Journal of Urban and Environmental Engineering, v.16, n.2, p.110-123

ISSN 1982-3932
doi: 10.4090/juee.2023.v16n2.110123

Journal of Urban and Environmental Engineering

www.journal-uee.org

# PlasME MODEL OF PLANT SELECTION FOR GREEN INFRASTRUCTURE

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Received 17 May 2022; received in revised form 16 October 2022; accepted 18 October 2022

**Abstract:** The process of selecting plant species directly impacts the efficiency and effectiveness of green infrastructure (IV). Despite that the IV can be inserted into the ecosystem concept of urban plants, the selection process for these structures is still done in a reductionist way. The aim of this paper was to present the PlasME model of plant selection for green infrastructure in an interdisciplinary way based on the interface of green technologies and functional ecology. To allow the design of structures that meet multiple objectives, such as pollution control, quantitative control of urban drainage waters, amenities, provision of habitats, places of contemplation and social interaction, the methodology of the work was divided into 3 phases. Initially, the key interdisciplinary terms were discussed: urban ecosystem, green technologies, bioretention systems, and functional ecology to structure the foundations of a new paradigm of planning and design of the urban ecosystem. Second, a dynamic and iterative species selection process was carried out based on the functional ecology of the interface of a kind of BS (Bioretention System) functions and the attributes of the vegetation in an BS. Finally, the third step was the application of the BS vegetation definition process in resting regions (typical coastal sandbank vegetation) in southern Brazil. The main functional attributes considered in the selection process were root depth, root system density, relative growth rate, root thickness, and leaf surface area, which directly influence the Ecosystem functions (EF) of regulation and purification of BS as interception, flow regulation, infiltration modification, perspiration, erosion control, and pollutant removal. At the end of the selection process, the following species were chosen: *Myrcia palustres*, *Lantana* sp, *Sphagneticola trilobata*, *Plumeria rubra*, *Vrisia friburguenses*, and *Typha domingensis,* considering the services of the regulatory and cultural ecosystem, as well as the EF already specified. The development of the process was dynamic and iterative, providing a new perception of the role and functionality of bioretention systems for the urban ecosystem, expanding to a more interdisciplinary and integrated process of adding structures to the urban space. The model can be improved by adding other ecosystem services using the same methodology we carried out.

**Keywords:** Urban Waters; Bioretention Systems; Functional Ecology; Plant Selection

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## INTRODUCTION

An evaluation of the historical evolution of stormwater management shows that, according to the systematization made by Fletcher *et al.*, (2014), the functions of drainage structures start from simple flood control, in the 1960s, to more extensive functions, such as recreation, pollution control, restoration of the flow regime, ecology of receptor bodies, use of rainwater as a resource, resilience, and microclimate, among other functions, today. This enhancement of functions is related to a systemic vision of the city and the various services involved in its management, as well as to multifunctionality as an emerging concept toward more intelligent and sustainable cities.

In the 1960s and 1970s, in the context of a growing focus on environmental issues, scholars and professional's began to give greater recognition to an ecological approach in urban planning and design (Wu, 2014; Heymans *et al.*, 2019). In the early 1960s, Landscape Ecology emerged, aiming to integrate varied and complex ecosystems and their biodiversity into urban planning (Heymans *et al.*, 2019), concomitant with the transition from quantitative to quality-quantitative hydrology. In 1972, the U.S. Water Act was published, with the proposal of BMPs (Best Management Practices), which reflects on the multidisciplinary nature of rainwater management. In 1977, the concepts of Low Impact Urban Development (LID) emerged, culminating in an alliance for natural hydrology, gaining more prominence during the 1980s and 1990s (Fletcher. *et al.*, 2015).

In the 1980s, Urban Ecology emerged, considering the interactions between natural and socioeconomic processes, evaluating cities as a unique ecosystem (Heymans *et al.*, 2019), i.e. expanding the concept of "insertion of the natural into the urban" of landscape ecology, to the vision of cities as an urban ecosystem (Heymans *et al.*, 2019). Increasingly multidisciplinarity has converged with interdisciplinarity in urban ecosystem planning. During 2000, Functional Ecology was solidified by providing for the use of functional classification schemes to examine the responses of ecosystems and organisms to disturbances and changes (Laureto, Cianciaruso and Samia, 2015). Thus, the historical sequence of rainwater management evolved from a multidisciplinary area to an interdisciplinary level, converging systemic, ecological, and structural thinking to integrate the design and planning of urban ecosystems (**Fig. 1**).

