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Evaluating the suitability of neotropical trees and shrubs for soil and water bioengineering: Survival and growth of cuttings from ten Caribbean species

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ABSTRACT

Soil and water bioengineering techniques are now increasingly adopted worldwide for controlling riverbank erosion but have not yet been implemented in the Caribbean Islands biodiversity hotspot. The selection of suitable native plant species is critical for successful soil bioengineering designs on riverbanks, but few data are available regarding Caribbean species. This study aimed to characterize the performance and biotechnical traits of native Caribbean species potentially compatible with soil and water bioengineering. In a six-month shade-house experiment, we measured the survival rate, biomass production and root growth of cuttings of ten native Caribbean shrub and tree species occurring naturally in a variety of riparian environments. All species appeared suitable for soil and water bioengineering but differed as to the specific bioengineering techniques they seemed particularly suited for, depending on their respective survival rates, growth performances and root system structures. Five tree species, *Citharexylum spinosum, Cedrela odorata, Ficus citrifolia, Chimarrhis cymosa, Homalium racemosum*, and three shrubs, *Piper dussii, Piper dilatatum* and *Phyllanthus mimosoides*, exhibited survival, growth and root characteristics compatible with a broad range of techniques, whereas *Tabebuia heterophylla* and *Cordia sulcata* may only be compatible with a few. We also propose using of the DEXi decision-support software for assessing species suitability to a series of widespread soil and water bioengineering techniques. Our results provide practical guidance for the integration of native species in soil and water bioengineering in the Caribbean and the Neotropics at large.

1. Introduction

Riparian ecosystems, because of their great ecological importance relative to their size, the diversity of ecological functions and services they support, and the rate at which they are being altered, are considered as global hotspots to prioritize for ecological restoration (Capon and Pettit, 2018; Tockner and Stanford, 2002). Riparian zones are being widely degraded as urbanization, agricultural expansion and industrial uses disrupt their structure and function (Feld et al., 2011; Nilsson et al., 2005). The Caribbean Islands biodiversity hotspot (Kobayashi et al., 2019) encloses a high diversity of ecosystems and species. In Guadeloupe, for example, 32 different ecosystems together harbor 1706 native vascular plant species (Fournet, 2002; Rousteau et al., 1996). Along the streams that drain through all these ecosystems, a high diversity of tree species are found in complex riparian forest assemblages that include many species from the neighboring communities (Gayot et al., 2018). As elsewhere in human-dominated areas, riparian Caribbean ecosystems are being altered by land development, biological invasions and stream management (Gayot et al., 2018; IGN, 2015). In areas where human infrastructures must be protected against erosion, conventional techniques to improve riverbank stability and control soil erosion mostly rely on civil engineering approaches involving stones and concrete. Although these widely-used civil engineering techniques are mechanically efficient, they deeply alter the pre-existing natural conditions of the riverbank, decrease species diversity and impair the associated ecological functions, disrupt the natural succession of riparian ecosystems and cause the degradation of the aquatic environment (Cavaillé et al., 2015; Dudgeon et al., 2006; Janssen et al., 2019).

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Nature-Based Solutions (NBSs) are a fairly recent concept that promotes nature as a solution for climate mitigation and adaptation (Cohen-Shacham et al., 2016; Nesshöver et al., 2017). NBS are supposed to help mitigate global environmental challenges while also promoting the economy via job creation, growth, and innovation (Maes and Jacobs, 2017). Soil and water bioengineering (SWBE) is an NBS (Weissteiner et al., 2019; Preti et al., 2022; Rauch et al., 2022). This interdisciplinary approach includes cost-effective, nature-friendly, resilient, and sustainable techniques to manage erosion problems on slopes and improve riverbank stability. SWBE aims to mimic nature and uses plants and/or plant parts (e.g. roots, stems, seeds) as live building materials, used alone or in combination with structural components such as stones, logs or fiber rolls (Clark and Hellin, 1996; Diaz, 2001; Zhang et al., 2019). SWBE triggers successional trajectories, facilitates the establishment of native plant and animal communities (Tisserant et al., 2020, 2021) and can contribute to species conservation (Popoff et al., 2021) while limiting the propagation of invasive alien species (Cavaillé et al., 2013; Martin et al., 2021). SWBE techniques have been recently extensively applied to riverbank restoration, vegetation reconstruction and riparian function improvement (Evette et al., 2009; Gray and Sotir, 1996; Rey et al., 2019). In the Neotropics, SWBE is currently gaining ground and several experiments have been conducted over the last decade (Hostettler et al., 2019; Maxwald et al., 2020; Petrone and Preti, 2008, 2013). However, in the Caribbean, SWBE experiments and implemented SWBE projects remain few and far between, and the lack of knowledge concerning suitable native species is hampering their development, given that this is one of the key conditions for successful project implementation (Maxwald et al., 2020).

As cuttings are economical, fast, and efficient for producing the large amount of woody plant material required for project implementation, they are the type of plant material most used in SWBE techniques. Most SWBE techniques, i.e. live stakes, brush mattresses, vegetated ripraps, fascines and brush layers, are based on the organized combination of live stakes, long branch cuttings and live poles (Diaz, 2001; Gray and Sotir, 1996; Lachat, 1994; Zeh, 2007). The selection of adequate plant species exhibiting the biotechnical traits best suited to the project's conditions is a prerequisite for success (De Baets et al., 2009; Ghestem et al., 2014; Stokes, 2006) and is most often based on observation. Native and site-specific plants well adapted to the local ecological conditions are recommended for the successful development of the plant cover while avoiding the introduction of invasive alien species (Krautzer and Hacker, 2006). Leblois et al. (2022) show that poor vegetation recovery concerns 60% of >200 cases of failed SWBE structures in France, confirming the importance of good vegetation development in the few years after implementation. Survival and growth data are the most informative indices reflecting the success of an SWBE project (Zhang et al., 2019) but various other plant traits are desirable for SWBE: resistance and resilience to disturbance, vegetative propagation, fast and dense root development, stem flexibility (Stokes et al., 2009). It is also important to use a diverse combination of species on SWBE sites because a greater species diversity improves worksite resilience to disturbances (e.g. drought, herbivory, flooding), probably resistance to pests and plant diseases, and soil aggregate stability (Pohl et al., 2009), while it has also been suggested that combining root systems of different shapes is more effective in reinforcing the soil (Stokes et al., 2009).

There is currently very little known about the performance and biotechnical traits, including data on rooting ability and growth, of native Caribbean species. Previous experiments on the rooting ability of 31 Caribbean tree and shrub cuttings gave first indications on their possible use in SWBE (Mira et al., 2021a). The aim of the current research was to determine the most appropriate species to use as cuttings in SWBE and specify to which SWBE techniques each species appears best suited. Cutting survival, growth and root system structure were assessed in a six-month ex situ experiment involving seven tree species and three shrub species. A new approach for SWBE was then conducted under DEXi, a modeling tool for multi-criteria analysis to assist complex decision-making (Craheix et al., 2015; Jiménez-Alfaro et al., 2020), used here to assess species suitability to the main SWBE techniques.

2. Materials and methods

2.1. Species selection and cutting collection

Ten native riparian species (3 shrubs and 7 trees) were selected according to their ecological status (early successional), resistance to disturbance, availability for providing material in large quantities and rooting ability of cuttings (Mira et al., 2021b). These species cover a wide ecological range (Table 1), in accordance with the broad types of environment occurring in Guadeloupe (Rousteau et al., 1996). Data on the geographical range and traditional uses of each species where extracted from the literature (Fournet, 2002; Rollet, 2010).

