, the initial beginning of the use phase appears different within different structure categories. This is because each of them has a varying degree of fulfilling the function. Whereas, non-living bioengineering structures can be considered to immediately fulfil total function after construction has been completed, the combined, and to a greater extent the plant based structure, need time for the growing-in of plants. The end of life scenarios look rather similar for all categories, with the option of demolition or decay. Additionally, the plant based structure has a third end of life option in terms of regaining achievement of natural state. This option does not come into question for combined or nature based structures, because they are dependent on the limited lifetime of the non-living materials.

The main goal of the current study has been to determine the use phase of different soil bioengineering structures. The results of the present paper point out the individuality of the use phase of soil bioengineering structures. Different maintenance concepts and conservation measures are necessary to provide individual use phase scenarios. Based on concepts which have been developed, it can be concluded that the individually defined main function and objective of a structure greatly influences required measures in the use phase, and additionally influences the energy balance and the carbon footprint. The more maintenance or conservation measures are necessary, the more energy is consumed and the more emissions are produced.

Furthermore, this study has identified the challenge to define a specific service life time for structures that are built in different environments with different influencing factors. One of the main factors of uncertainty is the use of living plants. Therefore, this study will serve as a base for future studies, where the service life time of structures including living plant material will be analyzed more precisely. Additionally, future studies should consider the further utilization of the biomass which derives from maintenance work.

6 DISCUSSION

However, there is no information in technical literature about how to plan maintenance work and apply it to specific structures thus far. The only references to concerning maintenance work were found in Florineth (2012) and Zeh (2007) as described previously in Chapter 3. Even in the appropriate Standard (DIN 18916, 2002, DIN 18918, 2002, DIN 18919, 2002) no specific information could be found. A reason for this could be the specific and unique situation which applies to every soil bioengineering structure. The European Guidelines for Soil and Water bioengineering (Europäische Föderation für Ingenieurbiologie, 2015) recommends maintenance work only if it is necessary to apply it to save resources, energy and costs, and to avoid any unnecessary interventions into the ecosystem. It is of utmost importance to define a maintenance goal for each particular soil bioengineering structure. In the best scenario, the achievement of this goal should be monitored regularly, and the maintenance procedure should be modified according to the results of the monitoring. Based on regular monitoring and a defined maintenance goal, an appropriate interval for tending can be established.

However, this proves the necessity of further research in this area. This applies to the definition of the service life time of different structures too. In specialist literature, as well as the directive of BMLFUW (2006), the service life time for structures, which include wood as building material, is between 15-50 years (Noda et al., 2014, Böll et al., 1999, Bergmeister et al., 2008, BAFU, 2015). The service life time for structures which have stones as the main building material is presumed to be within the range of 60-80 years (Bergmeister et al., 2008). Unfortunately, there is no data for the service life time of plant based structures. According to the directive of the BMLFUW (2006), a service life time of 40 years for plant based structures can be assumed. This is evidently important groundwork, but it additionally shows that more research on this topic is required.

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