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Herbaceous angiosperms, pteridophytes and shrubs cocktail for rapid ground cover for soil and water bioengineering in the Caribbean

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ABSTRACT

Among the Nature-based Solutions currently spreading worldwide, soil and water bioengineering techniques, are used to stabilize hill slopes, earth embankment, and riverbanks. They consist in the use of living plants, sometimes coupled with dead materials, to control erosion and restore ecosystems.

These approaches remain to be adapted to Neotropics and particularly to the Caribbean Islands biodiversity hotspot. The success of soil and water bioengineering designs depends on the selection of suitable native plant species and considering the hydrodynamic and geotechnical processes. In the Caribbean, data are available concerning woody species but are still lacking for the other constitutive components of riparian plant communities. The objective of this study was to identify the riparian forest understory species best suited for use in SWBE at their establishment phase. In a three-month ex situ experiment, we measured the survival rate, biomass production and root growth of propagules (cuttings and bulbils) of eleven native Caribbean species (5 herbs, 4 pteridophytes, 2 shrubs) occurring naturally in a variety of riparian environments. All the herb and shrub species studied displayed growth vigour adequate for a successful inclusion in soil and water bioengineering techniques. Among herbs, *Commelina diffusa, Hymenachne amplexicaulis* and *Sphagneticola trilobata* performed the best. *Gynerium sagittatum* and *Dieffenbachia seguine*, despite their slower growth and root development, remain suitable. Regarding the two shrubs, *Ludwigia octovalvis* gave better results than *Clidemia hirta*. Among the pteridophytes, *Adiantum latifolium, Thelypteris reticulata* and particularly *Lycopodium cernuum* appeared poorly suited to soil and water bioengineering. *Acrostichum danaeifolium* was the best-performing pteridophyte. These first experimental results focusing on the propagation and establishment of native herbs, pteridophytes and shrubs, allowed to identify a diversity of species of interest as cuttings for soil and water bioengineering and practical clues for their use in the Neotropics.

1. Introduction

Riparian ecosystems are considered as global hotspots for ecological restoration as they harbour a disproportionate diversity and provide numerous ecological functions relative to their reduced surface area (Capon and Pettit, 2018; Tockner and Stanford, 2002). For decades, riparian zones have been extensively altered by urbanisation, agricultural expansion and industrial uses (Feld et al., 2011; Nilsson et al., 2005).

The Caribbean Island biodiversity hotspot (Kobayashi et al., 2019), encompasses a high ecosystemic and specific diversity. In the Lesser Antilles, Guadeloupe is home to 1706 native vascular species distributed among 32 different ecosystems (Fournet, 2002; Rousteau et al., 1996). These very rich and complex communities influence the riparian forest assemblages along the streams that flow through all these ecosystems (Gayot et al., 2018). Land development, stream management and biological invasions resulting from the increasing anthropogenic pressure have severely degraded the riparian ecosystems of this small archipelago (Gayot et al., 2018; IGN, 2015). In areas where human interests must be protected, soil erosion control and riverbank stability improvement still mostly rely on conventional techniques based on mineral materials. These riprap and concrete civil engineering structures are mechanically efficient but decrease species diversity and associated ecological

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functions, change the natural conditions of riverbanks, cause the degradation of the aquatic environment and disrupt the natural succession of the riparian ecosystem (Cavaillé et al., 2015; Dudgeon et al., 2006; Janssen et al., 2019). To reduce negative ecological impacts of conventional civil engineering structures, Soil and water bioengineering (SWBE) approaches are cost-effective, resilient, and sustainable alternatives for enhancing riverbank stability and managing erosion problems on slopes. SWBE is a Nature-based Solution (Preti et al., 2022; Rauch et al., 2022; Weissteiner et al., 2019) and as such promotes nature as a solution to climate mitigation and adaptation (Cohen-Shacham et al., 2016; Nesshöver et al., 2017).

SWBE uses plants and/or plant parts (e.g. roots, stems, seeds) as live building materials, alone or in combination with inert materials such as rocks, wood, metal, or geotextile (Bischetti et al., 2014; Clark and Hellin, 1996; Diaz, 2001; Schiechtl, 1980; Zhang et al., 2019). Plants reinforce in a better way the banks with the development of their aerial and root parts (Gayathiri et al., 2022; Leblois et al., 2022; Pollen, 2007).

The success of SWBE projects depends beside understanding and taking into account the most relevant engineering processes on the selection of the adequate plant species (De Baets et al., 2009; Ghestem et al., 2014; Stokes, 2006). Native and site-specific plants adapted to the local ecological conditions are recommended for the successful development of a plant cover without introducing potentially invasive alien species (Krautzer and Hacker, 2006). Other desirable traits for SWBE are easy vegetative propagation, high survival, fast root development, resistance and resilience to disturbance, and stem flexibility (Stokes and Atger 2009; Gray and Sotir, 1996; Schiechtl et al., 1997).