Plant cuttings were collected during the rainy season, between August and November 2020, a period compatible with the implementation of SWBE projects (Diaz, 2001). Collection sites were located on Basse-Terre and Grande Terre Islands, the two largest islands of the Guadeloupe archipelago (Supplementary material, Fig. 1), at elevations ranging from 1 to 427 m a.s.l.. This altitudinal range is that of the most highly anthropized areas, where most SWBE projects are needed.

A total of 15 to 33 mature, healthy individuals per species were selected from between 3 and 11 natural populations depending on the species (Fig. S1 of the supplemental material, Table 2). On each individual, one branch with a minimum diameter of 1.5 cm for shrubs and 3 cm for trees was collected, yielding a total overall number of 253 cuttings (Table 2). The branches collected were kept for <48 h at ambient temperature in the shade, with leaves removed, and then divided into 60 cm-long cuttings.

2.2. Experimental conditions

The experiment were conducted in a shadehouse at the experimental INRAE station of Duclos, Guadeloupe FWI (16°12′11.02"N; 61°39′33.78"W; 99 m a.s.l.). The ten months of the experiment (August 2020–May 2021) started during the wet season and included drier periods. Climatic data were obtained by the Meteo France station located on the Duclos experimental station. Temperature, relative humidity and daily light integral varied respectively between 23 and 27 °C (mean: 24.5 °C), 82 and 86% (mean: 83%), and 1431 and 2260 J.cm^{-2} day^{-1} (mean: 1833 J. cm^{-2} day^{-1}) (Table 3). Cuttings were protected from light stress under a shadehouse with 60% light reduction to avoid the negative impact of light intensity on the rooting rate (Grange and Loach, 1985; Loach and Gay, 1979).

Prior to planting, each cutting was weighed and its basal diameter measured. The base was then soaked for 10 s in a rooting hormone solution of 1000 ppm of Indole 3 Butyric Acid (Hartmann and Kester, 1963). This treatment had previously been tested on the selected species and shown to induce a higher rooting rate in a preliminary experiment (Mira et al., 2021b). Shadehouse and hormonal treatments remain compatible with operational and cost constraints at soil bioengineering plantation sites.

Within 24 h after collection, each cutting was inserted vertically (according to the usage in live staking, a technique widely used in SWBE) to two-thirds of its length inside pilot holes previously made in the experimental substrate with a steel rod (to preserve the cuttings from abrasion). The experimental containers were polyethylene permeable 'bulk bags' (LxlxH 0.95 × 0.95 × 1.10 m) with open tops placed under a shadehouse (Fig. 1). These wide and tall containers were chosen to avoid restricting the development of the root systems. One cutting per container was planted randomly. The experimental substrate was a mixture of pozzolana and top layer of agricultural ferralsols (v:v 3/4:1/4) to simulate a poor alluvial soil. Grain size analysis of the mineral fraction corresponds to a very porous soil, with 75% gravel, 10% sand,

Table 1
Plant species tested and their families. For each species, biological and ecological type, distribution and traditional uses (following Fournet, 2002 and Rollet, 2010) are indicated.

Species	Family	Type	Coastal forest	Dry forest	Seasonal evergreen forest	Rainforest	Biogeography	Construction/ Carpentry	Medicinal proprerties	Attract pollinators	Charcoal production
Cedrela odorata L.	Meliaceae	Tree	x	x	x		Lesser Antilles, Greater Antilles, Central America, South America	x	x		
Chimarrhis cymosa Jacq.	Rubiaceae	Tree			x	x	Lesser Antilles, Greater Antilles, Trinidad	x			
Citharexylum spinosum L.	Verbenaceae	Tree	x	x	x		Lesser Antilles, Greater Antilles, South America		x	x	
Cordia sulcata DC.	Boraginaceae	Tree			x		Lesser Antilles, Greater Antilles, Trinidad				x
Ficus citrifolia Mill.	Moraceae	Tree		x	x		Lesser Antilles, Greater Antilles, Central America, South America	x			x
Homalium racemosum Jacq.	Salicaceae	Tree		x	x		Lesser Antilles, Greater Antilles, Central America, South America			x	
Phyllanthus mimosoides Sw.	Euphorbiaceae	Shrub			x	x	Lesser Antilles, Trinidad				
Piper dilatatum Rich.	Piperaceae	Shrub		x	x	x	Lesser Antilles, Greater Antilles, Central America, South America				
Piper dussii C. DC.	Piperaceae	Shrub			x	x	Lesser Antilles				
Tabebuia heterophylla (DC.) Britton	Bignoniaceae	Tree	x	x	x		Lesser Antilles, Greater Antilles	x			

and 15% clay. The substrate had a pH of 7.4, and 0.85% of total organic matter. A fertilizing treatment (10 g of 33.5% ammonitrate) was added on the surface of each container 110 days after plantation. Irrigation to field capacity with a drip irrigation system activated daily maintained a favorable water balance throughout the experiment. Weeds were mechanically removed once a month throughout the experimental period.

2.3. *Performance and traits of the cuttings*

The biotechnical traits studied were chosen for their importance in the context of soil bioengineering operations.

Throughout the experiment, evidence of herbivory on cutting leaves was recorded. Six months after plantation, survival rates (cuttings with live shoots) were recorded for each species. For the species showing a survival rate above 50%, 10 healthy cuttings were selected to be uprooted. For the species with a survival rate below 50%, all the surviving cuttings were uprooted.

Cuttings were carefully removed from the substrate. During this operation, we observed that roots exhibited clear interspecific differences in mechanical resistance. Some species had very fragile roots that broke easily, whereas others had stronger roots. We classified species into the three following empirical categories: high, intermediate and low root resistance. Roots were cleaned with water. For each cutting, we recorded the point of emergence of the roots and assigned root distribution to one of two categories: roots at the basal section only, or roots more broadly distributed along the buried section.

A quick estimate of root size was obtained by averaging the diameter of the five largest roots measured at their point of emergence on the cutting. Maximum root length and cumulative shoot length, corresponding to the total length of all emitted shoots, were measured on each cutting. New shoots (leaves and stems) and roots were removed from the original stem, dried at 80 °C for 72 h and weighed to measure newly produced aboveground (leaves + stems) and belowground (root) biomass. Biomass allocation was calculated as the ratio of belowground (root) biomass to aboveground (shoot) biomass. The initial biomass of the cuttings was not included in the biomass and root measurements given that we aimed to assess the biomass actually produced by the studied species over the period (Keita et al., 2021).

2.4. *Statistical analyses*

Statistical analyses were performed with the Xlstat software (Addinsoft). We have a few living cutting per species and stations considered. This choice was done to allow the study of a large number of species in order to have an efficient knowledge in a SWBE practice point of view. However, even if a random structure was considered in the experimental design, it could not be incorporated into the analyses as replication was too low for mixed models to converge. Non-parametric

Table 2
Number of sampled stations and parent individuals, and basal diameter of cuttings (mean and standard deviation). Mean wood density available for woody species extracted from Chave et al. (2009).

