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Soil and water bioengineering in cold rivers: A biogeomorphological perspective

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ABSTRACT

Soil and Water Bioengineering (SWBE) for river management is a viable alternative to civil engineering when bank stabilization is needed. Unlike riprap, SWBE techniques support bank stabilization while promoting the development of riparian vegetation. The preservation of vegetation biodiversity on riverbanks helps maintain and create essential ecosystem services such as recreation, carbon sequestration, pollutant filtration, and the creation of ecological niches and corridors. However, the potential of SWBE remains largely underestimated. Managers are often reluctant to use these techniques as they present failure risks, particularly in rivers with severe mechanical constraints. In cold environments experiencing freezing waters, ice-related processes such as ice abrasion or ice jams are significant disturbance factors for both river morphology and riparian vegetation. The marginality of SWBE is thus exacerbated in these environments, where considerable knowledge gaps persist regarding the interactions between ice, river channel morphology, and vegetation persistence. This review article aims to discuss the insights that biogeomorphology can provide for SWBE in cold environments. Biogeomorphology, a science that studies the interactions and feedbacks between living organisms and the physical processes shaping the landscape, offers new concepts and models as tools for understanding the co-development between landforms and vegetation. In the scope of SWBE, biogeomorphology can be used to (1) provide a better understanding of a river's dynamics and biogeomorphological changes in time and space to better identify the root causes of degraded riverbanks, (2) identify assemblages of species best suited to local conditions and better understand the relationship between channel morphology, vegetation, and ice to improve SWBE structure design, and (3) develop monitoring and evaluation tools to define the biogeomorphological functions of SWBE structure and improve maintenance strategies.

1. Introduction

River management has undergone a paradigm shift since the end of the 20th century, focusing on the control and manipulation of fluvial processes (Beechie et al., 2010). We now have a greater appreciation for the natural role of river erosion processes, which are essential for maintaining morpho-sedimentary equilibrium through energy dissipation and the input of organic debris and sediments needed to support biological and geomorphological diversity (Bigham, 2020; Florsheim et al., 2008). Understanding and taking into account the interconnectivity of these processes at different spatial scales (morphological unit, reach, landscape unit, watershed) allows for a more accurate assessment of river evolution and, consequently, leads to improved restoration strategies based on fluvial processes (Biron et al., 2013).

According to Johnson et al. (2020), process-based river restoration has become a standard practice but considering physical processes alone is no longer sufficient. They propose a shift toward a biomic restoration, defined as an approach that considers all living organisms that have effects on the physical environment. This new approach comes from a new management concept that emerged in the mid-2010s, i.e., the Nature-based Solutions (NbS). Gaining popularity, NbS encompass all actions that consider the physical and biological dynamics of a system while considering the added value of these actions on socio-environmental systems (Conte et al., 2020; Della Justina et al., 2020;

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Fernandes, 2018). NbS should play a significant role in the Anthropocene era as they address both hazard mitigation and natural processes restoration (Viles and Coombes, 2022).

Civil engineering techniques (e.g., riprap) are currently the most widely used solutions in riverbank stabilization since they offer immediate high bank protection and are part of a general political consensus (Bigham, 2020). However, these so-called "hard" restoration techniques have numerous consequences, such as hydrological disconnection, reduced fish habitat quality, inhibition of riparian vegetation development and associated ecosystem services (Massey et al., 2017; Reid and Church, 2015; Tisserant et al., 2021) as well as providing disputable aesthetical views. To limit these undesirable impacts, "soft" methods can be employed, such as Soil and Water Bioengineering (SWBE) techniques (Preti et al., 2022; Rauch et al., 2022; Rey et al., 2019).

SWBE in rivers involves stabilizing riverbanks by relying on the root systems of vegetation to consolidate sediments, the stems growth to provide resistance to flow and reduce shear stress, and stems bending to create a carpet protective layer upon the riverbank surface (Cavaillé et al., 2015; Rey et al., 2015). The use of pure techniques (exclusive use of organic materials) or mixed techniques (combined use of civil engineering and bioengineering) generally reduces construction costs, limits environmental impacts, and provides some of the natural riparian ecosystem services such as inland runoff-water filtration or habitat creation for animals (Moreau et al., 2022; Rey et al., 2019). As part of the NbS, SWBE techniques not only fulfill its function of erosion control but also increase biodiversity and enhance socio-environmental value through manipulation of ecological dynamics. Consequently, they merit particular attention from environmental managers (Preti et al., 2022).

The use of vegetation in bank restoration techniques has ancient roots. Civilizations such as China employed these methods approximately 2000 years ago, while in Europe these techniques were utilized both during the Roman era and, notably, throughout the 19th century (Evette et al., 2009; Frossard and Evette, 2009). Discussions surrounding the use of bioengineering resurfaced toward the end of the 20th century and have been gaining popularity, but this approach remains relatively marginal compared to civil engineering (Evette et al., 2009; Symmank et al., 2020). According to Moreau et al. (2022), this marginality is due to the higher risk of failure and a lack of theoretical and applied knowledge. Bioengineered structures are vulnerable during the first few years following their construction, when plant roots are not yet developed and sediments are not consolidated (Peeters et al., 2018). Furthermore, significant knowledge gaps persist regarding the design of the structures that remains mostly empirical and the selection of appropriate species (Rey et al., 2019). Yet, numerous examples have demonstrated the effective potential for ecological functions restoration and riverbanks protection through bioengineering solutions in various environments (Anstead et al., 2012; Hostettler et al., 2019; Karle et al., 2005; Miele et al., 2021; Peeters et al., 2018).

In colder regions where winters lead to river ice formation, a range of fluvioglacial processes (e.g., ice flooding and abrasion) add to the fluvial stresses applied on riverbanks and riparian vegetation, making the implementation of SWBE even more difficult (Poulin et al., 2019). Scientific literature and technical reports on bioengineering techniques in cold environments are scarce, and very few case examples are available. This limited use of bioengineering by managers in cold environments can be explained by knowledge gaps regarding the interactions between hydrogeomorphic processes, ice, and riparian communities (Karle, 2003; Poulin et al., 2019; Tuthill, 2008). However, the few existing SWBE projects in cold environments suggest that effectiveness of such techniques both in riverbank stabilization and ecological functions restoration can be reached (Karle et al., 2005).

It is necessary to consider hydrogeomorphic and ecological dynamics to improve SWBE conception and design (Peeters et al., 2018; Rauch et al., 2022). To implement the right structure and make it durable, managers must understand the fluvial dynamics of a specific watercourse. We believe that fluvial biogeomorphology could significantly participate in the development of such knowledge. Officially established in 1988 as a sub-discipline of geomorphology, biogeomorphology focuses on the interactions between ecological dynamics and the physical processes that shape landscapes (Viles, 2020). In river environments, fluvial biogeomorphology helps establish correlations and describe feedback processes between ecological dynamics (e.g., vegetation dispersal, recruitment, establishment, growth and succession) and hydrogeomorphic processes (e.g., flooding, sediment erosion and deposition) (Bätz et al., 2015; Caponi et al., 2019; Corenblit et al., 2007; Garófano-Gómez et al., 2017; Gurnell et al., 2012; Jansson et al., 2005; Tabacchi et al., 1998). The core concepts of fluvial biogeomorphology have yet to be applied in cold environments, underscoring a pressing need for such application. Developing this knowledge would provide invaluable insights into the possibilities and limitations of implementing SWBE in environments affected by ice processes and shed light on potential passive restoration management solutions.

This literature review aims to expose the insights that biogeomorphological knowledge can provide for managing rivers using soil and water bioengineering in environments characterized by cold winters. First, the context and current development of soil and water bioengineering techniques in cold environments are presented. We synthesize the marginality of these structures by describing the winter constraints that hinder their application. Second, the use of a biogeomorphological framework to enhance general soil and water bioengineering applications is discussed. The discussion focuses on three aspects of the SWBE practice: (1) the diagnosis of river's behaviour; (2) the conception and design of SWBE structures; and (3) the monitoring, assessment and maintenance strategies of SWBE. Third, these insights in the context of cold rivers experiencing ice dynamics are used to highlight the most important gaps and to propose research avenues and benefits of running biogeomorphological studies. In conclusion, we present key research questions to develop knowledge based on biogeomorphological dynamics in cold environments that would encourage the use of SWBE in these settings.