In recent years, in urban stormwater management, there has been an amplification of the quantitative control of drainage for the qualitative control of stormwater (NRC, 2008) in a decentralized manner, integrated with landscaping, as well as the understanding of the direct and indirect multifunctionality of these structures for urban ecosystems (Blum, 2016; Mak *et al.*, 2017; Christofidis *et al.*, 2019).

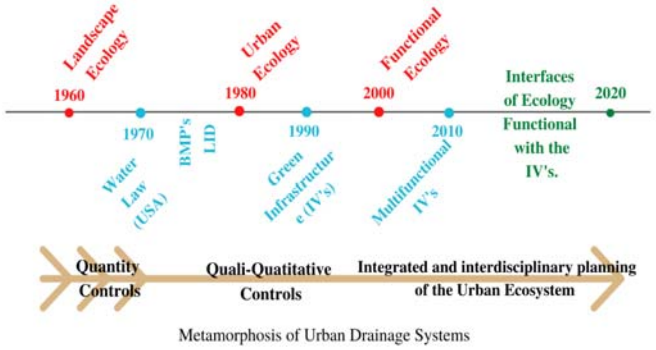


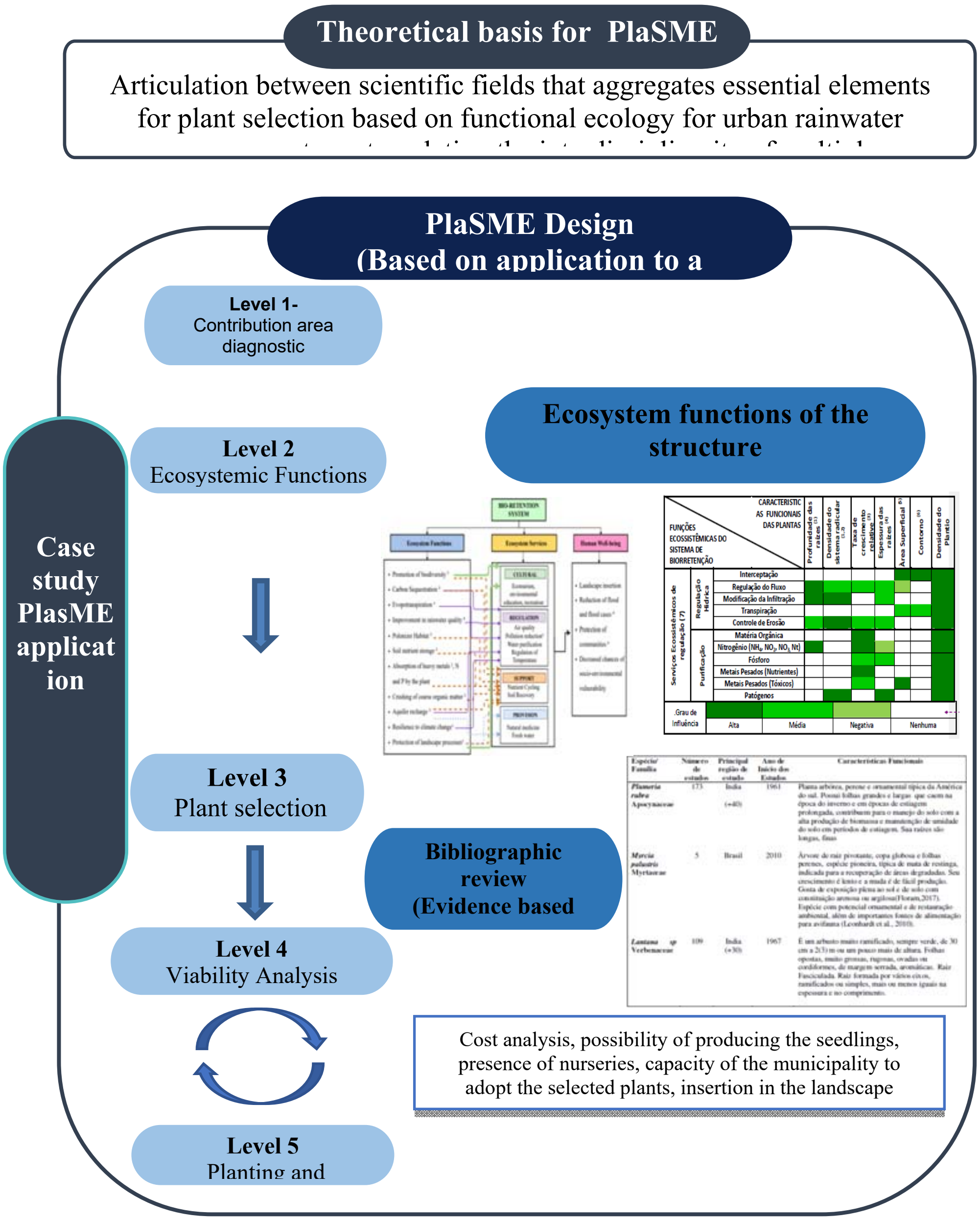
**Fig. 1** Timeline of Interdisciplinary convergence in urban ecosystem planning.