	N sampled stations	N total individuals	Mean basal diameter of cuttings ± SD (cm)	Mean wood density (g. cm^{-3})
Cedrela odorata L.	7	20	4 ± 0.7	0.45
Chimarrhis cymosa Jacq.	5	20	5 ± 0.9	0.71
Citharexylum spinosum L.	7	20	4 ± 0.7	0.70
Cordia sulcata DC.	11	30	5 ± 0.8	0.60
Ficus citrifolia Mill.	8	20	4 ± 0.8	0.40
Homalium racemosum Jacq.	7	20	4 ± 0.5	0.79
Phyllanthus mimosoides Sw.	3	15	3 ± 0.4	–
Piper dilatatum Rich.	4	30	2 ± 0.4	–
Piper dussii C. DC.	3	25	2 ± 0.4	–
Tabebuia heterophylla (DC.) Britton	6	20	4 ± 0.8	0.57

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

	Average daily light (J. cm^{-2} day^{-1})	Precipitation (mm)	Average temperature (°C)	Average relative humidity (%)
August 2020	2064	160	27	83
September 2020	1840	318	26	83
October 2020	1588	350	25	85
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
May 2021	2260	33	25	82
June 2021	1944	281	26	83

Kruskal Wallis tests in combination with a post-hoc Conover-Iman's test was used to reveal significant differences in traits between 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.

2.5. Suitability index

A specific index of species suitability to the major SWBE techniques was assessed using DEXi, a modeling tool for multi-criteria decision-making, whose original feature is that it deals with qualitative multi-criteria models (Bohanec, 2008). Qualitative modeling makes it possible to convert quantitative data into qualitative data. This flexibility takes advantage of including several types of information, such as field measurements or empirical knowledge formulated directly into qualitative and linguistic values (Sadok et al., 2009). It is freely available, simple to use, and the decision rules and input data can be easily modified, which makes it adaptable over time in case of any change. DEXi has been used to assist complex decision-making in various disciplines, such as agroecology (Craheix et al., 2015; Jiménez-Alfaro et al., 2020), and seems appropriate for selecting suitable species for SWBE.

The program uses 'options', 'attributes', 'values', 'utility functions' and 'evaluations' as fundamental terms. 'Options' is to be understood here as the native species tested. An 'attribute' is a biotechnical trait (e.g. survival rate) that can be obtained from expert knowledge, literature data or measurements (Supplemental material, Table 1). For quantitative values, a qualitative scale (defined by threshold values) is needed to translate quantitative variables into qualitative variables. Threshold values must be relevant, adapted to the assessment context and take into consideration stakeholder preferences. For each 'attribute' (biotechnical trait), each 'option' (species) has a 'value', which is defined according to this qualitative scale. The values of each option are aggregated in a bottom-up way according to the structure of the model, where attributes are organized hierarchically into a tree of attributes, and corresponding 'utility functions'. The 'utility functions' corresponds to rules that define the aggregation of attributes (Bohanec, 2008). The overall 'evaluation' of an 'option', here the suitability index of a species, is obtained by a set of attributes that are first evaluated individually and then aggregated.

First, we defined and organized 6 attributes based on biotechnical traits measured on the 10 native species tested in our study: 1) rooting ability; 2) total biomass production; 3) root:shoot ratio; 4) diameter (ability to produce large diameter cuttings, based on field in situ observations); 5) suitable aboveground architecture (ability to produce long, straight cuttings, based on field in situ observations); and 6) suitable belowground architecture (ability to emit roots all along the buried section). We also considered 3 attributes extracted from the literature: 1) wood density (taken as a rough index of wood resistance); 2)root self-grafting ability (reported for the genera *Ficus*, *Cedrela* and *Tabebuia*, in LaRue, 1952); and 3) species height (extracted from Fournet, 2002). We then entered these data into DEXi to construct a tree. For each individual quantitative attribute (survival, biomass, root-to-shoot ratio and wood density), we set boundaries to define 3 classes, e.g. 'low', 'medium', 'high'. For survival, these three classes were defined according to SWBE practices (% 0–30/30–70/70–100). According to Schlüter (1971), only

Fig. 1. Experimental setup located on the INRAE Duclos station, Petit Bourg, Guadeloupe.

plants with survival rates of 70% and above should be considered, but if the plant material available is abundant, the easy replacement of cuttings can compensate for low survival and a 30% survival rate can be sufficient. For biomass and root-to-shoot ratio, Kruskall-Wallis tests were used to divide the data observed in our study into three classes, fairly homogeneous in their range values. For wood density, we established the thresholds between classes using expert knowledge on the mechanical behavior and traditional uses of the selected woods (Rollet, 2010). Several Caribbean species with a high wood density, above 0.70 g.cm^{-3}, produce wood capable of withstanding high mechanical constraints and often used in heavy construction and carpentry. Species with less dense wood, with a density between 0.6 and 0.7 g.cm^{-3}, can still be used for cabinet-making and furniture. The four qualitative attributes (rooting ability, diameter, suitable belowground architecture and root self-grafting ability) are all considered as binary, with two classes each: species capable of rooting/incapable of rooting, species capable of producing cuttings of an appropriate diameter and length/incapable of producing such cuttings, cuttings emitting roots all along their buried section/cuttings producing roots otherwise, and species in which roots are known to self-graft/species not known to do so (Supplementary material Table S1).

We used a different combination of the 9 attributes of the species depending on the SWBE technique to be assessed. These combinations were based on expert knowledge. We considered six major SWBE techniques: live stakes, live poles, fascines, brush mattresses, brush layers and vegetated ripraps (Fig. 2, Table 4). Once the branching structure of the model was defined, we created a scale for each suitability index (suitability of a given species for a given technique) (e.g. 'Unsuitable' - 'Poor' - 'Good' - 'Excellent'). For each aggregate attribute, we defined a matrix of function rules, which DEXi uses to calculate the value of the aggregate attribute. We ran the software to generate the Suitability Indices per species for each technique (Dxi. file available in the supplementary material).

3. Results

3.1. Cutting survival, root emission and herbivory

Large differences in survival rates appeared between species (Table 5). The two shrubs, *Phyllanthus mimosoides* and *Piper dilatatum*, and the two trees, *Chimarrhis cymosa* and *Citharexylum spinosum*, had >70% of cuttings alive after 6 months. *Ficus citrifolia* and *Piper dussii*