2. Challenges in cold environments

Bioengineering structures have repeatedly been analyzed in temperate contexts to establish their resistance to fluvial disturbances (Anstead et al., 2012; Krymer and Robert, 2014). However, cold environments introduce a range of processes that have received little consideration to date. Characterized by a climatic regime where the temperature remains below 0 °C for at least one month per year, rivers in cold regions are subjected to ice formation and various fluvioglacial processes (e.g., mechanical ice breakup and ice jams) that affect hydrogeomorphological dynamics and riparian vegetation (Beltaos and Burrell, 2021; Ettema and Kempema, 2012; Lind et al., 2014a). In some contexts, erosion associated with glacial processes can account for more than 50% of total erosion (Vandermause et al., 2021). Chassiot et al. (2020) proposed an exhaustive literature review on riverbanks erosion processes in cold regions, and Lind et al. (2014a, 2014b) produced a review that addresses the impacts of fluvioglacial dynamics on vegetation distribution. These two reviews provide a significant amount of information to understand the importance of ice in the ecological and geomorphological dynamics of cold regions' rivers. This paper follows up the past research by narrowing down all the ice-related processes involved that can significantly and directly affect restoration structures in SWBE practices. Fig. 1 depicts the main processes and their effects on riverbanks that need to be addressed in the process of nature-based restoration projects, emphasizing on four specific constraints: temperature, riparian ice, ice scouring, and ice jams. Their importance relies on the fact that observations and findings of previous studies underscore their critical role in shaping vegetation communities (Egger et al., 2015; Lind and Nilsson, 2015; Uunila and Church, 2014; Vandermause et al., 2021) and riverbanks morphology (Boucher et al., 2009; Morin et al., 2015; Smith and Pearce, 2002). By focusing on these constraints and

Fig. 1. Pictures of the impact of ice abrasion on vegetation, riverbanks and SWBE structures. A. Fascine dislodged by the ice in the Rouge River; B. Frequently disturbed Salix species by ice (presence of ice scars and bending) in the Belle-Rivière river; C. Ice scars on trees in the Saint-Charles river; D. Fascine teared out by ice in the Beauport River; E. Ice scar on tree in the Matapedia River; F. Pile dislodged by ice in the Cap Rouge River; G. Two-level bank as a result of ice erosion in the Du Chêne River; H. Wattle fence torn out by ice in the Quilliams River; I. Geotextile torn out by ice in the Cap Rouge River. Pictures are all from rivers in Quebec, Canada, and taken by Maxime Tisserant.

their effects on both riverbank geomorphology and riparian ecology, this paper aims to provide targeted insights about ice-affected environment for management and risk mitigation purposes. Considering and understanding these processes would allow for a more nuanced and effective approach to SWBE practices, ensuring that design and conception are well suited for ice-affected environments.

Temperature. Temperature in cold regions indirectly affects SWBE by imposing constraints on plant development and destabilizing sediments. Studies in temperate environments have shown that SWBE structures are the most vulnerable from 1 to 4 years after the installation, the time needed for roots to develop and stabilize banks (Leblois et al., 2022; Peeters et al., 2018). However, the low temperatures and short periods of plant growth associated with cold regions slow down the development of stems and roots, exposing SWBE structures to a longer period of vulnerability compared to temperate regions (Karle, 2003). Seasonal transition periods, on the other hand, are associated with freeze-thaw cycles and strong subaerial processes (processes at the soil-atmosphere interface) that can significantly contribute to bank erosion mechanisms (Chassiot et al., 2020; Yumoto et al., 2006). Freeze-thaw cycles, common in cold environments, reduce sediment cohesion and act as "preparatory" processes that weaken banks and increase their vulnerability to other sources of erosion (Chassiot et al., 2020; Kimiaghalam et al., 2015; Turcotte et al., 2011). For example, the freezing of interstitial water can lead to the formation of ice needles that expand, displace sediments, and reduce cohesive strength.

Riparian ice. Riparian ice is an ice cover that forms on riparian areas that is often found in river reaches where anchor ice accumulation raises the water level and causes flooding of the riverbanks (Ettema and Kempema, 2012). Vegetation in direct contact with the ice may die due to ice burns and can be torn away if the ice cover is set in motion by fluvial or gravitational forces (Engström et al., 2011; Lind et al., 2014b). This movement has the potential to erode sediments and vegetation trapped in the ice cover, thereby disturbing the habitat. The plant composition in these sections is conditioned by the extent of the riverbank ice, which often limits the development of shrub species and favours communities of opportunistic annual species that can quickly colonize disturbed environments (Engström et al., 2011; Lind et al., 2014b). As SWBE principally relies on shrub species to stabilize sediments and reduce shear stress, the inhibition of such species can represent a challenge in implementing such structures. Thus, resilient fast-growing species must be prioritized.

Ice abrasion. Ice abrasion is defined here as the process by which ice rubbles or blocks from 1 to 10 m in width strip vegetation and banks, causing erosion (Vandermause et al., 2021). Such processes are the result of snowmelt and rainfalls rapidly increasing the water level while the river's ice cover is still present, causing its fracture and the transport of fragmented ice known as "mechanical" breakups (Beltaos and Burrell, 2021). They differ from thermal breakups in that they involve the mechanical transport of ice, which exerts strong pressure on banks and riparian habitats (Beltaos and Burrell, 2021). Numerous factors determine the type of breakup that occurs in a river, such as the river's morphology, temperature, and precipitation regime (for a comprehensive review of the hydroclimatic causes of mechanical ice jam formation, see Beltaos (2003)). Ice scouring and underscouring expose riverbank root systems to subsequent floods, thereby diminishing the shear strength offered by the root mat and facilitating fluvial erosion (Beltaos and Burrell, 2021; Vandermause et al., 2021). Consequently, ice abrasion can instigate direct riverbank erosion or heighten vulnerability to future floods by serving as a preparatory process. The effect of ice scouring on vegetation varies depending on the severity of the breakup and the type of vegetation it impacts. Some mature woody species can be stripped, fractured, sheared, toppled, or even uprooted by the passage of ice (Lind et al., 2014a, 2014b), while other more flexible species, such as willows and dogwoods, can be bent to the ground without any severe consequences (Karle, 2007; Poulin et al., 2019; Rood et al., 2007). Fig. 2 shows the impact of ice abrasion on natural and bioengineered riverbanks. Ice abrasion is driven by a complex interplay of the ice blocks' density and size, their impact speed, and collision angle with the riverbanks. These variables, subject to an array of environmental influences, modulate the shear forces exerted on the banks, contributing to

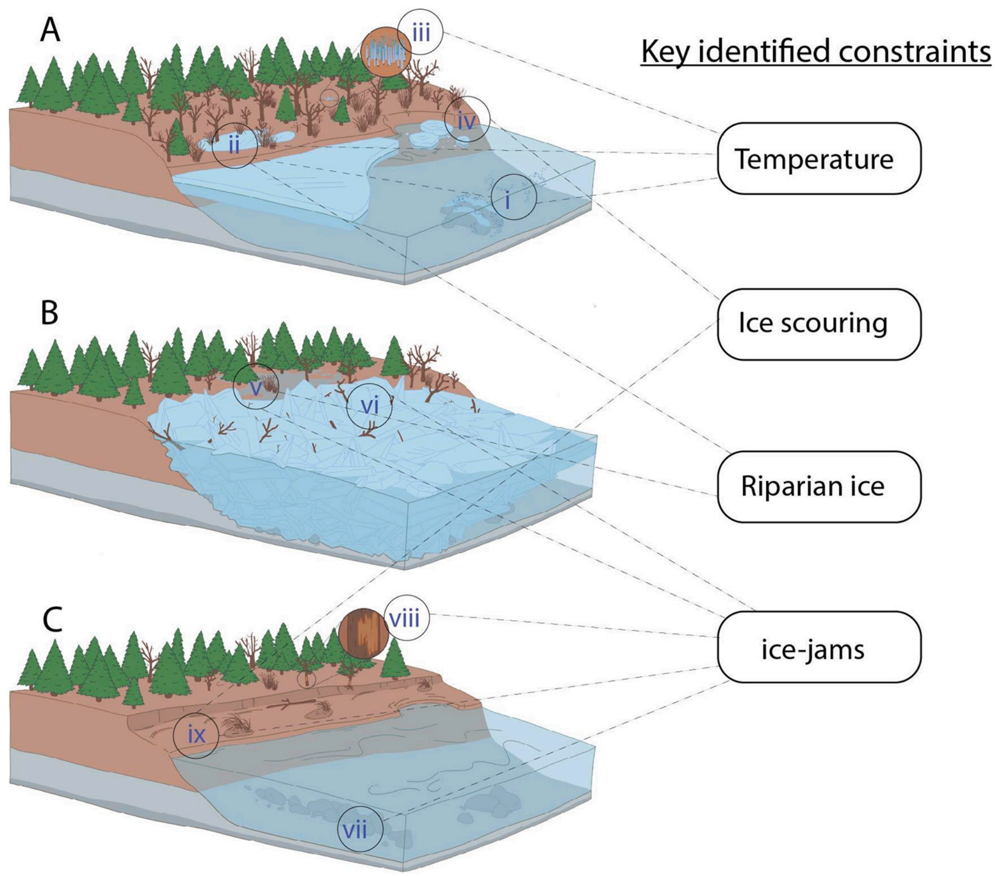

Fig. 2. Conceptual figure illustrating the ice-related processes and disturbances, and their relations to the key selected constraints (gray dashed lines) discussed in this paper. A. shows i) anchor ice that can accumulate to form an ice dam, elevate the water level and form riparian ice (ii), iii) needle ice formation due to freezing temperature and iv) ice abrasion by block transport during freeze-up and mechanical breakups. B. shows the formation of an ice-jam, reshaping the bank, v) causing high levelled floods on floodplain and vi) transport of wood debris. C. shows vii) pushed sediment by the ice-jam toe, viii) trees scarred by ice blocks during ice jams and ix) the typical two-level bank reshaped by a jave.

unpredictable patterns of sediment and vegetation disruption. This inherent complexity underscores the challenge to properly choose the SBWE structure to be implemented.