Unlike mono-functional "grey" planned infrastructure, green infrastructure (IV's) enhances and synergizes the benefits provided by nature (Hansen and Pauleit, 2014) in a multifunctional way. Along with interdisciplinarity, urban drainage has metamorphosed from grey technologies that accelerate runoff and focus on the distance of rainwater to green and compensatory technologies that integrate with the Urban Ecosystem.

In this context of nature-based solutions, Bioretention Systems (BS) (Winogradoff and Coffman, 1999) represent one of the most promising types of urban drainage control structures, developed from the characteristics and hydrological properties of a terrestrial forest ecosystem (Prince George's County, 2002). BSs are approached in a multidisciplinary way (Barraud *et al.*, 2002) in various areas of knowledge, including engineering, hydrology and hydraulics, surface flow and groundwater, soil science, horticulture, and landscape architecture (Davis *et al.*, 2009; Levin and Mehring, 2015). These systems have been internationally recognised as one of the best practices for rainwater management ( Dietz and Clausen, 2005, Davis *et al.*, 2009; Li *et al.*, 2008; Palhegyi, 2010). Its application and function have also varied according to the evolution that has been observed in the control of urban drainage over time. BS is an urban drainage control technique and has great potential to provide ecological functions, as well as regulating, purifying, and cultural ecosystem services for the urban ecosystem.

The fact that the IV's are inspired by forest systems makes urban water management more effective, with great potential for interdisciplinary governance of the Urban Ecosystem (Hansen and Pauleit, 2014; Lakshika Weerasundara *et al.*, 2016; Rathman *et al.*, 2017). Moreover, it has the potential to bring out interdisciplinarity by requiring greater interaction between disciplines around a problem situation,; consequently, a more integrated urban plan of the microsystem (Bioretention Systems) will enhance its ecosystem functions for the macrosystem (urban ecosystem).

Therefore, studies that integrate ecological concepts and functions in the development and improvement of IV's have great potential to expand their functions and bring greater advantages. The structure of green technologies is based on the use of water-soil-plant systems (SASP) to provide quality-quantitative control of rainwater, as well as the recovery of the urban ecosystem. Thus, the plant selection process is a critical design parameter, which impacts the efficiency and effectiveness of these systems. Although there is evidence that the presence of plants improves effluent quality, as well as extends the control of water volumes, it is not clear how plant specific characteristics influence the removal of pollutants or evapotranspiration and, therefore, which species or types of species are most suitable for use in BS (Read *et al.*, 2008). Furthermore, there are few studies that have assessed the plant characteristics that are determinants in hydraulic performance, nitrogen removal, pathogen presence, the role of trees in BS (Dagenais, Brisson and Fletcher, 2018), and how plants can integrate the ecological functions of these structures. There are several technical manuals for designing BS, including FAWB (2009), Prince George's County (2002), and Minessota Stormwater Mannual (2017), but few studies have correlated the performance of green technologies with the functional characteristics of plants (ABSjornsen *et al.*, 2011; Wang *et al.*, 2014; Dagenais *et al.*, 2018; Payne *et al.*, 2018), as well as with Bioretention systems.



| FUNÇÕES ECOSSISTÊMICAS DO SISTEMA DE BIORRETENÇÃO \ CARACTERISTICAS FUNCIONAIS DAS PLANTAS | | | Profunidade das raízes (1) | Densidade do sistema radicular (1,2) | Taxa de crescimento relative (3) | Espessura das raízes (4) | Àrea Superficial (5) | Contorno (6) | Densidade do Plantio |
|---|---|---|---|---|---|---|---|---|---|
| Serviços Ecossistêmicos de regulação (7) | Regulação Hídrica | Interceptação | | | | | ■ | ■ | ■ |
| | | Regulação do Fluxo | ■ | ▨ | ▨ | ▨ | ░ | | ■ |
| | | Modificação da Infiltração | ■ | ■ | | ▨ | | | ■ |
| | | Transpiração | | | | | ▨ | ▨ | ■ |
| | | Controle de Erosão | ▨ | ■ | ▨ | ▨ | | | ■ |
| | Purificação | Matéria Orgânica | | | ■ | | | | ■ |
| | | Nitrogênio ($NH_4$, $NO_2$, $NO_3$ Nt) | ■ | | ■ | ░ | | | ■ |
| | | Fósforo | | | ▨ | ▨ | | | ■ |
| | | Metais Pesados (Nutrientes) | | | ■ | | | | ■ |
| | | Metais Pesados (Tóxicos) | | | ▨ | | ■ | | ■ |
| | | Patógenos | | ■ | | ■ | | | ■ |

| .Grau de Influência | ■ | ▨ | ░ | □ |
|---|---|---|---|---|
| | Alta | Média | Negativa | Nenhuma |