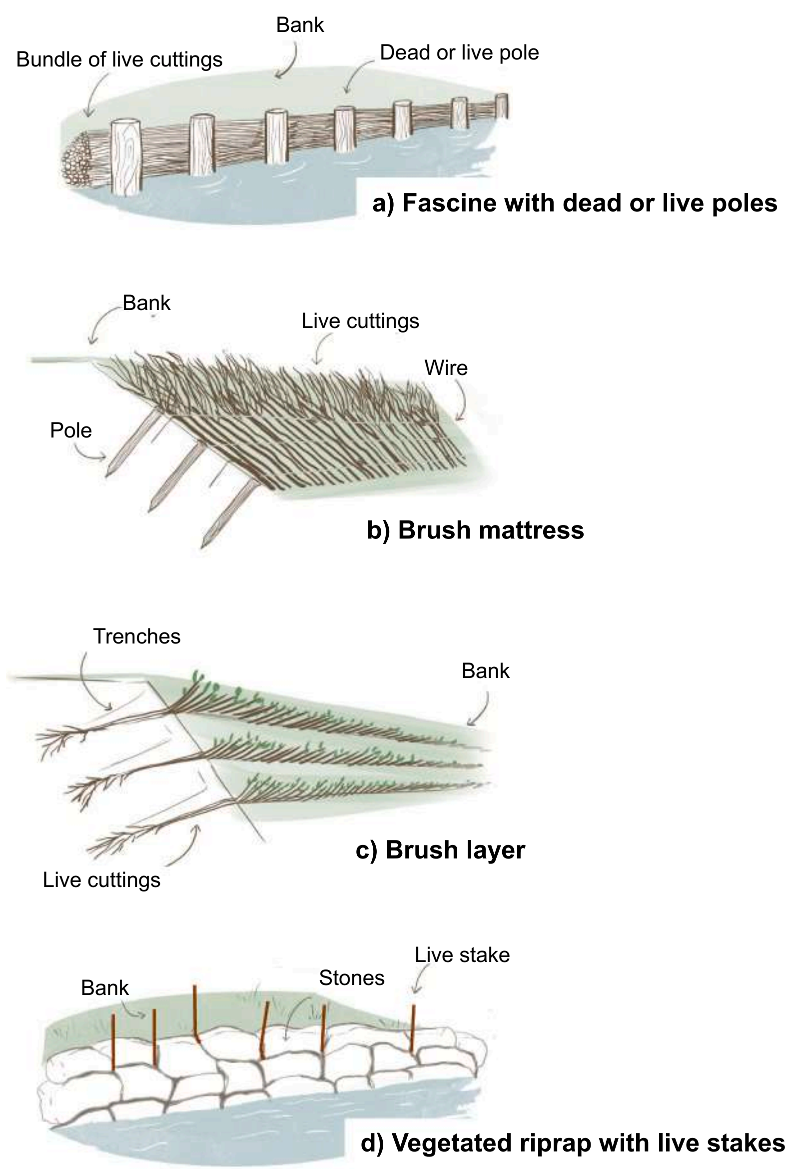

Fig. 2. Illustrations of four SWBE techniques, a: Fascine, b: brush mattress, c: brush layer, d: vegetated riprap.

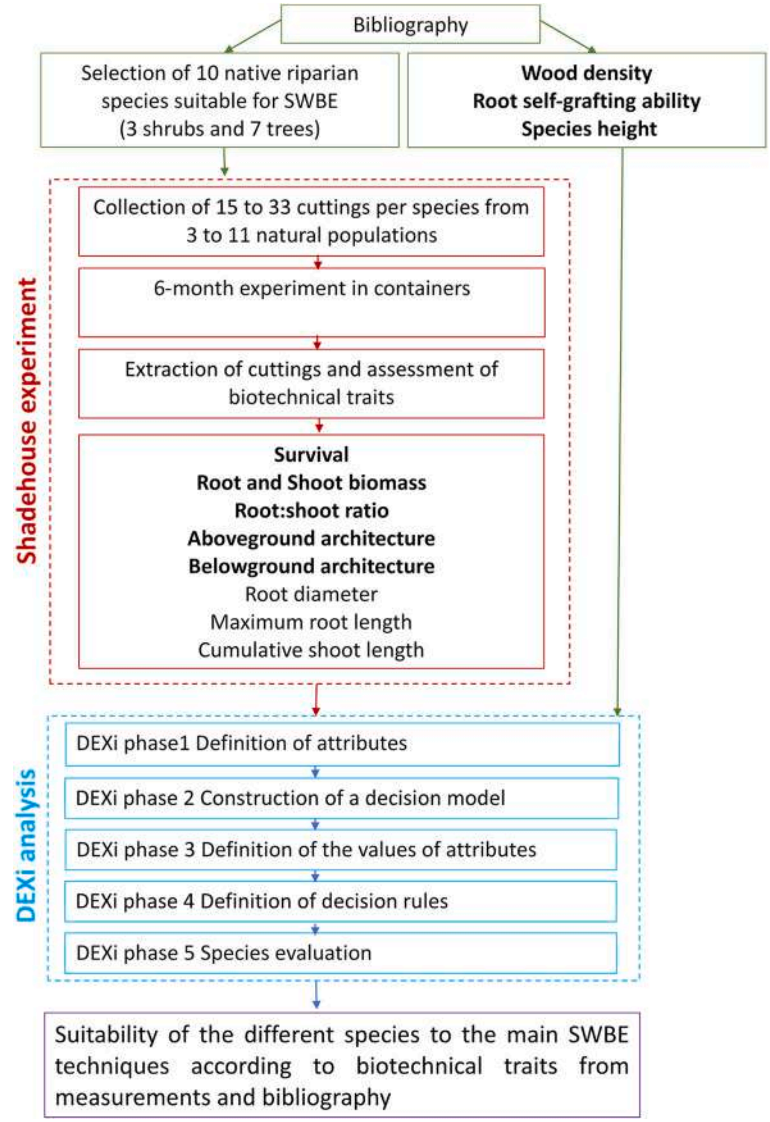

Fig. 3. Workflow chart of the study. Traits in bold are those included in the DEXi analyze.

displayed a survival rate of 50%, whereas the other species had a survival rate under 35%. Root resistance exhibited interspecific variations. It was greater in trees than in shrubs, except for *Cordia sulcata* and *Chimarrhis cymosa*, which were similar to shrubs in this respect, and *Homalium racemosum*, which had the most fragile roots of all, easily breakable. Half of the species tested had the ability to emit adventitious roots all along the buried section of the cuttings, most often at all nodes, whereas the others only emitted roots from the basal section (Table 5).

Sensitivity to herbivory also varied from one species to the next. During the experiment, *Homalium racemosum*, *Chimarrhis cymosa* and *Tabebuia heterophylla* displayed anecdotal traces of the leaf-cutting ant *Acromyrmex octospinosus*, with lower or equal to 15%of their cuttings damaged. *Citharexylum spinosum* and *Piper dilatatum* had 20% of their cuttings damaged by caterpillars. Other species of caterpillars were responsible for a larger-scale attack affecting 50% of the cuttings of *Phyllanthus mimosoides*. Scale insects were observed on *Piper dilatatum* leaves and *Ficus citrifolia* stems (Table 5).

3.2. Performance and biotechnical traits

The PCA summarized the six traits selected in the experiment on the 10 studied species. Significant relationships among traits appeared, with a positive correlation (Spearman coefficient) between biomass, root length and diameter ($p < 0.0001$). The first two axes produced by the PCA captured 74% of the total inertia, i.e. 55% for the first axis and 19% for the second (Fig. 4). The variables that contributed most to the first axis were shoot and root biomass, root length and mean root diameter on the positive side. This axis represented the growth vigor of the cuttings, with positive sign indicating more vigor. The variables that contributed most to the second axis were the root:shoot ratio and root biomass on the positive side, and cumulative shoot length on the negative side. This axis represented the biomass allocation strategy.

After 6 months of development, there were significant differences in growth between species (Fig. 5). Mean biomass production varied 20-fold between species (Fig. 6). The woody species *C. spinosum* and *C. odorata* displayed the greatest dry biomass productions, respectively 185 and 140 g. At the opposite end of the scale, *Tabebuia heterophylla* and *Phyllanthus mimosoides* exhibited the lowest mean biomass production at 15 g and 9 g respectively. The other species yielded intermediate mean total biomass values, between 30 and 85 g. Allocation pattern varied significantly between species. *C. spinosum* displayed the highest biomass allocation to the root system (root:shoot = 0.3 $g.g^{-1}$). *C. odorata, Chimarrhis cymosa, Homalium racemosum, Piper dussii* and *Piper dilatatum* exhibited fairly high mean root:shoot values, between

Table 4
Definition, function and plant material required for six SWBE techniques (Diaz, 2001).