Ice jams. When ice blocks move downstream a river, they may encounter morphological obstacles (e.g., meanders, channel narrowing, presence of islands and islets, or static ice cover) that immobilize them. The accumulation of blocks causes the formation of an ice jam that obstructs the channel (De Munck et al., 2017). The pressure exerted on the banks by the accumulation of ice blocks can cause significant sediment remobilization, alter the topographic structure of the banks, and destroy riparian habitats (Chassiot et al., 2020). In addition, the concentration of flows near the ice jam can erode the banks by undermining, causing runoff, and in some cases, provoking avulsion (Smith and Pearce, 2002). The obstruction of the channel causes the upstream water level to increase and results in significant flooding on the floodplains, conditioning the type of vegetation and contributing to the floodplain aggradation (Tolkkinen et al., 2020; Uunila and Church, 2014; van Eck et al., 2006). The release of an ice jam represents one of the most severe hazards in rivers of cold regions (Chassiot et al., 2020; Rokaya et al., 2018). It can trigger an ice wave, called a “jave”, where large ice blocks from 10 to 100 m in width are rapidly propagating downstream with the released flood wave while applying considerable shear stress on the bed and the banks (Beltaos and Burrell, 2021; Chassiot et al., 2020). When occurring frequently in a river corridor, these events that are associated with significant bank erosion and sediment remobilization have the potential to create typical and perennial fluvioglacial morphological structures, such as two-level banks (Boucher et al., 2009; Morin et al., 2015) (Fig. 2G). However, in some cases, the passage of a jave overtopping the floodplain can destroy vegetation without eroding the bank sediments, only toppling mature trees (Vandermause et al., 2021). The temporal frequency of ice jams is scarce and to a certain extent predictable with numerical models that consider the riverbed morphology and hydroclimatic variables. Although ice jams can be somewhat predicted temporally and spatially, anticipating the associated shear stress at the local scale poses a significant challenge due to the numerous variables influencing it, including ice block size and movement speed.

Although the literature on soil and water bioengineering techniques in cold environments is limited (Karle, 2003; Poulin et al., 2019; Tuthill, 2008), two examples illustrate the feasibility of this approach for bank protection. The first example involves the qualitative monitoring of 11 SWBE restored sites in Alaska between 2003 and 2007 (Karle, 2003; Karle et al., 2005; Karle, 2007). The results showed that most of the SWBE structures were resistant to erosion despite a year of significant ice jamming. Root wad structures showed some broken branches, but no significant erosion of sediment or vegetation was observed. The willows planted for stabilization were bent to the ground while the ice blocked passed but resprouted effectively in the summer following the ice-jam event. Most impacted sites were the ones colonized with mature trees; some soil erosion was observed as well as damage to the trees. The second example focuses on a comparative study of different bank stabilization techniques in the province of Quebec (Canada) on 55 meandering rivers (Tisserant et al., 2021). The authors observed higher biodiversity at bioengineering sites than at civil engineering sites. This study, however, does not address the effects of ice disturbances on SWBE structures. Nevertheless, it can be inferred that several of these structures have been exposed to ice dynamics, as many of the rivers studied in this research are exposed to ice jams, and some structures were over 20 years old and still functional (Tisserant and Poulin, 2021).

3. Biogeomorphological framework for soil and water bioengineering practices

Since the 21st century, biogeomorphology has been increasingly developed as a fundamental science, but has also made its way into environmental management based on natural processes (NbS) (Coombes, 2016; Larsen et al., 2020; Viles, 2020). Biogeomorphology focuses on the conceptualization, description, quantification, and modelling of the processes responsible for the co-development between landscapes and living organisms, where vegetation occupies an important part of the literature and is the main interest of this review (González del Tánago et al., 2021; Haussmann, 2011; Larsen et al., 2020; Viles and Coombes, 2022). It studies the dynamic equilibrium within ecosystems and landscapes, considering feedbacks between living organisms and geomorphological processes (Stallins, 2006). In a fluvial context, studies are supported by the fact that vegetation modulates hydrosedimentary dynamics (e.g., flow resistance, substrate cohesion and sediment accumulation), while floods and sediment deposition condition the characteristics of habitat (e.g., frequency/amplitude of disturbances and sediment texture), and consequently, the vegetation composition (Comiti et al., 2011; Kyuka et al., 2021; Picco et al., 2016). This approach allows correlating ecological dynamics (vegetation dispersal, recruitment, establishment, growth and succession) with fluvial geomorphological processes (sediment erosion, transport and deposition). It evaluates the co-adjustment mechanisms between plants and their fluvial environment across various spatial and temporal scales (Corenblit et al., 2020a; Gurnell et al., 2012). This includes exploring the reciprocal influence of fluvial landform construction and vegetation succession, as well as investigating the relationships between vegetation mosaics and corridor-scale channel dynamics at the landscape scale (Astrade and Dufour, 2010; Comiti et al., 2011; Han and Brierley, 2020; Ielpi et al., 2022).

Numerous biogeomorphological conceptual models have been developed (Table 1) and most of them can be used in practical management applications, such as the Fluvial Biogeomorphological Succession (FBS; Corenblit et al., 2007), the Fluvial Biogeomorphological Life Cycle (FBLC; Corenblit et al., 2014), the Vegetation-Hydrogeomorphology Interaction model (HOVI; Gurnell et al., 2016a, 2016b), the Window of Opportunity (WoO; Balke et al., 2011), and the Biogeomorphological Feedback Window (BFW; Eichel et al., 2016). Working in concert, these concepts facilitate hydrosystems' functional characterization, foster knowledge creation, and directly serve as decision-making tools for river restoration and management. For instance, Fivash et al. (2021) used the WoO concept to create suitable conditions for natural establishment of pioneer species and restore biogeomorphic dynamics and landforms stability in Rattekai salt marsh, Netherlands. These concepts provide methodological frameworks for fluvial environment analysis that can be used to assess past and ongoing biogeomorphological dynamics. In SWBE, however, discussions on biogeomorphological dynamics seem sparse. While theories such as the influence of vegetation on flow velocity and sedimentation rate are used (Bigham, 2020; Leblois et al., 2022; Rauch et al., 2022), explicit incorporation of biogeomorphological approaches is infrequent. More commonly, these approaches are invoked in the context of restoring natural processes, such as by incorporating deadwood or protecting certain areas from human interference (González del Tánago et al., 2021; Larsen et al., 2020; Viles and Coombes, 2022), and have not been applied to riverbank stabilization projects as the basement of these approaches is to recover natural dynamic river's processes.

Here, we argue that biogeomorphological insights could refine bioengineering techniques by recontextualizing, from a functional perspective, the site and restoration action within its physical

Table 1
Key concepts in biogeomorphology and their definition based on their original references.

Concept	Definition	References
Co-adjustment	The process by which plant communities simultaneously affect sediment transport (e.g., deposition) and adjust to it in terms of distribution and composition.	Corenblit et al. (2007)
Feedback functional traits	Morphological and biomechanical traits of plants that provide a response to the modification they induced in their geomorphic environment (e.g., stems height, diameter and flexibility)	Corenblit et al. (2015)
Biogeomorphological behaviour	A river behaviour can be defined as the reflection of the ongoing hydrogeomorphological processes and adjustments. It represents a set of specific process-form interactions within reaches. Behavioural regime, whether it is dynamic or not, is defined through boundaries of dynamic changes. Thus, the biogeomorphological behavioural regime of a reach represents the set of ongoing biogeomorphological feedbacks defining the changes in time and space.	Fryirs (2017); Gurnell et al. (2016a, 2016b)
Pioneer landforms	Landforms that are initiated and newly formed through self-organizing processes induced by interactions between vegetation (i.e., aquatic plants, trees and wood) and hydrological/geomorphological processes.	Gurnell et al. (2016a, 2016b)
Biogeomorphological units	Morphological units (e.g., bars, islands and floodplains) for which their construction has been actively controlled by positive feedback between communities and hydrosedimentary dynamics.	Corenblit et al. (2016)
Fluvial biogeomorphological succession (FBS)	Refers to the dynamic and cyclical process by which biotic (living) and abiotic (non-living) factors interact within a riverine system, leading to the formation, growth, and decay of fluvial landforms through four distinct phases; (1) geomorphological, (2) pioneer, (3) biogeomorphological and (4) ecological.	Corenblit et al. (2007)
Fluvial biogeomorphological life cycle (FBLC)	Refers to the reciprocal coupling between the biological cycle development of long-lived riparian plants and the durable modifications they induce in their hydrogeomorphological environment. This model aligns with the model of positive niche construction of Odling-Smee et al. (2003)	Corenblit et al. (2014)
Hydrogeomorphology-vegetation interactions model (HOVI)	Refers to a conceptual framework that describes the interactions between hydrology, vegetation, and geomorphology in river systems, emphasizing the dynamic and reciprocal relationships among these components and divides the river corridor in 5 different functional zones, including a critical zone; (1) perennially inundated, (2)	Gurnell et al. (2016a, 2016b)

(continued on next page)

Table 1 (*continued*)

Concept	Definition	References
	fluvial dominated with sediment erosion and deposition, (3) fluvial dominated with fine sediment deposition, (4) inundation dominated and (5) soil moisture regime dominated.	
Windows of Opportunity (WoO)	Describes the period required for pioneer vegetation to develop sufficient resistance to survive the next disturbance.	Balke et al. (2011)
Biogeomorphological Feedback Window (BFW)	Describes the period during which biogeomorphological effects of vegetation occur and identifies the thresholds at which feedback processes cease.	Eichel et al. (2016)

environment (material and energy fluxes) and its biological characteristics (e.g., reproduction strategies; effect, response and feedback traits of keystone engineer species (Corenblit et al., 2015); functional guilds of responses and effects (Diehl et al., 2017)). This approach allows for a more comprehensive understanding of a river's behaviour at both the fluvial corridor and riverbank scales, paving the way for methodological enhancements not solely based on structures but also on functions. By explicitly integrating this knowledge – and considering the potential for reciprocal coupling between biotic and abiotic factors – into the design of SWBE projects, river managers can better account for the intricate interplay between vegetation dynamics and geomorphological processes occurring at various spatiotemporal scales. This refined perspective fosters the development of more sustainable and effective restoration and management strategies, ultimately leading to resilient and adaptable river systems that optimally support both human needs and ecological requirements.