Plant establishment represents a critical period for slope stabilization (Stokes et al., 2014; Sidle and Bogaard, 2016). The quick development of plant is of primary importance to avoid erosion, to develop a fast surface cover, which reduce the speed of runoff and catch the debris, thereby armouring the surface quickly just after the implementation of a SWBE project. The use of fast-growing ground-covering low plants such as herbaceous species rapidly stabilises the soil. Planting a mix of trees, shrubs, grasses and macrophytes in the stream bed, on the banks and along the stream margins is also an important aspect of managing the riparian zone to improve riverbank stability. A diversity of root system shapes is believed to be more effective for reinforcing the substrate (Stokes et al., 2009) and improving soil aggregate stability (Pohl et al., 2009). Trees, understory species, ground-cover species and macrophytes complement each other spatially and functionally in protecting the river bank. Trees are deep-rooted species more capable of reinforcing riverbanks against mass failure than shallow-rooted ground-cover plants. Understory and ground-cover species provide mid- and upper-bank sections with greater protection from scour. Lower bank sections that tend to remain under water throughout the year are best protected by macrophyte species where they can be established (Abernethy and Rutherfurd, 1999; Schiechtl et al. 1996). All structural groups interact with and modify subaerial processes. By consuming water, plants accentuate desiccation cracks, thus increasing the permeability and volume available for infiltration (Clark et Hellin 1996, Gray et Sotir 1996, Díaz 2001). Smaller plants complement the protection provided by tree leaves and could contribute to limit the effects of rainsplash or rill erosion (Abernethy and Rutherfurd, 1999; De Baets et al., 2006; Diaz, 2001;). Increasing the species diversity also enhances site resilience to disturbance (drought, herbivory, flooding …) because the coexistence of many species improves the chances that some species will continue to play their part even if others fail (Yachi and Loreau, 1999).

In the last decades, several SWBE experiments have been conducted in the Neotropics, highlighting the suitability of native woody and semi-woody species for slope stabilization (Hostettler et al., 2019; Maxwald et al., 2020; Mira et al., 2021, 2022a, 2022b; Petrone and Preti, 2008, 2013). However, few studies considered riparian banks or involved understory plant species, and further investigations are therefore needed concerning these overlooked components of the riparian flora. In the Caribbean, macrophytes, herbs, shrubs and pteridophytes all contribute to the understory structuration of riparian ecosystems and develop to form a ground cover (Gayot 2016).

Herbaceous plants are non-ligneous species that form dense ground coverage with a shallow root system. Their root systems are usually more diffuse or fibrous than those of woody plants (Stokes et al., 2009). Compared with roots of woody species, fibrous roots possess a greater number of thin roots, resulting in a higher root area ratio, while tensile root strength is comparable (Mattia et al., 2005; De Baets et al. 2008; Loades et al., 2013). Herbaceous species are recommended in erosion control measures because their short life cycle and fast development allow them to quickly cover the ground and prevent the superficial soil erosion that can occur before the development of the ligneous species (Diaz, 2001; Comino et al., 2010; Gayathiri et al., 2022; Zhu and Zhang, 2016).

Pteridophytes are a highly diverse group well represented in Caribbean riparian ecosystems (Gayot et al., 2018). Of the 33 families reported from tropical America, 28 are represented, totalling 292 species, in Guadeloupe, a territory >11,000 times smaller (Mickel, 1983; Christenhusz, 2009). A number of species can develop a creeping trellis of rhizomes and roots at the soil surface (Proctor, 1977; Christenhusz, 2009). Their flexible fronds can create a carpet effect protecting the surface layer of the soil from erosion during floods. Some pioneer species, such as *Gleichenella pectinata* or *Lycopodium cernuum*, are particularly efficient for the fast colonisation of lateritic areas.

Riparian shrubs (semi-ligneous species <2 m high, with multiple basitone stems) are also very valuable in a SWBE perspective (Clark and Hellin, 1996; Diaz, 2001). The presence of multiple flexible stems increases bank roughness, potentially protects the substrate by carpet effect, and prevents strong turbulent flows that can lead to the destruction of the work site (Evette et al., 2018).

Macrophytes are defined as 'the macroscopic forms of aquatic vegetation' Wetzel (2001). They are shallow-rooted species that grow at the margin of the mean water level. They colonise waterlogged areas where terrestrial plants cannot establish. They flourish in conditions of low water velocity (about 0.2 m/s) but will withstand short periods of flooding and high velocity, when the stream is in flood (Abernethy and Rutherfurd, 1999). Macrophytes slow down flow velocity near the bank and their shallow root mat contribute to reinforce the bank surface (Frankenberg et al., 1996). Because macrophytes are important at the bank toe for controlling sub-aerial erosion and scour, SWBE techniques such as macrophyte fascines have been developed and are now widely used around the world (Abernethy and Rutherfurd, 1999; Diaz, 2001; Zeh, 2007). In tropical areas, macrophytes can be trees, shrubs, herbs or pteridophytes.

In the Neotropics, the few available recommendations regarding the use of low plants in SWBE mostly focus on exotic herb species such as *Chrysopogon zizanoides* or *Arachis pintoi* (Clark and Hellin, 1996; Diaz, 2001). Identifying suitable native herbs, pteridophytes and shrubs is necessary to enrich the pool of species that can be used in SWBE to control riverbank erosion in the Caribbean.