SWBE techniques	Definition and functions	Plant material used
Live stakes	Live cuttings, mainly used for trees and shrubs. Live stakes can be used as a primary treatment or in conjunction with other types of stabilization technique, as the developing roots contribute to stabilize the slopes. They can also be used to facilitate the filling of gullies. Planted very close to each other, forming clumps to trap sediment.	Live stakes must have a diameter between 1 and 4 cm and a length of 60 cm to 1 m.
Live poles	Live cuttings of greater diameter and length, mainly used for erosion control on riverbanks, for the construction of retaining trenches on slopes, and for the construction of trench-type landfills in channel bottom control.	Live poles must have a diameter between 5 and 15 cm and a length of 2 to 5 m.
Fascines	Bundles of live cuttings laid in shallow trenches across the slope or along the bank toe. These give rapid and increasingly strong protection and reinforcement. After plantation, the cuttings put out roots and shoots, forming a strong line of vegetation. Their main engineering functions are to armor and reinforce the bank toe and slope, and to catch debris. They can also be angled to enhance drainage.	Cuttings for fascines must have a diameter between 1 and 4 cm and a length of 150 cm.
Brush mattresses	Living structures made of a pile of live branches and twigs covered with a thin layer of soil and fixed with stakes and wire. Brush mattresses are used for armoring banks, controlling scour and revegetating. The dense layer of brush increases roughness, reduces velocities at the bank face, and protects the bank from scour, while trapping sediments and providing habitat directly along the waters' edge.	Cuttings for brush mattresses must have a length between 1.5 and 2 m.
Brush layers	Live cuttings laid in shallow trenches across the slope. These give immediate and increasingly strong protection and reinforcement. Woody cuttings form a strong barrier that prevents erosion and the development of rills, and traps material moving down the slope. In the long term, a small terrace develops. Their main engineering functions are to armor and reinforce the slope, and to catch debris.	Cuttings for brush layers must have a length between 0.80 and 1.5 m.
Vegetated ripraps	Live stakes are placed inside the riprap. Once they form roots and foliage, the cuttings act as an anchor for the riprap, contribute to create an environment more conducive to the development of terrestrial biodiversity, producing a more pleasant landscape while at the same time improving resistance to erosion.	When the cuttings are installed at the same time as the inert materials, they need to be fairly long, between 3 and 5 m. They can be shorter if planted after the inert material is in place.

All these methodological steps and their links are summarized in the workflow chart Fig. 3.

Table 5
For each species tested, percentage of surviving cuttings 6 months after planting, root resistance (empirical comparative assessment), and location of emerging roots on the cuttings (Basal = species in which roots emerged at the basal section only; Broadly distributed = species in which roots were emitted all along the buried part of the cutting), see Fig. 5. Herbivory observed during the experiment is quantified as the percentage of damaged cuttings and, when identified, the species involved: *Acromyrmex octospinosus* is an exotic leaf-cutting ant, and *Gonodonta incurve, Melanchroia chephise* and *Yponomeuta* sp. are leaf-eating caterpillars.

	Survival rate (%)	Root resistance	Root distribution	Herbivory	Damaged cuttings (%)
Cedrela odorata	30	High	Basal	None	–
Chimarrhis cymosa	85	Intermediate	Broadly distributed	Ant (*Acromyrmex octospinosus*)	10
Citharexylum spinosum	70	High	Basal	Caterpillar (*Yponomeuta* sp.)	20
Cordia sulcata	17	Intermediate	Basal	None	–
Ficus citrifolia	50	High	Basal	Scale insects (*Phalacrococcus* sp., *Ceroplastes sp*)	20
Homalium racemosum	35	Low	Broadly distributed	Ant (*Acromyrmex octospinosus*)	15
Phyllanthus mimosoides	93	Intermediate	Basal	Caterpillar (*Geometridae*)	50
Piper dilatatum	77	Intermediate	Broadly distributed	Caterpillar (*Gonodonta incurve*)	23
Piper dussii	52	Intermediate	Broadly distributed	None	–
Tabebuia heterophylla	25	High	Broadly distributed	Ant (*Acromyrmex octospinosus*)	5

0.2 and 0.3 g.g^{-1}. *Tabebuia heterophylla*, *Phyllanthus mimosoides* and *Ficus citrifolia*, on the other hand, invested less in roots (root:shoot 0.08 g.g^{-1}) (Fig. 7). In this last species, field observations revealed cases of root anastomosis (Fig. 8). *C. sulcata*, displayed the lowest root:shoot ratio (0. 05 g.g^{-1}). Root characteristics also differed between species. *C. odorata, C. spinosum* and *F. citrifolia* exhibited the ability to emit the longest (between 78 and 112 cm) and thickest (between 0.5 and 0.98 mm) roots, ensuring their fast anchorage, whereas *C. sulcata*, *T. heterophylla* and *P. mimosoides* displayed the shortest (mean length below 34 cm) and the thinnest (mean diameter below 0.28 mm) roots (Fig. 7).

3.3. Suitability index

By using DEXi methodology, the selected species were compared on the basis of combinations of relevant basic attributes, i.e. biotechnical traits (Table 6). This made it possible to analyze their suitability to six major SWBE techniques. The evaluation revealed that for each SWBE technique considered there were at least 4 species that appeared to be suitable (Table 7). Live staking, for which the number of required traits is limited (n = 3), appeared to be the technique in which the greatest number of plant species tested could be used: one species, *Citharexylon spinosum*, was thus rated "excellent" for this technique, and seven others rated "good" (Table 7). Fewer species appeared suitable for live poling and vegetated ripraps, with three species evaluated as "excellent" and two as "good". Fascines, brush mattresses and brush layers required the same five plant traits, and four species were rated "excellent" for these techniques. Eight species among the ten studied exhibited traits compatible with at least two SWBE techniques, and *Cordia sulcata* and *Tabebuia heterophylla* were the only species to obtain a poor suitability index for all the SWBE techniques considered.

4. Discussion

The species studied exhibited marked variations in survival rates, growth and root:shoot ratio. Among the ten species that can be propagated by cuttings, we identified significant differences in performance and allocation strategies. These first experimental data make it possible

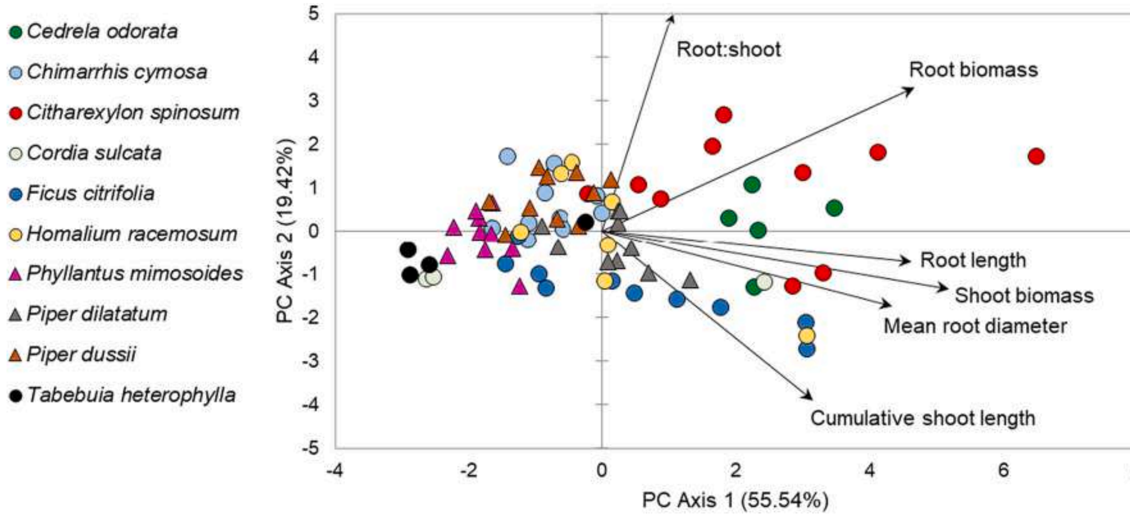

Fig. 4. Principal components analysis (PCA) on seven biotechnical traits of soil bioengineering interest, for 79 cuttings from the ten native riparian species tested. Tree species are identified by circles and shrub species by triangles.