The failure of SWBE structures is mainly due to (1) poor vegetative recovery, which limits the stabilizing effect on the bank; (2) poor design of the structure, which promotes mechanical failure; and (3) inadequate consideration of fluvial dynamics and its interaction with plants (Leblois et al., 2022; Peeters et al., 2018). These failures are principally conditioned by knowledge gaps and research limitations on certain fundamental aspects of SWBE, such as species ecology or structure selection, structure design, or consideration of watershed-scale processes (Rey et al., 2019). We have identified three aspects of SWBE for which biogeomorphology can provide enhancing insights: (1) diagnosis of a river's behaviour and trajectory; (2) design and conception of SWBE structures in a functional framework; and (3) monitoring and maintenance strategies. From a biogeomorphological framework (Fig. 3), a multiscale diagnosis along a river corridor would improve conception and design choices while the monitoring and assessment of biogeomorphological functions could help to identify failure causes, help to manage maintenance strategies, and predict future development. The following section is dedicated to the discussion of such biogeomorphological insights.

3.1. Diagnosis of river's behaviour and trajectory

Rivers are shaped by a range of processes cascading at multiple spatial and temporal scales, going from the watershed's geologic and topographic features (e.g., lithology, slope and degree confinement) to local channel adjustment dynamics (e.g., widening, incision, lateral migration) and hydrosedimentary processes (e.g., erosion, transport and deposition) (Beechie et al., 2010). As the selected strategies of intervention depends on the erosion mechanism (e.g., channel incision, meander migration, underscouring) (Peeters et al., 2020), consideration of the interrelations at multiple spatiotemporal scales is necessary for SWBE implementation to identify the root causes of riverbank degradation and choose the adequate restoration or stabilization technique. Several river management frameworks have been developed over the past decade to assist river managers in characterizing fluvial processes and integrating different scales of analysis (Beechie et al., 2010; Gurnell et al., 2016b; Pinto et al., 2019; Rinaldi et al., 2016); but the most of them are specifically oriented on physical processes.

A biogeomorphological multi-scale assessment of a river corridor, by identifying key characteristics (e.g., vegetation types, reaches behaviour, landforms' stabilization and construction) and quantifying the rate and trajectory of morphological and vegetation changes, represent an effective way for managers to understand ongoing behavioural regime and predict possible changes both in channel structure and vegetation distribution (Larsen et al., 2020). For instance, it can predict key moments of biogeomorphological changes, such as an increase in flooding frequency potentially causing a shift in vegetation composition, and help anticipate geomorphological trajectories of changes, informing strategies like strategic tree planting to control erosion (Larsen et al., 2020; Viles and Coombes, 2022). Depending on the root cause of erosion at a specific site, whether it takes its origins from local, reach or catchment scale's processes, management actions might be applied either directly on the eroded riverbank or by restoring natural processes at multiple sites across the fluvial corridor (Beechie et al., 2010). In

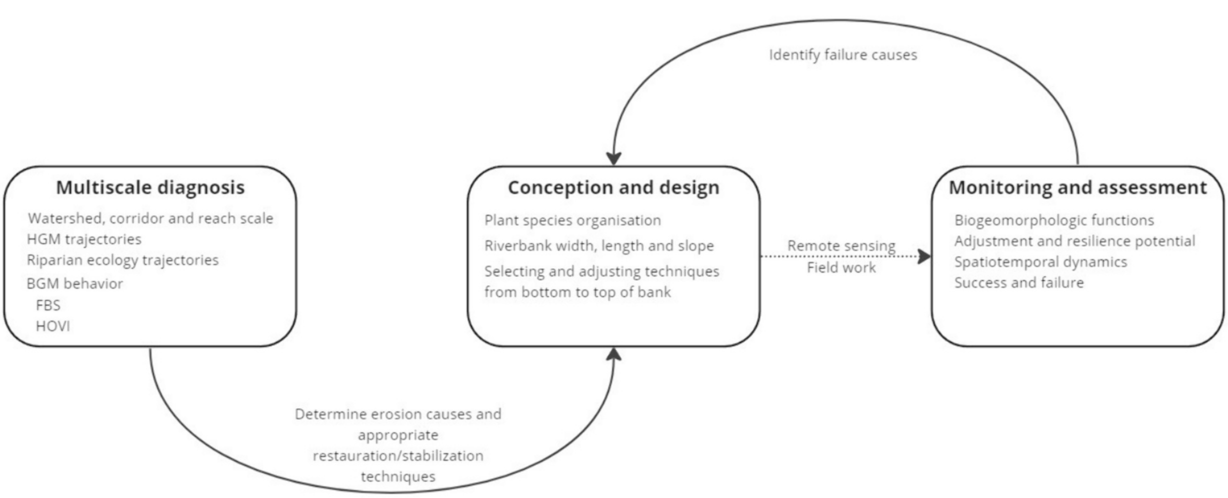

Fig. 3. Conceptual framework illustrating the biogeomorphological dynamics to be considered for the implementation of SWBE. On one hand, multiscale diagnosis is essential to assess the biogeomorphological behaviour of a river hydrosystem. On the other hand, insights created from SWBE structures monitoring can help determine the BGM functions of such structures and identify factors explaining its failure.

order to ensure appropriate protection and restoration measures, a first step would be to acknowledge the different types of erosion, such as river incision due to the increase in discharge or lowering of base level, lateral channel migration associated with natural meandering dynamics, or river widening due to sediment aggradation. Thus, a biogeomorphological diagnosis combining hydrogeomorphological, ecological (vegetation) and anthropogenic components at multiple spatial scales could not only contribute to our understanding of a river's behaviour, but also act as a tool to identify which site should be stabilized or restored. For instance, it may help to avoid potential future erosion by limiting channel incision or providing initial information for calculating scouring depths along SWBE structures. Determining in advance the reaches and riverbanks potentially subjected to a specific type of erosion, instead of reacting to erosion events, would improve the management strategies for erosion control.

Although we acknowledge that vegetation plays an important role in hydrosedimentary dynamics, it remains challenging to apprehend and accurately measure the extent to which it locally influences sediment transport and rate of deposition (Rey et al., 2019). The FBS and HOVI (Corenblit et al., 2007; Gurnell et al., 2016b) models can, however, be useful tools to qualitatively apprehend the biogeomorphological behaviours across multiple reaches and segments along a river's corridor. The former can be used to describe the most probable successional trajectories of vegetation and their associated impact on fluvial landforms stabilization and construction while the latter can provide insights about the spatial relationships between various types of habitats and hydrogeomorphological regimes (e.g., magnitude and frequency of flood, sediment budget, shear stress).

The FBS assessment can be used to (1) identify the development stage of biogeomorphological units; (2) describe potential changes in riparian vegetation composition (and function) related to channel changes; and (3) anticipate the development trajectories of fluvial landforms and their effects on fluvial processes. Corenblit et al. (2007) proposes a 4-phase model which encompasses the geomorphological phase (fluvial processes dominating with little to no vegetation), pioneer phase (pioneer vegetation establishment phase), biogeomorphological phase (presence of pioneer plants interacting with fluvial processes) and the ecological phase (presence of mature vegetation with little to no direct interactions with fluvial processes, at least during the ordinary floods). Characterizing a river corridor with the FBS phases enable researchers and practitioners to associate specific keystone engineer species or communities (groups of species) to each phase and assess their biogeomorphological functional status in the systems, whether they actively interact with flow and sediment or not, and to which magnitude. For example, Corenblit et al. (2009) shown on the Tech River, France, that each specific unit of vegetation has a specific functional role where (1) herbaceous units act as facilitating agents for shrubs and pioneer trees recruitment and establishment, (2) shrubs and pioneer trees act as ecosystem engineers on fluvial habitat and (3) post-pioneer trees act as a diversity reservoir (seeds and fragments) that can support post-disturbance ecological and landforms regeneration. For management and SWBE practices, it offers a framework that not only produces knowledge about biodiversity and ecological dynamics but also on the role and function of such dynamics onto the hydrogeomorphological features of the river. The progression of the FBS is not a linear process, e.g., moderate to high floods can either reset riparian habitat to the geomorphological phase (Garófano-Gómez et al., 2017; Han and Brierley, 2020) or participate to landforms construction such a bar accretion or floodplain aggradation (Corenblit et al., 2009, 2020b). Understanding and anticipating where and when gradual or abrupt geomorphological changes may occur along a river corridor, and in response to what flood magnitude and frequency and vegetation structure, can inform managers about the feasibility of stabilization or restoration techniques and better anticipate how the system should react depending on the selected solutions (e.g., SWBE, sediment or dead wood input, alluvial forest plantation).