**Fig 2.** Methodological procedure for PlasME development

To deepen the multi-functionality of BSs and to evolve from a multidisciplinary to an interdisciplinary context and from efficiency to effectiveness, this article presents the development of a methodological selection procedure for green infrastructure based on functional ecology, called PLasME (Plant Selection Methodology based on functional Ecology), which is focused on a systemic and iterative process. This tool was built by aggregating the principles and objectives of technologies based on the use of plants and the systemic control of rainwater in urban ecosystems: principles of Nature-based Solutions (NbS), functional ecology, phytoremediation, detention, retention, and infiltration. Sustainability increases the resilience of the urban diffuse pollution. To do so, we started from a conceptual structure of the ecological use of IV's, such as the BS in Urban Ecosystems, which materialized in a practical example of selection of plant species for BS. This process was applied in the selection of plants in a field experiment with real BS implanted in an area of the Atlantic Forest Restinga in the South of Brazil, Florianópolis-Santa Catarina/Brazil.

## MATERIALS AND METHODS

The procedures for the development of the methodology for plant selection were based on functional ecology (PlaSME) and articulated according to the flow chart shown in the **Fig. 3**.

First, the various scientific fields that could contribute to a more objective, targeted, and scientific selection of plants were raised. Then, PlasME was effectively created, considering the scientific contributions from the previous stage. There were 5 stages of development. The presentation of the stages of creation of PlasME was illustrated with a case study of the application of the methodology to the selection of species for a BS located in the coastal city of Florianópolis, south of Brazil.

### Theoretical basis for plant selection methodology based on functional ecology - PlasME

In the current paradigm of urban development, anthropic actions in rainwater management, when purely technical and mechanistic, become ineffective and unsustainable both environmentally and economically. The result has been chaotic cities, in which solutions are thought out in a disconnected way from the whole and are focused on only one aspect of the system dynamics, which often presents greater externalities than the initially projected benefits. In this context, the urban environment increasingly needs interdisciplinary and systemic approaches. One of the growing approaches that can reduce the externalities in rainwater management is the understanding of Cities as Urban Ecosystems (Levin and Mehring, 2015), i.e. formed by biotic and abiotic interactions and flows of energy, matter, and nutrients.

The ecology of ecosystems tracks the flow of energy, water, nutrients, and other materials through the system and determines how these flows interact with the environment and organisms. The big difference between natural and urban ecosystems is that the primary drivers in urban ecosystems are human beings with their goal-oriented technology and behaviour, not the abiotic factors, such as climate and nutrients, that govern natural ecosystems and influence the persistence, extinction, interaction, and adaptation of species (Adler and Tanner, 2015).

With population densification and high urban growth, forest-based IV's and NbS present themselves as an important alternative for the recovery of cities by reducing energy consumption, increasing nutrient cycling, and reducing waste (Levin and Mehring, 2015). According to Li (2016), Urban forests, parks, woods, green roofs, wetlands, rivers, and other natural spaces play a key role in improving urban environments, as well as offering opportunities to improve the ecological processing of pollution and moderate the local climate. These systems are based on natural systems, and in addition to preventing natural disasters and reducing areas of vulnerability in cities, they reduce negative externalities in/to the river catchment area and neighbouring catchments. The open space also offers ecological amenities, including shade from trees, aesthetic benefits of the natural setting, and leisure space, for all citizens. They are new technical and ecological possibilities that add value and multifunctionality to public spaces, thus contributing to environmental quality in cities (Benini, 2015).

Green Infrastructure (IV’s) includes a range of products, technologies, and practices that use natural systems - or designed systems - that mimic natural processes. IV converges in the recognition of the role of soil and plants (natural drainage systems) for the urban ecosystem, directly impacting the processes of infiltration, evapotranspiration, retention, and inactivation of pollutants in soil and plants (Souza *et al.*, 2012; Fletcher *et al.*, 2015; U.S.EPA, 2017). IVs in urban ecosystems represent the arteries of cities, passing in different ways through the urban water cycle (surface, ground, and waste water) and providing regulatory, provisional, and cultural functions for the urban ecosystem (Pataki *et al.*, 2011; Hansen and Pauleit, 2014).