Fig. 5. Uprooted 6-month-old cuttings of the ten Caribbean species tested. a. *Cedrela odorata*, b. *Citharexylum spinosum*, c. *Chimarrhis cymosa,* d. *Cordia sulcata*, e. *Ficus citrifolia*, f. *Homalium racemosum*, g. *Piper dilatatum*, h. *Piper dussii*, i. *Phyllanthus mimosoides*. j.*Tabebuia heterophylla*.

to assess the suitability of the species for different SWBE techniques.

4.1. Performance and biotechnical traits of Neotropical species for SWBE

In the ten species studied here, the survival rates of cuttings ranged between 17% and 93%, comparable to those of other temperate or

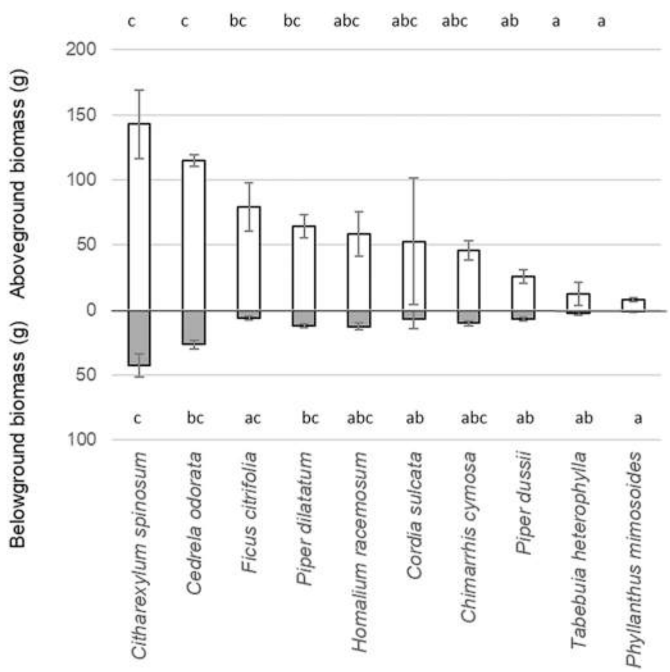

Fig. 6. Bar plot of belowground and aboveground biomass for the ten species studied (*Citharexylum spinosum* n = 10; *Cedrela odorata* n = 5; *Chimarrhis cymosa* n = 10; *Cordia sulcata* n = 3; *Ficus citrifolia* n = 10; *Piper dilatatum* n = 10; *Homalium racemosum* n = 7; *Tabebuia heterophylla* n = 4; *Phyllanthus mimosoides* n = 10; *Piper dussii* n = 10). Thin bars represent the standard error. Different alphabetic designations indicate significant differences between types according to the Kruskal-Wallis test ($P < 0.05$) and Conover-Iman peer-to-peer comparison procedure.

tropical species (references in Table 8). The survival of cuttings depends on a large number of parameters, such as the age of the parent plant that provided the cuttings, with a greater success in cuttings from young plants (Hartmann and Kester, 1963). The place on the plant where the cuttings are collected can also influence rooting success, and younger material collected at the base of the plant have better rooting rates (Zalesny and Wiese, 2006). The period of collection and the duration and conditions of cutting storage before plantation can also impact rooting ability (Bellefontaine, 2018; Hoag, 2000). In our experiment, collections and plantations were conducted during the rainy season, as recommended by Clark and Hellin (1996) and Diaz (2001). We adopted an opportunistic strategy for harvesting the cuttings, feasible in SWBE contexts, deliberately taking into account neither the age nor the architectural position of the branches collected.

For the species studied here that exhibited poor survival rates, it is possible that results could be improved by taking into consideration additional parameters or practices that may influence rooting ability, i.e. diameter (Weissteiner et al., 2019), position in the plant, age of the collected shoot, other hormonal treatments (Hartmann and Kester, 1963), soil conditions (Jean et al., 2020), or inserting a nursery phase to facilitate early cutting development before plantation at SWBE sites (Baird et al., 2015).

During the experiment, some cuttings of *Homalium racemosum, Chimarrhis cymosa* and *Tabebuia heterophylla* sustained noticeable damage due to *Acromyrmex octospinosus*, an alien invasive leaf-cutting ant (Therrien et al., 2019). Despite the low rates of attack (≤15% of the cuttings), this revealed that the ants find these species palatable and particular care to prevent attacks must be anticipated in situ. Attacks by caterpillars on *Citharexylum spinosum* and *Piper dilatatum* concerned 20% of the cuttings but had little short-term impact as the cuttings quickly emitted new leaves afterwards. Greater damage was inflicted by caterpillars on 50% of the *Phyllanthus mimosoides* cuttings; since it occurred at the end of the experiment, no observation regarding leaf emission after the attacks could be made. Repeated leaf damage may affect growth and increase cutting mortality, and herbivory is an important parameter to take into consideration in the implementation of SWBE designs in the Neotropics. These longer-term effects of herbivory could be tested in further, longer in situ experiments.

Eight species had characteristics that suggested a high potential for SWBE. Differences in development and traits were reflected by the two main axes of the PCA along which species were distributed. The first axis represented growth vigor, along which the species were distributed from slow growers to fast growers. The second axis reflected relative resource allocation to the root system. The best-performing species, *Citharexylum spinosum*, combines many characteristics desirable for SWBE. Its high rooting ability, fast growth, and biomass allocation favoring fast and efficient root development, suggest it could be used in a large number of techniques - except fascines, brush layers and brush mattresses because the roots emerge at the basal section only of the cuttings (even though this is less of a problem in the case of brush layers). Despite not performing as well as *Citharexylum spinosum* regarding survival rate and root biomass respectively, *Cedrela odorata* and *Ficus citrifolia* have an interesting potential for the fast stabilization of riverbanks. Their long, thick, and strong roots suggest an efficient strategy, allowing the exploration of a deeper foraging area and ensuring that the cuttings will benefit from a larger and deeper rhizosphere as well as a strong anchorage (Ghestem et al., 2014; Stokes et al., 2009). Species with such traits tend to resist better to droughts or floods (Chapin III et al., 1990; Norris et al., 2008; Rood et al., 2003). Moreover, the roots of tropical *Ficus* and *Cedrela* have the natural ability to self-graft. Anastomoses of aerial roots can thus develop into walls or shields (LaRue, 1952; Ludwig et al., 2019; Rao, 1966) that substantially improve substrate fixation, sometimes to the point of enclosing rocks (Fig. 8) - a characteristic particularly interesting in SWBE. *Piper dilatatum* is the shrub with the fastest growth rate, close to that of the best performing woody species. Added to its high cutting survival rate, this species is another good candidate for various techniques. *Chimarrhis cymosa*, *Homalium racemosum* and *Piper dussii* had a slower growth rate but a good biomass allocation to roots and can also be used in a range of SWBE techniques. Given that the use of tall trees is often discouraged in SWBE at the bottom of riverbanks because of the risk of their being uprooted or tipped over, this gives an advantage to these low trees and shrubs. *Phyllanthus mimosoides* displayed the highest survival rate but low biomass acquisition and poor root:shoot ratio. This species of riparian stands and riverbanks can be found growing directly on gravel bars. It has very flexible aerial parts that respond to frequent floods by bending without breaking. *Tabebuia heterophylla* and *Cordia sulcata* were the least performing species. However, both can still be used in a few SWBE techniques to increase species diversity, system resilience and soil stability (Pohl et al., 2009, 2012). In addition to cuttings, seeds and seedlings of other species than those considered here can be used in order to increase the species diversity: some tree legumes have already been shown to be suitable for SWBE in the Lesser Antilles (Mira et al., 2022).