Data on vegetative propagation, growth vigour and biotechnical traits are currently lacking for natives species of herbs, pteridophytes and shrubs, whether terrestrial or macrophytic, constraining their integration in SWBE. Herbs are generally used as seedlings to cover the soil quickly after implementation of the SWBE work to protect it against erosion. In Guadeloupe there is no native seed production chain and herbs have to be used in the form of cuttings. Pteridophytes are not usually used in SWBE, but there is a large species diversity in the Caribbean and some can develop as pioneer plant species on eroded slopes, therefore knowing their potential for SWBE to cover the soil and diversify species, especially as cuttings, is of particular interest. Shrubs are widely used in SWBE worldwide, and their living branches can contribute to the stabilization of the bank toe and the slopes, through their implementation in the form of fascines, cuttings, brush mattresses or brush layers.

The objective of this study was to identify the riparian forest understory species best suited for use in SWBE. In order to find out how to use herbs, pteridophytes and shrub cuttings for riverbank stabilization biotechnical traits known to be relevant for SWBE, survival, growth and root system structure, were assessed on 11 species of terrestrial and macrophytic pteridophytes, herbs and shrubs in a three-month ex situ experiment.

2. Material and methods

2.1. Species selection and cutting collection

Eleven native riparian species of low stature (4 pteridophytes, 5 herbs and 2 shrubs, including macrophytic species) were selected according to their ecology, ecological status (early successional), and resistance to disturbance, and because they display interesting properties for SWBE, such as fast growth and covering rate and general availability for providing material in sufficiently large amounts. In accordance with the broad types of environment that occur in Guadeloupe (Rousteau et al., 1996), species displayed different ecological ranges (Table 1). Data on species biogeography were extracted from the literature (Fournet, 2002). Beyond their distribution in the Caribbean islands, the selected species are distributed in all the neotropics. Plant material was collected during the rainy season between November 2020 and January 2021, a period consistent with SWBE project implementations (Diaz et al. 2001). The collection sites were located on the Basse-Terre island of the Guadeloupe archipelago, at elevations ranging from 5 to 320 m a.s.l (Supplementary Material, Fig. S1). This elevational segment corresponds to highly anthropised areas, where SWBE projects are the most likely. For each species, a total of 10 to 16 healthy mature individuals (sporophytes in the case of pteridophytes) per species were selected from 4 distinct natural populations.

In the case of pteridophytes, because of differences in availability, architecture and particular structures dedicated to asexual propagation, the type of material collected and the way it was used varied from one species to the next (Table 2). For *Adiantum latifolium,* sections of rhizome were used as cuttings and the major part of the fronds were removed to limit transpiration and avoid death by desiccation. For *Lycopodium cernuum,* sporophyte stem segments with microphylls and rhizome were prepared, whereas young sporophytes were collected for *Acrostichum danaeifolium,* and vegetative bulbils from segments of rachis for *Thelypteris reticulata.* Leaves on cuttings of herbs and shrubs were removed

Table 2
Plant material collected and planting procedure for each species in study.

Species	Type of plant material	Characteristics of planted material	Planting procedure
Pteridophytes			
Acrostichum danaeifolium Langsd. & Fisch.	Small individuals	Length <10 cm	Roots were buried
Adiantum latifolium Lam.	Cuttings	10 cm rhizome with one pinna of one frond left	All the rhizome segments were buried
Lycopodium cernuum L.	Cuttings	10 cm erect stem with microphylls and basal roots	The basal extremity of the stem, with its roots, was buried
Thelypteris reticulata (L.) Proctor	Vegetative bulbils	A pair of basal bulbils	The section of stem supporting the bulbils was buried
Herbs			
Commelina diffusa Burm.f.	Stem cuttings	6 nodes, 19–37 cm in length, with 2 apical leaves left	The stem was buried up to the apical leaved node
Dieffenbachia seguine (Jacq.) Schott	Stem cuttings	length 31–74 cm, leaves removed	2/3 of the stem was buried
Gynerium sagittatum (Aubl.) P.Beauv.	Stem cuttings	6–18 nodes, length 39–84 cm, leaves removed	2/3 of the stem was buried
Hymenachne amplexicaulis (Rudge) Nees	Stem cuttings	length 49–82 cm, leaves removed	2/3 of the stem was buried
Sphagneticola trilobata (L.) Pruski	Stem cuttings	length 9–26 cm, with 2 apical leaves left	The stem was buried up to the apical leaved node
Shrubs			
Clidemia hirta (L.) D. Don	Stem cuttings	length 48–72 cm, leaves removed	2/3 of the stem was buried
Ludwigia octovalvis (Jacq.) P.H. Raven	Stem cuttings	length 42–72 cm, leaves removed	2/3 of the stem was buried

Table 1
Studied species, specifying for each one its family, maximum height at adult stage, ecological type, and distribution range following Fournet (2002).