Gurnell et al. (2016a, 2016b), with the HOVI, proposed a 5 functional zones classification representing different degree of connectivity to flood, groundwater and distance to channel, where each zone is described with a specific set of ecological (e.g., species assemblages) and geomorphological (e.g., sediment texture, topographic morphometrics) characteristics. The authors highlight the importance of fluvial styles and geological-topographical features conditioning the spatial and lateral distribution of the zones, with the identification of a critical zone corresponding to a zone where pioneer landforms formation can be initiated through interactions between vegetation and fluvial processes. As such, assessing the spatial distribution and dominance of certain functional zones can reflect the biogeomorphological behaviour of river reaches and guide managers to implement the best solutions according to the dominant processes.

3.2. Conception and design

Practitioners that work in riverbanks' restoration and stabilization through a bioengineering approach employs a wide range of diverse techniques and species. For instance, some of the most used techniques include brush layers, drain fascines, vegetated crib walls, brush mattresses and root wads (Evette et al., 2018; Karle et al., 2005; Rey et al., 2019), along with a combination of herbaceous, reed and shrub species (Cavaillé et al., 2015; Delage et al., 2019; Peeters et al., 2018). The type of structure and the choice of species used in SWBE to restore a degraded riverbank must be defined based on the environmental context (e.g., soil texture, humidity and acidity, light exposure, climate, topography, stakes to protect and available space) and the characteristics of the river (e.g., hydrological regime, suspended and bedload sediment flows, river morphology and behaviour, shear stress distributions) (Peeters et al., 2020). Classical approaches consider the assessment of hydrogeomorphological processes to choose the right type of SWBE structure (Evette et al., 2018) and plant ecology insights to choose species well adapted to local habitat conditions and to the hydrogeomorphological disturbances regime (Rauch et al., 2022). However, those two components (i.e., geomorphology and vegetation) are rarely taken intrinsically together by considering the bidirectional effects of vegetation on landforms and vice versa. We believe that adopting a biogeomorphological perspective, particularly at the riverbank scale, can improve decision-making regarding selection of species (or group of species) and SWBE designs by better understanding the relationship between plant functional traits, morphometric features of the riverbanks and the co-adjustments between the vegetation structure and the riverbank profile.

Functional trait-based analyses allow for studying the relationship between plant morphological, biomechanical, physiological, phenological, and life history response and effect traits and environmental factors (e.g., flooding, erosion, drought, etc.) (Corenblit et al., 2015; Diehl et al., 2017; Tabacchi et al., 2019; Viles and Coombes, 2022). This approach uncovers key traits that contribute to species' resistance and resilience to fluvial disturbances and participate to our global understanding of the reciprocal relationships between physical and biological processes that shape the fluvial landscapes. For instance, dense root systems and aerenchyma provide riparian vegetation with resistance to hydraulic forces and anoxic conditions (Bejarano et al., 2018), while biomass, stem height and flexibility control the intensity of biogeomorphological feedbacks (Bywater-Reyes et al., 2022). Merritt et al. (2010) suggest multiple approaches to identify the feedbacks between riparian vegetation and rivers, including characterizing vegetation at different levels (i.e., species populations, communities and functional groups), classifying communities into cover types, modelling spatial distribution, examining stand attributes, grouping species based on functional traits, and using structured and eco-geomorphic modelling to understand the dynamics of riparian ecosystems. Averaging functional traits at the community level allows analysis of plant structure and composition impact on hydrogeomorphological processes (Corenblit et al., 2015), e.g., correlations have been observed between the community's average height, occupied area or biovolume with sedimentation rates and fluvial morphology development (Corenblit et al., 2009; Bywater-Reyes et al., 2017). These tools allow the quantification of flow regimes required to support desired vegetation functions by establishing links between specific streamflow attributes and the riparian plant attributes, facilitating effective river management for desired vegetation outcomes (Merritt et al., 2010). Rey et al. (2019) suggest that both mono-specific or multiple species could be use in the conception of SWBE structures, that it depends on the objectives of the restoration projects, whether its primary goal is to protect a riverbank or restore a natural habitat. In that matter, quantification of response, effect and feedback traits related to individual species and group of species (i.e., communities) can be used to identify the biogeomorphological function of specific selected species or communities for SWBE. Biogeomorphological analysis of plant communities' functional traits can enlighten the role they play in shaping riverbank profiles and ultimately help managers for the right selection of species or functional guilds.

Biogeomorphological feedback processes should not be overlooked during the design phase of a SWBE restoration project as they foster biodiversity and increase resilience and resistance of riverbanks. Moderate but frequent disturbances shape communities through complex mechanisms that inhibit the establishment of strong competitive species, which results in highly diversified pioneer trees, shrubs, and herbs communities. According to the biogeomorphological framework, those diversified communities are found where the interactions between fluvial processes and vegetation are strong (Corenblit et al., 2009). The combination of inundations, scouring, burial, and interspecific interactions filters species to varying degrees based on their adaptation to diverse habitat conditions and various sources and types of disturbances, resulting in high specific richness (Gurnell et al., 2012). Thus, it makes sense to try and reproduce highly interactive zones when designing a SWBE structure. However, excessive sediment accumulation can have the opposite effect and inhibit the establishment of riparian species through burial stress and facilitation of terrestrial and competitive tree species establishment (Corenblit et al., 2020a; Stallins et al., 2010). To ensure the good development and survival of planted species, the right combination of riverbank morphometric (e.g., slope profile and height), textural characteristics and suitable soil bioengineering techniques and species must be selected.

Vegetation recruitment is conditioned by sediment texture, relative height to base flow, disturbances regime, and hydro-sedimentary dynamics; meanwhile, vegetation development and survival are contingent upon their connectivity to disturbances, a factor that is partially governed by the topographic features of the bank (Astrade and Dufour, 2010; Corenblit et al., 2020a). As classical SWBE techniques overcome the natural establishment by forcing the recruitment phase, a biogeomorphological approach could potentially be used to facilitate a natural recruitment through an efficient design of structures. In order to achieve such an approach, one must explicitly consider the relationship between morphometric and textural characteristics of the riverbank and vegetation ecological requirements. More importantly, those relationships must be placed in a specific context. Depending on the flood regime (magnitude, frequency and duration) and the local environment characteristic (e.g., valley confinement), variables such as the height above base-flow level and riverbank slope can vary and is of most importance for vegetation persistence.

The design effort must also consider the time it takes for a certain species or communities to become sufficiently rooted to stabilize sediments and increase cohesion (Rey et al., 2019; Leblois et al., 2022). At present, commonly used methods to indirectly help vegetation encroachment is the application of a biodegradable geotextile or coir mat to provide protection against surface erosion, giving vegetation time to develop its roots (Peeters et al., 2018; Leblois et al., 2022). In the biogeomorphological framework, the use of the Recruitment box model (sensu Mahoney and Rood, 1991, 1998) and WoO (window of opportunity sensu Balke et al., 2011) concepts can be applied to define the ideal geomorphological conditions for a successful recruitment and establishment of specific types of vegetation (Balke et al., 2011). The analysis of natural examples in a similar context of a designated SWBE project site (i.e., identical flood regime, sediment textural structure and species pool) where the WoO was successfully achieved could help managers identify the best suited riverbanks and vegetation characteristics to reproduce such successful natural models. By identifying and taking advantage of these spatiotemporal windows suitable for vegetation establishment, practitioners can increase the chances of successful vegetation establishment and improve the overall performance of SWBE projects. This approach can ensure that vegetation has the opportunity to develop strong root systems and provide long-term bank stabilization and habitat benefits.

If the window of opportunity can be completed, the vegetation enters the Biogeomorphological Feedback Window (BFW). In its simplest form, the BFW model represents the place and the period were and when feedbacks between fluvial processes and vegetation are occurring (Eichel et al., 2016; Hortobágyi et al., 2018). However, the use of this model goes further as it helps to describe in which conditions (both geomorphological and ecological) feedbacks are active and to identify thresholds delimiting when and where biogeomorphological feedbacks initiate and terminate (Eichel et al., 2016; Hortobágyi et al., 2018). In line with the application of the WoO, the BFW can be employed to replicate the optimal conditions that promote biogeomorphological feedbacks, thereby ensuring the longevity and adaptability of a geomorphological structure through self-sustaining abiotic-biotic feedback mechanisms, while potentially fostering biodiversity and riverbank resistance. Those approaches could help reconstitute natural habitats by considering not only the intrinsic ecological dynamics (e.g., survival, growth, competition, facilitation, resistance, resilience) but also the biogeomorphological functions actively participating in landforms construction, i.e., the SWBE nature-based development.

3.3. Monitoring, assessment, and maintenance

Monitoring of restored and stabilized riverbanks is a crucial component of SWBE practices (Peeters et al., 2018; Rey et al., 2019). It is through evaluation that managers can identify causes of failure and refine their techniques through iterative learning. In addition, monitoring serves as a management tool by establishing success indicators and maintenance requirements. The key benefits of using a biogeomorphological approach include the ability to (1) understand the biogeomorphological impacts of SWBE projects on rivers by assessing changes in river morphology, sediment dynamics and vegetation establishment; (2) define the co-adjustment dynamics in SWBE structures and the responses of such habitats to disturbances; and (3) identify key moments for maintenance actions by identifying critical periods where the habitat could shift.