4.2. *Which species for which SWBE technique?*

Identifying the best plant species for ecological restoration is critical in the Caribbean and elsewhere, and a theoretical framework is currently being developed (Davis and Pinto, 2021). Evaluating and ranking native plants on the basis of biological attributes to optimize their use in restoration is an increasingly applied method (Rantala-Sykes and Campbell, 2019). In this species evaluation study, we employed an innovative approach for SWBE based on the DEXi decision model method for identifying suitable species.

In general terms, SWBE requires a diversity of species that can quickly take root from cuttings, grow fast, and produce a large quantity of biomass, allocated in particular to the root system (Gray and Sotir, 1996; Stokes et al., 2009). However, certain techniques require

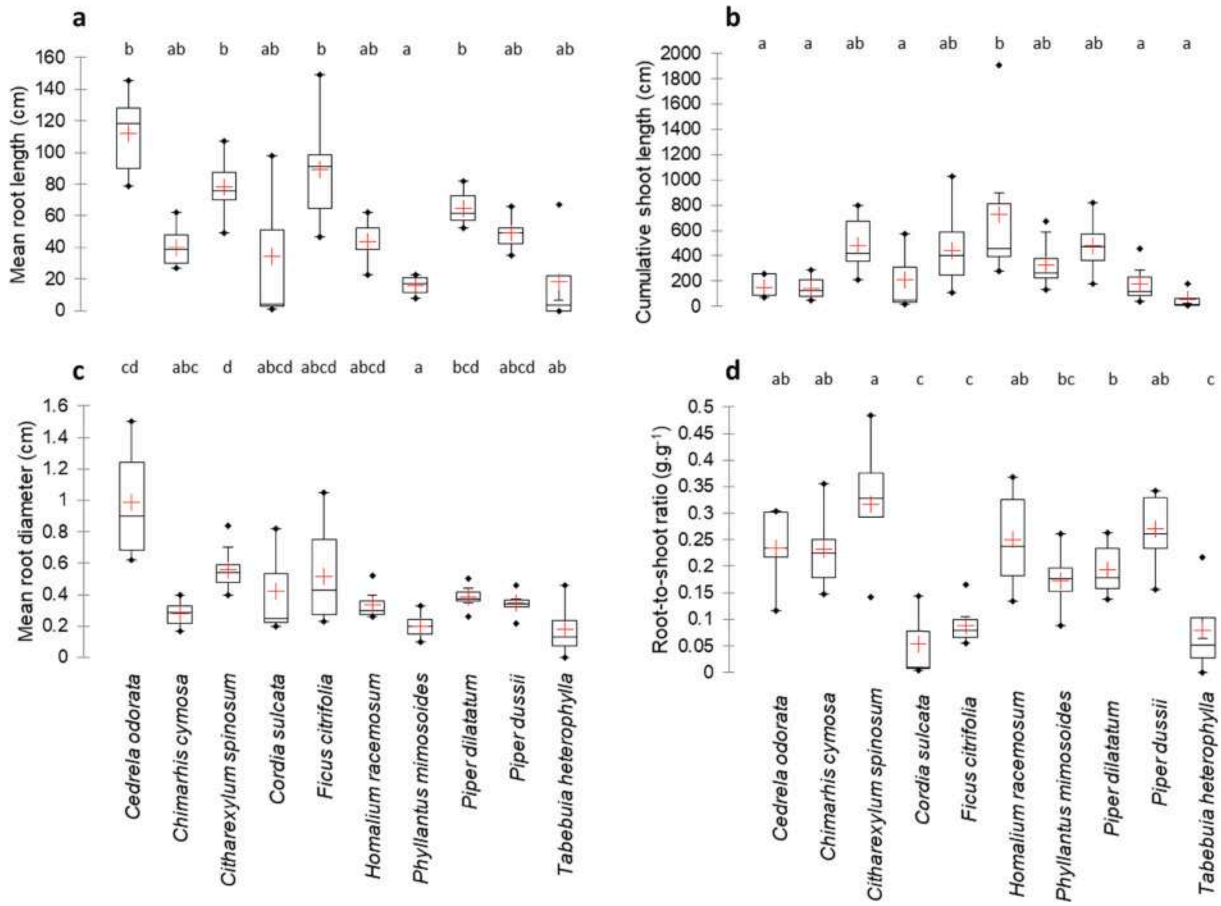

Fig. 7. Boxplots of biotechnical traits (a. Mean root length, b. Cumulative shoot length, c. Mean root diameter, d. Root:shoot ratio) for the ten species studied (*Cedrela odorata* n = 5; *Chimarrhis cymosa* n = 10; *Citharexylum spinosum* n = 10; *Cordia sulcata* n = 3; *Ficus citrifolia* n = 10; *Homalium racemosum* n = 7; *Phyllanthus mimosoides* n = 10; *Piper dilatatum* n = 10; *Piper dussii* n = 10; *Tabebuia heterophylla* n = 4). Boxplot middle lines represent medians, crosses represent means, boxes represent the first and third quartile values, whiskers represent 1.5 x the interquartile range, and points represent outliers. For each trait, different alphabetic designations indicate significant differences between types according to the Kruskal-Wallis test ($P < 0.05$) and Conover-Iman peer-to-peer comparison procedure.

Fig. 8. Root anastomoses in *Ficus*, forming a shield on rocks.

additional, specific characteristics. Live stakes, long branch cuttings and live poles are the basic plant material used in many SWBE techniques (Diaz, 2001; Zeh, 2007). For live staking, species must have a high rooting ability and biomass production. Eight of the species tested here seem suitable for this technique, and the lower-performing *C. sulcata* and *T. heterophylla* can still be included to increase species diversity and improve soil aggregate stability and general resilience of the system to disrupting factors (herbivory, drought, etc.) (Pohl et al., 2009; Stokes et al., 2009).

Species suitable for making live poles must produce straight, long (2–3 m) branches of a large diameter (8–20 cm), strong enough to be driven deep into the substrate without damage (Diaz, 2001; Zeh, 2007). Wood density is strongly correlated with mechanical strength (Pratt et al., 2007). *H. racemosum* excepted, the species tested here have a medium to low wood density, and we noticed some weakness of the wood when hammering the cuttings gently in the pilot holes. It follows that, when implementing a SWBE project, propagation stakes and poles must be planted with caution. Their use in a context of mechanized mass planting operations (e.g. threshing bell) should be tested beforehand.