Species	Maximum height (m)	Coastal forest	Dry forest	Seasonal evergreen forest	Rainforest	Macrophyte	Biogeography
Pteridophytes							
Acrostichum danaeifolium Langsd. & Fisch.	3	x				x	Lesser Antilles, Greater Antilles, Central America, South America
Adiantum latifolium Lam.	0.5			x			Lesser Antilles, Greater Antilles, Central America, South America
Lycopodium cernuum L.	0.2			x	x		Lesser Antilles, Greater Antilles, Central America, South America, North America, Asia, Africa
Thelypteris reticulata (L.) Proctor	1.5			x	x		Lesser Antilles, Greater Antilles, Trinidad, Central America, South America, Florida
Herbs							
Commelina diffusa Burm.f.	0.2	x	x	x	x		Lesser Antilles, Greater Antilles, Central America, South America, North America
Dieffenbachia seguine (Jacq.) Schott	1.5	x	x	x		x	Lesser Antilles, Greater Antilles, Central America, South America, North America
Gynerium sagittatum (Aubl.) P.Beauv.	3			x		x	Lesser Antilles, Greater Antilles, Central America, South America, North America
Hymenachne amplexicaulis (Rudge) Nees	1.5			x		x	Lesser Antilles, Greater Antilles, Trinidad, Central America, South America, North America, Asia, Africa
Sphagneticola trilobata (L.) Pruski	0.3		x	x			Lesser Antilles, Greater Antilles, Trinidad, Central America, South America, North America
Shrubs							
Clidemia hirta (L.) D. Don	1			x	x		Lesser Antilles, Greater Antilles, Trinidad, Central America, South America,
Ludwigia octovalvis (Jacq.) P.H.Raven	1			x		x	Lesser Antilles, Greater Antilles, Trinidad, Central America, South America, North America, Asia, Africa

except for *Sphagneticola trilobata* and *Commelina diffusa,* for which a previous test had shown the failure of stem cuttings planted without leaves.

One unit of propagation (one rhizome or stem segment, or one pair of bulbils) was collected on each individual, totalling 159 propagules, all species combined. Plant material was wrapped in wet paper and slipped inside a sealed black plastic bag at ambient temperature. Plantation occurred within the next 24 h.

2.2. Experimental conditions

The experiments were conducted outdoors, at the experimental INRAE station of Duclos, Guadeloupe FWI (16°12′11.02″N; 61°39′33.78″W; 99 m a.s.l.) in November 2020 toApril 2021. Climatic data were obtained at the Meteo France station located on the experimental station.

Temperature, relative humidity and daily light integral varied respectively between 23 and 24 °C, 82 and 86% (mean: 83%), and 1431 and 2018 J.cm^{-2} day^{-1} (mean: 1745 J. cm^{-2} day^{-1}) (see Table 3 for climatic conditions).

The propagules of the light-sensitive species (*Adiantum latifolium*, *Thelypteris reticulata* and *Dieffenbachia seguine*) were protected from light stress under a shade house with 60% light reduction. The other, heliophilous, species were placed in full sunlight. Propagules were planted randomly, each in its own 25 L pot, mixing the species. The experimental soil was a mixture of pozzolana and top layer of agricultural ferralsol (v:v 3/4:1/4) to simulate poor alluvial soil. The grain size analysis of the mineral fraction revealed a very porous soil with 75% gravel, 10% sand, and 15% clay. The pH was 7.4 and the percentage of total organic matter 0.85%. Irrigation to field capacity with a daily drip irrigation system maintained a favourable water balance throughout the experiment. Mechanical control of weeds was conducted every week throughout the experimental period.

2.3. Survival, growth and traits

The biotechnical traits studied were chosen for their importance for SWBE purposes (Stokes et al., 2009). Three months after plantation, corresponding to the critical establishment phase where a quick development of plant cover is required, survival rates (percentage of propagules still alive, i.e. with developed, turgid leaves) were recorded for each species. For the species with a survival rate above 60%, 10 to 12 healthy propagules were selected to be uprooted. For the species with a survival rate below 60%, all the surviving propagules were uprooted (from 5 to 8). They were carefully removed from the substrate and roots were cleaned with water. A quick estimate of root diameter was obtained by averaging the values measured on the five thickest roots at their point of emergence on the cutting. Maximum root length was measured on every cutting. Shoots (new leaves and new stems) and new roots were separated. Roots and shoots were then dried at 80 °C for 72 h and weighed to measure newly-produced aboveground (leaf + stem ramifications) and belowground (root) biomass (Perez-Harguindeguy et al., 2013). Root to shoot ratio was calculated as the ratio of belowground biomass to aboveground biomass.

Table 3
climatic conditions during the experiment (Meteo France, Duclos station).

	Mean daily light integral (J.cm-2 day-1)	Precipitation (mm)	Mean temperature (°C)	Mean relative humidity (%)
November 2020	1431	419	24	86
December 2020	1610	142	23	83
January 2021	1584	92	23	83
February 2021	1810	254	23	82
March 2021	2017	151	23	82
April 2021	2018	70	24	83

2.4. Statistical analysis

Statistical analyses were performed with the Xlstat software (v.2022.2.1 Addinsoft). As the data distribution appeared not normal, non-parametric Kruskal-Wallis' tests in combination with a post-hoc Conover-Iman's test was used to reveal significant differences in traits between the species. A principal component analysis (PCA) was conducted on reduced centered data to position the species in relation to one another according to their traits.

3. Results

3.1. Survival

Large differences in survival rates appeared between species (Table 4) and eight species exceeded 50%. With the exception of *Gynerium sagittatum*, which had a survival rate of 33% only, the survival rate of herbs exceeded 87%. Among Pteridophytes, while the survival rate of the small sporophyte of *Acrostichum danaeifolium* reached 92% and that of *Adiantum latifolium* cuttings 67%, the other species displayed survival rates of 50% or below. *Ludwigia octovalvis* was the shrub with the best survival rate (67%), whereas *Clidemia hirta* gave poorer results (40%).