Most impact studies of bioengineering have primarily examined plant biodiversity, fish habitat, and macroinvertebrate habitats, highlighting numerous ecosystem benefits such as increased habitat diversity and quality for various organisms (Bariteau et al., 2013; Cavaillé et al., 2015; Janssen et al., 2021; Martin et al., 2021; Schmitt et al., 2018; Symmank et al., 2020; Tisserant et al., 2021). Bioengineering outperforms civil engineering in ecological aspects, as it sustains longitudinal connectivity of riparian habitats and fosters ecosystems to simulate natural environments (Martin et al., 2021; Tisserant et al., 2021). However, there is a lack of research on its hydrogeomorphological effects, which are critical to understand the broader implications of SWBE on river systems. Bank erosion, a natural mechanism essential for maintaining geomorphological and ecological complexity and richness (Florsheim et al., 2008), requires careful consideration when implementing bank stabilization measures. Inhibiting erosion processes might potentially create a sediment budget deficit and eventually trigger the channel adjustment (e.g., channel incision) (Surian and Rinaldi, 2003). While SWBE effects of channel adjustment has not been profoundly explored, long-term monitoring of both sediment and vegetation dynamics in bioengineered reaches could assist in determining its biogeomorphological function. Understanding the mid- and long-term impacts by monitoring and assessing river reaches can determine what components (e.g., composition and structure of vegetation, extent of the restored site, type of SWBE techniques) should be enhanced to improve future management projects.

The success and effectiveness of bioengineering for bank stabilization rely on controlling successional processes to achieve a plant composition that enhances bank cohesion (Bischetti et al., 2021; Schmitt et al., 2018; Tisserant et al., 2020). Not all species provide strictly beneficial effects; some ligneous species have the potential to trigger instability to the bank because of considerable added weight or internal erosion increased by the preferential pathways of stems and roots (Leblois et al., 2022; Rood et al., 2007). To cope with such problematics and ensure persistence of SWBE over time, regular maintenance actions are necessary, such as controlled cuts to prevent undesirable species growth (Peeters et al., 2020; Rey et al., 2019). As successional trajectories are closely linked to feedback dynamics – where vegetation establishment and development are conditioned by the disturbance regime, connectivity to hydrosedimentary dynamics, and sedimentation rate (Bywater-Reyes et al., 2022; Corenblit et al., 2007; Corenblit et al., 2020a, 2020b) –, the assessment of those feedbacks in relation with vegetation composition and landforms construction could participate in defining critical moments where biogeomorphological changes are to be triggered. For example, empirical evidence has shown that trees have limited flexibility upon reaching a specific diameter threshold, consequently inducing turbulent water flow and exacerbating sediment erosion (Bonin et al., 2013). Those insights could then be applied by managers to schedule a maintenance calendar with a clearer view of the system's development.

Finally, another important problematic is to be considered in the SWBE management strategies: Invasive Exotic Species. Riparian habitats are areas prone to the introduction of exotic invasive species due to the hydrochorous capabilities of many invasive species (Tickner et al., 2001). Some species can be particularly harmful to fluvial systems, such as the Japanese knotweed (*Reynoutria japonica*), which significantly accelerates bank erosion processes by reducing sediment cohesion (Didier et al., 2023; Matte et al., 2022; Viles and Coombes, 2022). In contrast to civil engineering stabilization techniques, bioengineering is known to counter the introduction of invasive species due to the high plant diversity that increases competition for resources (Dommanget et al., 2015; Evette et al., 2021; Hoerbinger and Rauch, 2019; Martin et al., 2021). However, these techniques are not foolproof, as some exotic species have been observed in various bioengineering works (Evette et al., 2021; Tisserant et al., 2020). There is a need to enhance our understanding of the conditions that foster the introduction of exotic invasive species, and how these systems would respond to such introductions (O'Briain et al., 2023). If some exotic species exhibit morphological and physiological traits providing them a competitive edge over native species (Viles and Coombes, 2022), it becomes critical to foresee the implications of these functional traits on the stability of bioengineering structures. For example, Matte et al. (2022) have observed on the highly ice-disturbed Etchemin River, Québec, Canada, that riverbanks colonized by the exotic invasive species Japanese knotweed were dominated by this species and that such colonisation resulted in 92% to 290% increased erosion rate when compared to other riverbanks in the absence of Japanese knotweed. Matte (2020) also pinpoint the role of ice dynamics increasing the colonisation by Japanese knotweed through mechanisms of propagule transport and deposition. Aligned with the later, Colleran et al. (2020) synthesized the effects of Japanese knotweed on riverbanks through different study cases and suggests that (1) it exacerbates top-of-bank erosion following autumnal dieback when banks are exposed to floods and under-bank erosion by inhibiting native vegetation regeneration that normally provides strong root reinforcement, and (2) propagation of Japanese knotweed is fostered by erosive floods through the spread of propagules and its ability to vegetatively reproduce. The significant challenge posed by such species lies in the feedback loop they create, where their propagation boosts the erosion rate along a river corridor, which in turn facilitates their propagation.

4. Implications for cold rivers

In the case of cold rivers, very few guidelines exist on the application of soil bioengineering techniques in rivers subject to fluvioglacial processes (Tuthill, 2008). The marginal presence of these guidelines is, in part, due to the lack of knowledge about the interactions and feedbacks between vegetation, hydrogeomorphic dynamics and ice dynamics, which limits managers' ability to develop these techniques (Tisserant and Poulin, 2021). The following section highlights the most important gaps and propose how biogeomorphology can create knowledge to enhance SWBE practices in cold rivers.

4.1. Developing biogeomorphological behaviour knowledges of cold rivers

Ice dynamics strongly vary from river to river, from reach to reach and from one year to the other, due to differences in microclimate, riverbed morphology, vegetation cover, land-use and interannual meteorological variability (Beltaos and Burrell, 2021; Bergeron et al., 2011). For example, ice-jams will be fostered in certain reaches' settings, such as the presence of fluvial islands, the abrupt narrowing of the channel or the presence of bridges (De Munck et al., 2017). On its hand, anchor-ice formation is driven by a combination of factors, such as flow velocity, water depth and bed morphology, that condition water supercooling and creation of sticky frazil that can attach to the riverbed materials (Ettema and Kempema, 2012). Predicting the type of ice dynamics (ice runs, ice jams, thermal breakup, anchor ice) in a given reach is difficult due to an array of factors – such as water level, ice thickness, freeze-up condition, air condition and topography – that interacts together to initiate ice dynamics (Beltaos, 2003). Studies are needed to understand where and when certain ice forms are initiated, as well as their specific biogeomorphological impacts on river reaches. Understanding the biogeomorphological responses and plant regeneration capacities to different ice forms would provide a basic knowledge of the interactions between ice, vegetation and channel morphology and ultimately enlighten managers to select the appropriate solutions for riverbank stabilization or restoration techniques.

Relatively recent studies have begun to explore the role of ice on vegetation, such as Lind et al. (2014a, 2014b) who observed the inhibition of shrubs establishment in anchor-ice rich reaches due to flooding turning into riparian ice; or Uunila and Church (2014) and Boucher et al. (2009) who observed a strong ice-related control on riverbanks profile and vegetation rejuvenation in frequent ice-jams disturbed reaches. However, it appears that no studies have explored in more details the resiliency to ice disturbances of riparian communities nor the effects it has on riverbanks biogeomorphological functions. Determining the spatiotemporal dynamics of biogeomorphological landforms (i.e., landforms constructed through processes of biogeomorphological feedbacks) through different models such as the HOVI or the FBS would create a new understanding of the ice implications and could be used as a decision-making tool. For example, the magnitude of the effects related to each type of ice processes could be assessed and measured before and after disturbances, the recovery time could be determined and the biogeomorphological trajectories (e.g., vegetation species and succession, landform dynamics) in ice-driven fluvial corridors could be described.

Furthermore, we need to assess changes in these dynamics in the context of a changing climate (Capon et al., 2013; Death et al., 2015; Goudie, 2006). On the one hand, the global increase in temperatures could lead to a higher number of winter thaws, consequently increasing the frequency of mechanical breakups and ice jams, which in turn will intensify glacial abrasion processes (Lind et al., 2014a; Nilsson et al., 2013). This could not only increase the frequency of ice-related erosion, but also alters annual sediment budget and dynamics throughout an entire watershed. On the other hand, the reduction of summer precipitation could cause more severe low flows, thereby reducing the accessibility of riparian vegetation to water resources and increasing the hydric stress experienced by communities (Martínez-Fernández et al., 2018). The combination of mechanical disturbances caused by ice and physiological stress caused by drought could have significant consequences for the survival of riparian plants and potentially favour the development of new species. Predictions on the future state of cold region rivers is thus essential to understand how they will change and ultimately assess those changes for durable management practices.