Fascines, brush mattressing and brush layering require the same set of desirable traits: species that produce a large amount of long, straight branches (1–2 m), capable of taking root when laid horizontally on the substrate and emit flexible ramifications that can withstand frequent floods. In this study, we did not test the effect of cutting orientation, which can impact the rooting rate (Jean et al., 2020). However, we can hypothesize that species that produce adventitious roots all along their buried section in a vertical orientation are more suitable for use in fascines, brush layers and brush mattresses than species in which roots emerge from the basal section only. It would be interesting to test the cuttings in a sub-horizontal position, covering them with a layer of soil, in order to reproduce more closely the conditions encountered with these particular SWBE techniques. Cutting performance could be different, including the distribution of the root system along the stem. Certain results indicate better performances in willow cuttings planted horizontally (Jean et al., 2020), while others suggest that vertically planted cuttings fare better (Edelfeldt et al., 2015).

Table 6
DEXi Attributes corresponding to the selected biotechnical traits for evaluation of the species suitability index for each of the six major types of SWBE techniques. The definition of attributes and their scale are reported in supplementary material, Table S1.

SWBE techniques	Rooting ability	Biomass production	Root: shoot ratio	Diameter	Suitable aboveground architecture	Suitable belowground architecture	Wood density	Root self-grafting ability	Height
Live stakes	x	x	x						
Live poles	x	x	x	x			x		
Fascines	x	x	x		x	x			
Brush matresses	x	x	x		x	x			
Brush layers	x	x	x		x	x			
Vegetated ripraps	x	x						x	x

Table 7
Suitability of the ten species tested for the major SWBE techniques (**** excellent suitability, *** good suitability, **poor suitability, *unsuitable).

	Live stakes	Live poles	Fascines / Brush mattresses / Brush layers	Vegetated ripraps
Cedrela odorata	***	***	*	*
Chimarrhis cymosa	***	****	****	***
Citharexylon spinosum	****	****	*	****
Cordia sulcata	*	**	*	*
Ficus citrifolia	***	***	*	***
Homalium racemosum	***	****	****	**
Phyllanthus mimosoides	***	*	*	****
Piper dilatatum	***	*	****	****
Piper dussii	***	*	****	**
Tabebuia heterophylla	*	*	**	*

Table 8
Non-exhaustive literature review of data on survival rate of cuttings in ex situ experiments.

Species	Location	Survival rate	Duration of the experiment	References
Alnus incana (L.) Moench *Populus nigra* L.	United Kingdom	25–30%	69 days	Francis et al., 2005
Myricaria germanica Desv. *Tamarix gallica* L. *Salix purpurea* L.	France	83–87%	3 months	Lavaine et al., 2015
Salix discolor Muhl. *Salix eriocephala* Michx. *Salix interior* Rowlee	North America	90%	3 months	Keita et al., 2021
Gliricidia sepium (Jacq.) Steud. *Cordia dentata* Poir. *Jatropha curcas* L. *Bursera Simaruba* Sarg.	Nicaragua	34 and 90%	2 months	Petrone and Preti, 2008
Peltophorum pterocarpum (DC.) Backer ex K.Heyne	Malaysia	66%	6 months	Saifuddin et al., 2013
Euphorbia balsamifera Aiton	Africa	42 and 80%	2 months	Bellefontaine, 2018

A low survival rate is not an important constraint for fascines, and species with cutting survival rates as low as 30% can be used. Fascines can even include a proportion of inert material in order to save on live material (Zeh, 2007). The *Piper* species, *H. racemosum* and *C. cymosa* are particularly well-suited to fascines, brush mattressing and brush layering. Moreover, these species, and especially *Piper* spp., are often observed resprouting naturally from fallen trunks or branches lying on the ground.

In Guadeloupe, vegetated riprap is a widespread structure that occurs naturally on riverbanks (Evette, 2015) and its implementation in SWBE has the advantage of stabilizing and protecting riverbanks while at the same time restoring habitat diversity (Evette et al., 2015; Fischenich, 2003). This type of structure is favorable to the spontaneous establishment of pioneer species seedlings. Species selected for vegetated ripraps must have a high rooting ability because accessible areas of soil are small and scattered between the blocks, making it impossible to offset high cutting mortality rates by high planting density. Moreover, species must be small in size because trees of significant height are more likely to destabilize the structure if they tilt over. *Citharexylum spinosum*, *Phyllanthus mimosoides* and *Piper dilatatum* could prove particularly well suited to this technique. Despite their height, *Chimarrhis cymosa* and *Ficus citrifolia* (with its easily self-grafting roots), could also be of interest. One constraint concerning vegetated ripraps is their colonization by alien herbaceous species or climbing lianas, as invasive alien species can cover greater areas on ripraps than on banks treated using other SWBE techniques (Cavaillé et al., 2013; Martin et al., 2021). Invasive alien species are widely distributed in disturbed riparian habitats in Guadeloupe (Gayot et al., 2018) and can compete with live stakes during their first year of establishment. Planting native ground-covering herbaceous species is a low-cost and environmentally-friendly alternative to chemicals for controlling invasive alien species in degraded riparian areas (Viljoen and Groenewald, 1995). Grasses can be effective for controlling erosion because they germinate quickly and produce a dense root network and a complete ground cover (De Baets et al., 2006; Zuazo and Pleguezuelo, 2009). The proposed model based on trees and shrubs could be completed with further results concerning suitable native herbaceous species. Relevant additional knowledge could be gained by focusing on other biotechnical traits, such as stem flexibility to assess species suitability to other SWBE techniques (e.g., wattle fences, etc.) or drought resistance to predict the resilience of species and SWBE-restored sites in the face of climate change. Furthermore, part of the variation observed in the biotechnical traits could be due to the maternal line or the population of origin of the cuttings. These factors should be studied in further experiments to assess how such genetic variability could influence biotechnical traits.

The eight species that gave the most promising results in our study are all widespread in the Neotropics (Rollet, 2010; Fournet, 2002) and, moreover, not being strictly riparian, occur naturally in various terrestrial forest ecosystems. Considering the urgent need for riparian ecosystem restoration, using cuttings of abundant species can increase the number of possible options in reforestation programs, bypassing operational constraints such as having to produce seedlings in nurseries beforehand. These early successional species can thus help the natural recovery of Neotropical forests at large.

5. Conclusion

Our study provides new information on the potential of Caribbean tree and shrub species in SWBE. We present here the first experimental results focusing on the survival, growth, biomass allocation and root characteristics of cuttings from a large selection of native Caribbean riparian species potentially suitable for SWBE. Even though a six-month shadehouse experiment is probably too short, and medium- to long-term monitoring is necessary for a complete evaluation of subsequent survival and performances, our experimental results provide valuable information on the first phase of cutting establishment. They lay the groundwork for further, in situ experiments. Employing an innovative method for SWBE based on DEXi, a modeling tool for multi-criteria decision-making, we show that eight native species possess key traits that make them particularly promising for use in soil bioengineering techniques and in tropical riparian forest restoration at large. The proposed DEXi model, which will be able to be fed with further results on additional species, represents is easy to handle for selecting species for SWBE. Our results open a new avenue for the selection and use of native species for SWBE in the Neotropics.

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Data availability statement

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

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 no conflict of interest. The funding bodies have had no role in the design of the study; in the collection, analyses, or interpretation of the data; in the writing of the manuscript, and in the decision to publish the results.

Data availability

Data are available in a table on the supplementary material

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