3.2. Biomass and biotechnical traits

After 3 months of growth, there were significant differences in biomass and root characteristics between species (Fig. 1). The PCA summarised the five traits of the 11 species studied. Significant relationships among traits appeared, with a positive correlation (Spearman coefficient) between belowground biomass, aboveground biomass, and root length ($p < 0.0001$). The first two axes produced by the PCA captured 63% of the total inertia, i.e. 34% for the first axis and 29% for the second (Fig. 2). The main variables contributing to the first axis were belowground biomass and root length on the positive side. This axis can be considered to represent the root growth strategy, i.e. fast vs slow. The main variables contributing to the second axis were aboveground biomass, root diameter and root:shoot on the positive side.

Table 4
Survival rate and number of planted propagules for the eleven species studied. Macrophytic species are indicated in bold.

Species	Survival rate (%)	Number of planted propagules
Pteridophytes		
Acrostichum danaeifolium Langsd. & Fisch.	92	13
Adiantum latifolium Lam.	67	15
Lycopodium cernuum L.	20	15
Thelypteris reticulata (L.) Proctor	50	16
Herbs		
Commelina diffusa Burm.f.	100	15
Dieffenbachia seguine (Jacq.) Schott	100	15
Gynerium sagittatum (Aubl.) P. Beauv.	33	15
Hymenachne amplexicaulis (Rudge) Nees	87	15
Sphagneticola trilobata (L.) Pruski	100	10
Shrubs		
Clidemia hirta (L.) D. Don	40	15
Ludwigia octovalvis (Jacq.) P.H. Raven	67	15

Fig. 1. Uprooted 3 month-old propagules of the eleven Caribbean species tested. Ferns: a. *Acrosticum danaeifolium*, b. *Adiantum latifolium*, c. *Lycopodium cernuum,* d. *Thelypteris reticulata*, Herbs: e. *Commelina diffusa*, f. *Hymenachne amplexicaulis*, g. *Sphagneticola trilobata*, h. *Dieffenbachia seguine*, i. *Gynerium sagittatum*, Shrubs: j. *Clidemia hirta*, k. *Ludwigia octovalvis*. Bars = 10 cm.

This axis reflected the biomass allocation strategy.

Biomass production varied twentyfold (Fig. 3), root length 7 fold, root:shoot 58 fold and root diameter 3 fold (Fig. 4). These traits were less variable among pteridophytes than among herbs and shrubs. Distributed on the negative side of the first PC axis, pteridophytes displayed a small root system with a low root biomass, below 2 g. Most herb species were distributed along the other side of the axis, displaying a fast development of long roots with a high biomass of 12-25 g. Root development varied considerably between herb species. *Dieffenbachia seguine* and *Gynerium sagittatum* had a root biomass close to that of pteridophytes, below 1.5 g, whereas *Commelina diffusa*, *Sphagneticola trilobata* and *Hymenachne amplexicaulis* had a fast-growing root system, with the highest mean root length (50–60 cm) and root biomass (4-11 g). *Dieffenbachia seguine* exhibited a particular set of traits: its green succulent cuttings produced short, thick roots (the roots with the greatest diameter) before starting to emit leaves, which resulted in a high root:shoot ratio (2.3 $g.g^{-1}$). The shrubs *Clidemia hirta* and *Ludwigia octovalvis* displayed intermediate mean newly-produced biomass values, between 2 and 8 g, with a high investment in roots (root:shoot of 2.2 and 1.6 $g.g^{-1}$), and a root biomass of 1.2 and 4 g, respectively. The macrophytes

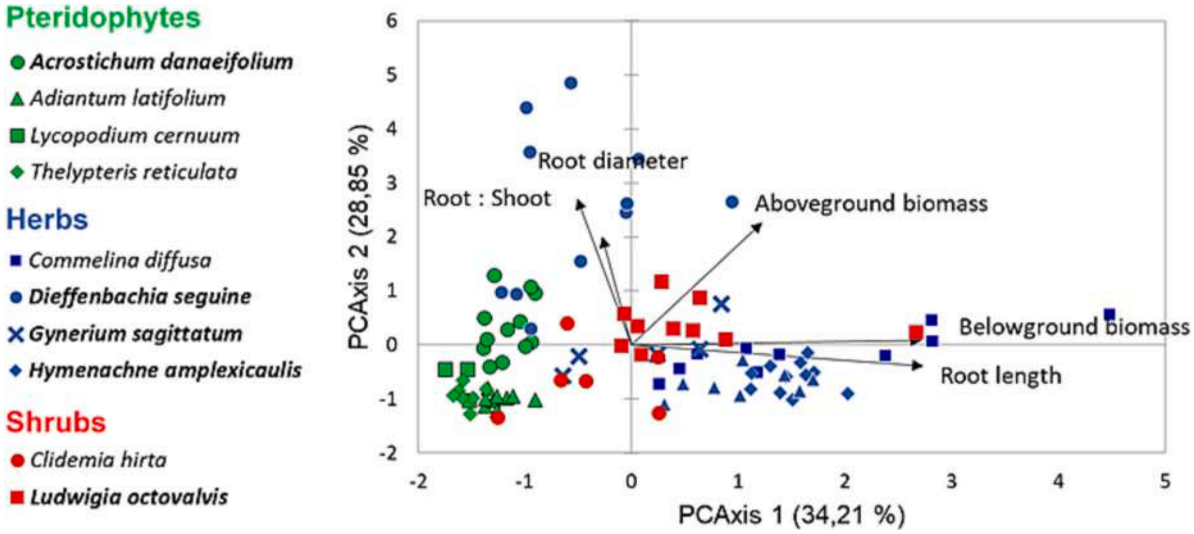

Fig. 2. Principal components analysis (PCA) on five key biotechnical traits of SWBE interest, measured on 92 propagules from eleven species of riparian herbs, pteridophytes and shrubs. Macrophyte species are indicated in bold.