Numerical models of interactions between geomorphological processes and riparian vegetation to assess biogeomorphological characteristics and predict river evolution are emerging. For example, the NUMRIP project (Garófano-Gómez et al., 2022) focuses on the association between functional traits of riparian vegetation, hydrogeomorphological processes, and fluvial geomorphology. This type of model can be particularly useful for predicting whether the impact of changes in the hydrological regime on the distribution of plant species, or the impact of changes in vegetation type on river morphology. Similarly, Martínez-Fernández et al. (2018) coupled a vegetation development model with a morphodynamic model to assess biogeomorphological changes in the context of climate change within the Mediterranean Curueño River. Their results allow for the prediction of changes in vegetation cover and hydrogeomorphological adjustments under different climate scenarios. These two models are examples of applications that can be used for river management in cold environments. Integrating ice dynamics into those types of models could provide further understanding both on the ongoing biogeomorphological behaviour of ice-driven rivers (by the assessment of past and present adjustment of vegetation and river's morphology) and future behavioural regime.

4.2. Defining suitable species and SWBE structure design for ice disturbances resistance

Apart from a few articles that describe the effects of ice erosion on riparian habitats patterns (Engström et al., 2011; Lind et al., 2014b; Rood et al., 2007; Uunila and Church, 2014; Vandermause et al., 2021), we have limited knowledge of the underlying mechanisms of resistance or vulnerability of different species subjected to ice constraints. Some groups of species have been identified as resistant to mechanical ice breakups due to their flexible stems that can be laid flat on the ground instead of being uprooted by ice, such as shrubby or juvenile willows (*Salix* spp.), poplars (*Populus* spp.*)*, alders (*Alnus* spp.), and dogwoods (*Cornus* spp.) (Poulin et al., 2019; Rood et al., 2007). Among those groups certain species have particular capacities to resist to the effect of ice erosion. In the last 5 to 10 years, particular interests have been put toward the sandbar willow (*Salix interior*) due to its high plasticity and regeneration potential (Keita et al., 2021; Randall, 2015). Studies suggest that the rapid root growth, high clonal propagation, and high resistance to intermittent flooding offer great opportunities for lower bank stabilization. In addition, it is worth noting that this species is well known for its resistance to ice abrasion in the Flore Laurentienne, a major botanical reference (Marie-Victorin Brouillet and Goulet, 1995).

Biogeomorphological studies at the individual, population and community levels focusing on the vegetation responses to various ice disturbances (e.g., breakups, abrasion, ice burns) could help to determine the relationship between the riverbank's morphology, vegetation, and ice dynamics. Going from functional trait-based approaches to the relationship analysis between biogeomorphological characteristics and ice disturbances, choices on the adequate species to use in SWBE projects and the riverbanks' shape, height, width, slope and grain size to implement could be enhanced. In cold environments, phenological traits have been linked to temperature, such as seed opening periods and dormancy periods that are synchronized with seasonal changes (Kozlowski and Pallardy, 2002), but traits responsible for resistance to mechanical ice constraints have been poorly explored (Poulin et al., 2019). Identifying and especially quantifying the key traits that provide resistance (or resilience) could be used to identify species adapted to a given context (Table 2). As previously mentioned, different types of vegetation are not similarly impacted by ice runs; for instance, mature and non-flexible trees can be more subjected to ice damage as they are unable to be bent. With this line of ideas, there's a need to consider the relationship between certain long-lived species life stages and the variation in their key functional traits such as regeneration capabilities or flexibility. Could a riverbank vulnerability increase with time, either by a decrease of flexibility for a given population or by successional processes introducing new ligneous post-pioneer species? Such questions must be addressed. Analysis of best suited species (either one species or a combination of species) for SWBE in ice-disturbed environment must not only consider plant species specific traits, but rather the relationship between a combination of individual and community key functional traits and its variance through time.

As mentioned in the section 3, the sole consideration of the choice of species for SWBE implementation isn't enough as plants' survival and resiliency are directly correlated to the riverbanks' textural and topographic characteristics that control exposition to disturbances. For example, Rood et al. (2007) and Uunila and Church (2014) have observed that in reaches experiencing an ice-jam event, the erosional patterns were not homogenous; even though the established communities' composition were identical, some riverbank sections presented a total destruction of habitat while others were undisturbed. Thus, the explanation of vegetation's resistance or vulnerability to ice dynamics and its capacity to regenerate after destruction is a function of multiple environmental factors, not merely a characteristic intrinsic to the species itself. That vulnerability could potentially be explained by the intensity of local ice abrasion (size, speed, and impact angle of ice blocks), geomorphic structure (e.g., sediment cohesion, topographic profile) and

Table 2
Key functional traits promoting resistance and resilience to ice disturbances, adapted from Catford and Jansson (2014).

Trait	Function	References
High flexibility	Ability to bend and resist strong mechanical stresses and create a carpet effect to protect against erosion	Catford and Jansson (2014); Clark and Hellin (1996); Gray and Sotir (1996)
Deep/Wide root systems	Resistance to drag forces from floods and ice	Catford and Jansson (2014); Capon and Pettit (2018) Karrenberg et al. (2002); Stromberg and Merritt (2016)
Low shoot/root ratio	Increases soil cohesion and resistance to drought	Catford and Jansson (2014); Clark and Hellin (1996); Gray and Sotir (1996)
Fast growing root and root mat formation	Stabilize sediment and offer resistance through a fibrous carpet effect	Clark and Hellin (1996); Gray and Sotir (1996); Schiechtl and Stern (1996)
Lateral spread	Recolonization time decreased in disturbed patches	Catford and Jansson (2014); Xiong et al. (2001)
Persistent seed bank	Better chances for viable seeds to germinate after habitat reset	Catford and Jansson (2014); Xiong et al. (2001)
Vegetative reproduction	Fast recolonization after disturbance	Catford and Jansson (2014); Engström et al. (2011); Rood et al. (2007)
High growth rate	Enhanced capacity to take advantage of favourable environmental conditions, which might be temporary	Catford and Jansson (2014); Karrenberg et al. (2002); Mahoney and Rood (1998)
Early reproduction	Enhance the chances of reproduction and population growth when environmental conditions are favourable.	Catford and Jansson (2014); Pettit and Froend (2001)

ecological variables (e.g., species type, density, distribution, life stage). Cold environment rivers, however, add a layer of complexity for considering environmental factors: it is necessary to consider the type of fluvioglacial disturbances (e.g., ice abrasion, ice jam, anchor ice and riparian ice), their magnitude, and their frequency of occurrences (Karle, 2007; Tuthill, 2008). With a full consideration of bio-geomorphological development of such habitat, future empirical and experimental studies are needed to understand how riparian stands are developing and reacting to a specific type of ice disturbance, as the responses and effects of vegetation are closely linked with the channel morphology development through time and space (Fig. 4). This should be done both in natural habitats so that we can reproduce resistant and resilient configuration, and in SWBE structures so that we can identify failure causes and enhance our strategies through trial and errors.

We must pinpoint that those thoughts consider the ecological and morphological aspects of restored riverbanks. However, for SWBE structures to be effective, the right type of bioengineering technique (e.g., fascines, brush mattress or brush layers) must be chosen according to its resistance to a specific hazard context and intensity. This aspect is not discussed in this paper but must be considered with particular interest as it is one of the principal components that enable SWBE structures to be resistant until the vegetation acts as the dominant protective feature (Schiechtl, 1997). In cold environments, little studies have been made to compare the existing structure and their resistance to ice abrasion. Studies involving biogeomorphological framework with engineering expertise must be put together for efficient implementation of SWBE in cold rivers.

4.3. Monitoring of SWBE biogeomorphological responses to ice dynamics

Long-term monitoring and assessment of biogeomorphological features in cold rivers could not only benefit our understanding of SWBE function in rivers' reaches in general but also enlighten managers on how bioengineering structures specifically respond to ice disturbances. As mentioned in the section 2, ice runs and ice-jams have the potential to denude riparian habitats and reset succession (Uunila and Church, 2014; Vandermause et al., 2021). Examples from nature showed us that habitats denuded from major floods can recover their vegetation cover through seed bank and/or root systems maintained into the riverbank's sediments (O'Donnell et al., 2015; Reid and Church, 2015). Same applies for some willow species (such as *Salix interior*) uprooted by ice-jam events, for which they were able to quickly resprout from root suckering after the disturbance (Rood et al., 2007; Uunila and Church, 2014). However, how is the recovery potential of artificialized bioengineered banks? Can a vegetation turnover caused by an important disturbance recover its riparian structure quickly enough to maintain its protective feature? Insights from SWBE responses to ice disturbances could benefit managers in understanding biogeomorphic dynamics of such habitats and eventually promote actions in harmony with these Nature-Based Solutions (Moreau et al., 2022; Preti et al., 2022). On one hand, monitoring of biogeomorphological effects of SWBE on ice-driven river reaches would foster knowledge about resistance and resilience capacities of different techniques and potentially help in identifying failure causes in different hydrogeomorphological contexts. On the other hand, it would benefit maintenance strategies on what kind of actions can be made to ensure durability and effectiveness according to the fluvial context.