A. danaeifolium, *D. seguine*, *G. sagittatum*, *H. amplexicaulis*, and L. *octovalvis* differed widely in these traits, and included both highly performing herb and shrub species and slow-growing pteridophytes.

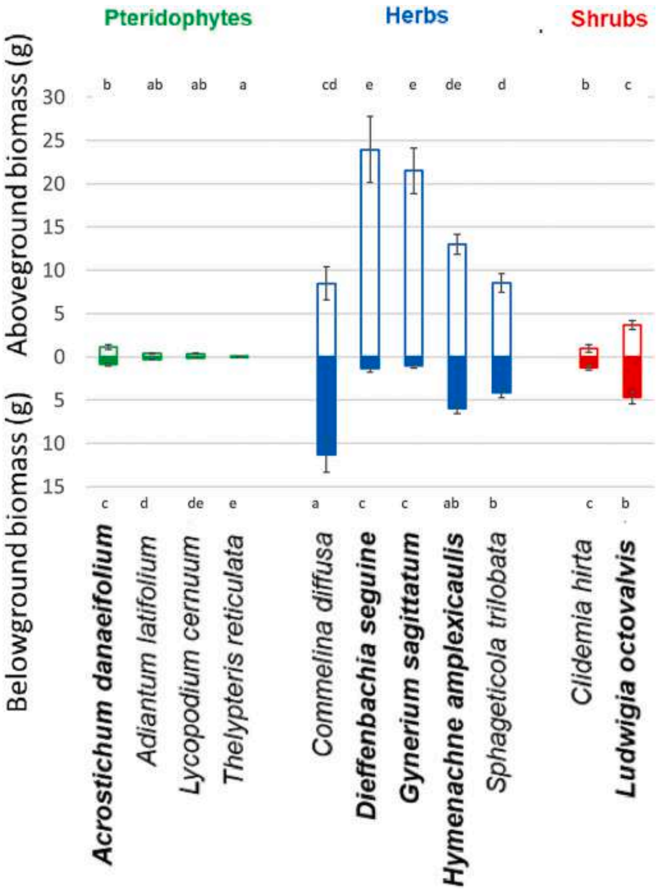

Fig. 3. Bar plot of belowground and aboveground biomass in the eleven species studied (*Acrostichum danaeifolium* $n = 12$, *Adiantum latifolium* $n = 10$, *Clidemia hirta* $n = 6$, *Commelina diffusa* n = 10 *Dieffenbachia seguine* n = 12, *Gynerium sagittatum* $n = 5$, *Hymenachne amplexicaulis* $n = 11$, *Ludwigia octovalvis* n = 10 *Lycopodium cernuum* $n = 3$, *Sphageticola trilobata* $n = 8$, *Thelypteris reticulata* $n = 7$). Bars represent standard error. Different alphabetic designations indicate significant differences between types according to Kruskal-Wallis' test ($P < 0.05$) and Conover-Iman's peer-to-peer comparison procedure. Macrophytes are indicated in bold.

4. Discussion

The eleven species studied exhibited marked variations in survival rates, growth and root investment. We identified significant differences in survival, growth and allocation strategy, within and between pteridophytes, herbs and shrubs. These first experimental data provide indications concerning the suitability of these plant categories for SWBE.

4.1. Growth, survival, and biotechnical traits of Neotropical herbs, pteridophytes and shrubs

At three months, species' rates of survival ranged between 20 and 100%. Survival rate was high in five species, above 87%, and low in four species, below 50%. Large variations in the survival rate of cuttings have already been reported in Caribbean trees and shrubs (Mira et al., 2022a, 2022b) and in various Indian bamboo species (Kaushal et al., 2011).

We followed an opportunistic strategy for collecting the plant material, transferable to a SWBE context, willfully paying no attention to the age of the collected material for the longer-lived species such as *Gynerium sagittatum* and *Clidemia hirta,* on which young green stems were observed to survive better as cuttings than older brown ones. Our results with the species exhibiting low survival rates could be improved by taking into consideration parameters potentially affecting rooting ability, such as the age of the material used as cutting (Hartmann and Kester, 1963) or soil conditions (Jean et al., 2020), or by introducing a nursery phase to facilitate early development before plantation in situ (Baird et al., 2015). However, the fact that these short-cycle plants are easy to collect and widely available is likely to offset their poor survival. Other methods could be tested to improve the survival of L. *cernuum*, such as collecting and planting out vegetated clods. The range of variations observed in shrub species was similar to that reported for other Caribbean riparian understory species (Mira et al., 2022b).

Seven herb and shrub species displayed characteristics revealing a high potential for SWBE. Variations in growth and other traits were reflected by the two main axes of the PCA along which species were distributed. The first axis can be seen as representing growth intensity, along which species were ranked from slow to fast growers. The second axis reflected relative resource allocation into the root system. The best-performing herb species, the ground-covering *Commelina diffusa* and

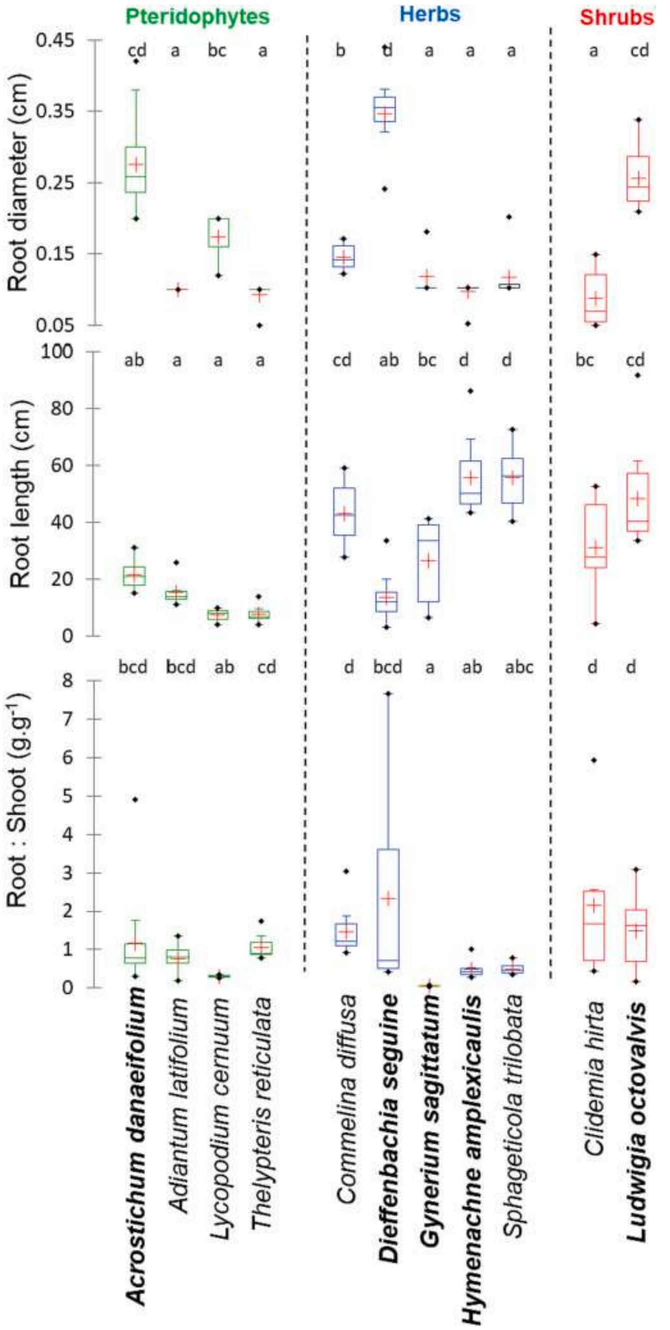

Fig. 4. Boxplot of biotechnical traits for the eleven species studied (*Acrostichum danaeifolium* n = 12, *Adiantum latifolium* n = 10, *Clidemia hirta* n = 6, *Commelina diffusa* n = 10, *Dieffenbachia seguine* n = 12, *Gynerium sagittatum* n = 5, *Hymenachne amplexicaulis* n = 11, *Ludwigia octovalvis* n = 10, *Lycopodium cernuum* n = 3, *Sphageticola trilobata* n = 8, *Thelypteris reticulata* n = 7). Boxplot midlines represent medians, crosses represent means, boxes represent the first and third quartile values, whiskers represent 1.5× the interquartile range, and points represent outliers. For each trait, different alphabetic designations indicate significant differences between types according to Kruskal-Wallis' test ($P < 0.05$) and Conover-Iman's peer-to-peer comparison procedure. Macrophytes are indicated in bold.

Sphagneticola trilobata and the macrophytes *Hymenachne amplexicaulis* and *Ludwigia octovalvis,* combined a number of characteristics desirable for SWBE. *Gynerium sagittatum*, despite its low survival, and *Clidemia hirta*, despite its low mean biomass, also displayed root traits relevant for SWBE. *Dieffenbachia seguine* exhibited a remarkable behaviour. The mobilisation of reserves contained in its photosynthetic crassulescent stem favours the emission of roots before that of shoots and leaves. The short and thick roots emitted have limited abilities for fast exploration of the substrate but are able to quickly form clones by root sprouts. This capacity for clonal expansion is useful in soil bioengineering practice, as it increases resilience after SWBE project completion, with a possible recolonisation of poorly vegetated and/or disturbed zones. At the opposite end of the scale, pteridophytes displayed a set of traits – with low interspecific variability – that denotes a poor suitability of these species to SWBE.

4.2. *Pteridophytes: helpful to enhance biodiversity*

A recent body of evidence has shown the high potential of ferns for erosion control in Asia (Chau, 2017; Sanchez-Castillo et al., 2019) and New Zealand (Denton-Gilles, 2006). Despite their ability to spread in infertile soils, high declivity areas (Walker et al., 1996) and riparian understory (Gayot et al., 2018), pteridophytes have been a neglected group in Neotropical SWBE. Our results highlight that Caribbean pteridophyte species, with their slow development and low investment in roots, call for a degree of caution when included in SWBE projects. Although the initial establishment of pteridophytes using propagules is a sensitive phase, subsequent reproduction by spores can occur rapidly, and efficiently give rise to a dense population (Denton-Gilles, 2006; Chau, 2017). However, a preliminary nursery phase appears unavoidable for the stem cuttings of L. *cernuum* and the diminutive bulbils of *T. reticulata*. Faster development and spore production could be achieved for *A. latifolium* with recourse to large-size vegetated clods. Regarding *A. danaeifolium*, the small sporophytes can easily be collected and directly included in SWBE worksites as seedling beds.