A multifaceted monitoring strategy needs to be implemented in restored river reaches to efficiently assess the biogeomorphological behaviour and understand the recovery potential of SWBE structures. This strategy should encompass the analysis of ice regimes and their interactions with geomorphology and vegetation dynamics. To accurately measure ice-related parameters, it is recommended to deploy sensors locally to monitor water temperature, ice thickness, and water level. These instruments can facilitate the assessment of conditions preceding ice breakup events and the subsequent hydrological responses (Turcotte et al., 2011). Such data collection can enhance our understanding of these events, improve the predictability of severe occurrences, and contribute to a dataset on ice parameters. To assess bigoeomorphological characteristics, the use of Unmanned Aerial Vehicles (UAVs) offers a practical approach because annual photogrammetric survey can easily be conducted (Corenblit et al., 2016; Vautier et al., 2016). Hortobágyi et al. (2017) advanced a multi-scale approach using this technique and were able to generate dense three-dimensional point clouds, offering insights into geomorphological features (e.g., length, width, height and sediment volume) and vegetation

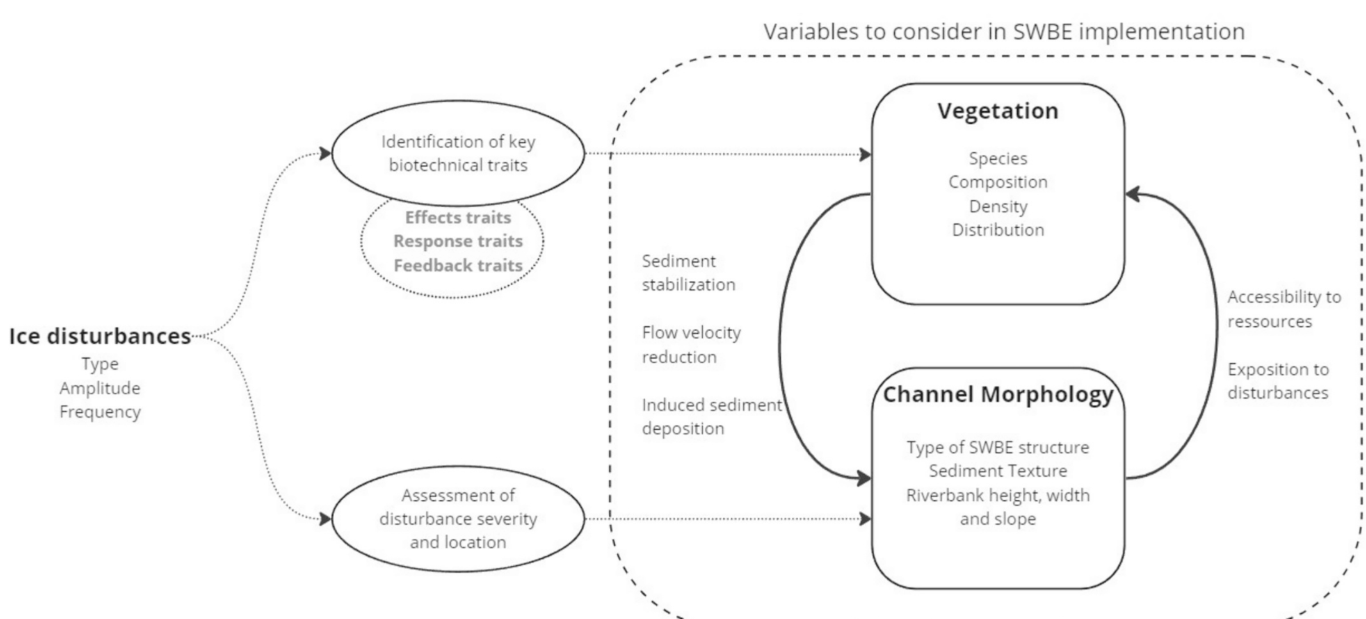

Fig. 4. Conceptual diagram of the consideration of fluvioglacial disturbances in the development of SWBE structures in a biogeomorphological perspective and presentation of the interactions between vegetation variables and morphological characteristic. Represents all the variables that must be considered for the design of SWBE.

characteristics (height, density, biovolume, patch richness and diversity) at the microsite, bar and corridor scale. If iterated annually, this technique can provide insightful information about co-adjustment dynamics between a riverbank's morphology and its vegetation.

Integrating these two techniques would at first enable practitioners and researchers to assess vegetation responses and effects to various types of ice disturbances. Furthermore, long-term monitoring could help in evaluating the resilience potential following severe events that have destroyed habitats, by examining which species naturally recolonizes first, evaluate their growth rates, and assess their capacity of restructuring riverbanks through natural biogeomorphological feedbacks. A detailed understanding of these temporal interaction dynamics between riverbank morphology, plant communities, and ice disturbances would provide a new knowledge base to develop innovative approaches for riverbank restoration and stabilization techniques that align with nature-based solutions. For instance, if the geomorphological and biological state of a resilient bank is identified, design efforts could then leverage this knowledge to develop resilient bank designs that can passively and naturally recover their vegetation, thus maintaining their protective function despite events that damage plant communities. Such an approach must necessarily come with a risk acceptance component (Moreau et al., 2022) but would allow for the maintenance of dynamic habitats along with all the associated ecosystem services.

5. Conclusion

Soil and water bioengineering (SWBE) techniques in cold environments is a realistic alternative to civil engineering for stabilizing riverbanks that require it. This management technique is all the more essential in the Anthropocene era in order to balance civil security needs and the environmental quality of riparian and river habitats as it provides many ecological services and share similar objectives targeted by nature-based solutions. However, the lack of applications and fundamental research on the durability and effectiveness of SWBE in environments disturbed by fluvioglacial processes seems to discourage managers from applying these techniques. Furthermore, it is worth noting that civil engineering and SWBE do not have to be in opposition and can be employed together for effective protection. In that scenario, vegetation encroachment allows ripraps to be strengthened by the root systems linking rocks together and the aerial systems reducing flow velocity and shear stress (Schiechtl, 1997).

This review article, based upon prior research and reviews concerning SWBE management, ice disturbance effects on riverbanks and biogeomorphological dynamics, presents insights that biogeomorphology can bring to SWBE techniques in cold environments. It introduces a new synthesis merging these distinct components into an integrated approach to the development and monitoring of riverbank restoration and stabilization practices. Approaching fluvioglacial systems with an emphasis on feedback and co-adjustment processes between vegetation, hydrosedimentary processes, and fluvioglacial dynamics would inform managers about design choices, monitoring, and management strategies. It is crucial to develop knowledge on the biogeomorphological functions and processes of fluvioglacial environments, both in natural and restored settings. Analyzing the biogeomorphological functions of SWBE and its interactions with fluvioglacial dynamics would help identify causes of failure and better evaluate its benefits. However, very little progress has been made so far, and it is essential to address numerous questions to improve this management (Table 3). Interdisciplinary research is essential to answer these questions. Practitioners in the field of river management must actively conduct collaborative work with researchers in the fields of riparian ecology and hydrogeomorphology to better assess the complex interactions involved in cold rivers restoration. It is by an iterative process of restoration project and study cases that knowledge will be fostered, and techniques will be enhanced. Furthermore, a biogeomorphological approach would encourage the development of new nature-based solutions focused on the creation of naturally resilient system instead of purely resistant-oriented approaches, while maintaining floods and erosion risk mitigation.

Table 3
Research questions presented for research areas in need of knowledge creation.

Research areas	Research questions
Vegetation and ice interactions	What functional traits promote plant resilience and resistance against glacial abrasion? How the life stage of a species influences its vulnerability to ice? How vegetation has effects on fluvioglacial dynamics?
Co-adjustment and biogeomorphic feedbacks	In fluvioglacial environments, does vegetation actively participate in the construction of fluvial morphologies? Under what morphometric characteristics (height, slope, width) of the bank is vegetation most vulnerable to glacial disturbances? How does vegetation evolve, and how do the intensity of biogeomorphological interactions vary in time and space under different glacial constraints? What are the successional trajectories and the intensity of associated biogeomorphological feedbacks? What is the response of biogeomorphological units to fluvial constraints? Is recovery rapid?
Biogeomorphological functions of SWBE techniques	Does SWBE significantly affect the biogeomorphological behaviour of hydrosystems at various spatiotemporal scales? If yes, to what extent? Does SWBE in cold environments can significantly contribute to ecological services? How resilient are SWBE structures against changes in vegetation cover (e.g., global change or alien species introduction) or environmental changes (e.g., increased/decreased ice dynamics or drought)?
SBWE techniques and strategies	What are the best-adapted designs for sustainability in a fluvioglacial system (bank stabilization structure, high-bank morphological structure, and vegetation structure/composition)?
SBWE biogeomorphological monitoring and assessment	How do biogeomorphological processes evolve within vegetation engineering structures over time and space under ice pressure? Can key moments for maintenance be identified based on ecological and geomorphological characteristics? What quality indices are best suited to characterize the durability and benefits of SWBE?

To promote the use of nature-based solutions and change the "predict and control" management paradigm to an "adaptive" paradigm based on natural processes, it is essential to establish sustained communication between science and managers (Moreau et al., 2022). One of the main drivers for generating this change comes from the creation and sharing of knowledge. While SWBE in fluvial systems is already an interdisciplinary discipline combining ecology, engineering and hydrogeomorphology, the insights from biogeomorphology can largely contribute to enhancing sustainable implementation of SWBE in strong physical constraints environments. A shift toward soil and water bioengineering as a NbS restoration practice is all the more relevant in an era where climate change and increased human pressure apply significant environmental constraints.

CRediT authorship contribution statement

Matthieu Prugne: Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Dov Corenblit:** Writing – review & editing. **Maxime Boivin:** Writing – review & editing. **André Evette:** Writing – review & editing. **Thomas Buffin-Bélanger:** Writing –

review & editing.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used GPT4 from Open AI in order to translate the original text (French) to English. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

None.

Data availability

No data was used for the research described in the article.

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