4.3. *Native herbs and shrubs for erosion control and much more*

To successfully implement a soil bioengineering project, it is a great advantage to be able to choose from a large pool of species displaying a variety of ecological and morphological characteristics in order to compose the assemblage that best meets the requirements of the local environment and technique employed. A degree of diversity was noted in the various traits examined, as well as in ecology, morphology and size, among the herbs and shrubs studied here. This category included a great variety of habits, from ground-covering to erect, as well as macrophytes from 0.2 to 3 m tall. Several successful erosion control experiments using herb species in SWBE have been reported from tropical areas (Zhu and Zhang, 2016; Ramos Santana et al., 2003; Dorairaj and Osman, 2021) and our results reveal the high potential of certain Caribbean species. Some of the species studied displayed a fast growth and root system establishment strategy, with root length reaching 80 cm in *Hymenachne amplexicaulis* and *Sphagneticola trilobata* - comparable in this aspect to Vetiver (Islam et al., 2016) - ensuring fast and deep anchorage. This fast development, coupled with an efficient vegetative propagation, quickly produces a dense root network and significant ground cover.

The active introduction of these pioneer herbaceous plants in SWBE can initiate the process of stabilization and accelerate vegetation dynamics (Giupponi et al., 2019). In tropical riparian ecosystems, herbaceous species dominate the early stages of ecological succession and can improve growing conditions for other native plants, leading to more mature and stratified plant communities (Kalliola et al., 1991; Manrique-Hernández et al., 2016).Ground-covering herbs can also be a relevant tool for controlling invasive alien species, which are widely distributed in Guadeloupean disturbed riparian habitats (Gayot et al., 2018). Certain SWBE techniques, such as vegetated ripraps, are more exposed than others to subsequent colonisation by invasive species (Cavaillé et al., 2013; Martin et al., 2021). In the first years after the initial setup alien herbaceous species or climbing lianas may compete with the planted material (such as live stakes or poles). Planting native ground-covering species is an NBS alternative to chemicals for controlling invasive alien species in degraded riparian areas (Viljoen and Groenewald, 1995). Ground-cover plants are already used as an ecological tool to manage weeds through competition in agrosystems (Tardy et al., 2015).

Most terrestrial herb species used in SWBE projects are planted by sowing seeds (Zeh, 2007) but there are several constraints on this type of propagation. It depends on the fructification phenology, and seeds can be difficult to harvest because of their small size and narrow window of maturity. It also requires to set up a seed preservation protocol and to study the germination pattern of each species. Our results provide elements to facilitate the inclusion of herb species in SWBE projects by vegetative propagation. This study could be complemented by additional useful investigations aiming to conceive well-adapted seed mixes and to reduce the cost of using herbs in SWBE projects by promoting the development of a local industry.

Among the herbs and shrubs of this study, macrophytes are important natural agents that accelerate the natural succession. Stands of macrophytes constitute hotspots for the retention of hydrochorously-dispersed plant propagules as well as sediments, building up both seedbank and sediment and thus initiating bed aggradation and stabilization, bank extension and terrestrialisation of the vegetation (Gurnell et al., 2007).

5. Conclusion

This study enriches the current knowledge on the use of native neotropical riparian species for SWBE. We provide here the first experimental results focusing on the growth, biomass allocation and root characteristics of a large selection of herbs, pteridophytes and shrubs potentially suitable for SWBE in the Neotropics. All the herb and shrub species in this study should prove useful in SWBE projects, being suited to a wide range of the ecological conditions and to many techniques. The best-performing herb species, the ground-covering *Commelina diffusa* and *Sphagneticola trilobata* and the shrub *Clidemia hirta* present great potential for the quick establishment required in earth slope stabilization, vegetated gabions, vegetated ripraps or to control alien species invasions during the development of woody vegetation. The macrophytes *Hymenachne amplexicaulis, Ludwigia octovalvis, Gynerium sagittatum* and *Dieffenbachia seguine* combined a number of characteristics desirable for fascines and benches. On the other hand, pteridophytes need more care and additional experiments.

The species studied here will be tested again in situ in already planned SWBE projects in Guadeloupe with longer-term monitoring on their survival and development.

Our experimental results complement previous studies on native woody species and provide clues for composing the best-performing blends of Neotropical species suitable for SWBE.

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CRediT authorship contribution statement

Eléonore Mira: Conceptualization, Data curation, Formal analysis, Investigation, Visualization, Writing – original draft. **Alain Rousteau:** Conceptualization, Formal analysis, Supervision, Validation, Writing – review & editing. **Régis Tournebize:** Conceptualization, Supervision, Writing – review & editing. **Marie Robert:** Conceptualization, Funding acquisition, Writing – review & editing. **André Evette:** Conceptualization, Formal analysis, Funding acquisition, Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data supporting the results reported can be found in the supplementary material.

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