SASP compensates for the urban water cycle and remedies, to varying degrees, the pollutants carried by runoff to surface and groundwater bodies. Therefore, from an ecological perspective, these systems can provide resilience, resistance, and sustainability for the urban ecosystem. Resilience is understood as the system's ability to remain unchanged after a disturbance, resilience is understood as the system's ability to recover after a change promoted by a disturbance (Fragoso *et al.*, 2009), and "sustainable development is a process of change in which the exploitation of resources, the direction of investments, the direction of technological development and institutional changes are in harmony and increase the current and future potential to meet human needs and aspirations" (WCED 1987, p. 46). It is simultaneously an objective, a process, and a discipline of global interest, involving local nuances and aims (Heck *et al.*, 2018). Thus, sustainability in cities mobilizes all disciplines and fields of knowledge for their scalable impact and the complex analyses and solutions they demand (Sotto *et al.*, 2019).

Another concept integrated into the systemic and interdisciplinary vision of IV's is phytoremediation, a set of techniques that use plants as a means to remedy contaminated environments, involving processes, such as extraction, immobilization, retention, and/or degradation of pollutants (EPA, 2000). Phytoremediation has been considered an environmentally effective alternative, as it does not cause disturbances to ecosystems, and it comes at a lower cost than other remediation technologies (Lasat, 1999). Reeves (2003) presented several species of plants, mostly tropical, with the potential to phytoremediate heavy metals. In BS, it was possible to identify a significant reduction in the concentration of some heavy metals, highlighting that the growth and harvesting practices of the species present in the environment could potentiate the removal of metals (Davis *et al.*, 2003). In addition to SASP processes, BS is associated with Phytoremediation, which can be enhanced using the concepts of Functional Ecology.

Functional Ecology is a new approach that associates the morphological or physiological characteristics of plants with their function in the ecosystem. The parameters for evaluating the ecosystem functions of plants are called functional attributes, which are morphological, ecophysiological, biochemical, and demographic characteristics of an organism considered relevant to its response to the environment and/or its effects on the function of the community ( Meirelles, 2013). These present characteristics optimize

the perception between vegetation and environmental changes because a functional type aggregates a group of plants that affects the environment in a similar way or that present a similar response to the same environmental variations (Mioduski and Moro, 2011). According to Fernandes (2018), to understand the correlations between different traits and their interactions with abiotic components of the degraded environment, there should be greater generalizations and predictions regarding the performance of individuals of different species. Furthermore, they reflect the ecological strategies of species in response to environmental factors and are associated with several important ecological processes of ecosystems at different scales (Pérez-Harguindeguy *et al.*, 2013). Thus, use of the functional attributes of plants becomes an important tool for designing studies of green technologies from the point of view of being structures of recovery and increasing the resilience of urban ecosystems.

The theoretical conception of the plant selection process that we propose in this work incorporates the concepts of these areas of knowledge articulated to enhance the design and operation of technologies that use vegetation for some type of control in the city (**Fig. 1**). The selection of plants becomes more conscious, directed to the desired function of the structure, and becomes a critical point for the design of technologies used in green infrastructure. In the case presented here with the application of the selection process, we deal with the use of BS for urban drainage and water control.

Plant selection is not a topic explored in drainage or BS control manuals, nor in scientific literature. Hunt (2015) synthesised from the literature the following species selection criteria for BS: form of growth (extensive root structure), water requirement, density of planting (increases root density, maintains infiltration capacity, and surface porosity), high variety, and types of species (plants are able to "self-select" appropriate establishment areas), as well as local rules of landscape insertion. Central Coast LID Initiative (2018) considers plants that are: tolerant to varying conditions of humidity (wet and dry), tolerant to varying soil types and growing conditions, low maintenance requirements, non-invasive weeds, not having aggressive / invasive root systems, and having an attractive appearance. The manual of the Prince George's County (2007) reefers to the spatial arrangement of plants, but does not specifically list criteria for their choice. Its indications for the spatial arrangement are: a minimum of three tree species and three shrub species to ensure diversity, protection from insect and disease infestation's, and can ensure a more constant rate of evapotranspiration and absorption of nutrients and pollutants throughout the growing season. Furthermore, they indicate the use of herbaceous forage to prevent erosion of the mulch and soil layers, combining at least 3 to 4 species of herbaceous cover, with two to three shrubs for each tree. Plants at the bottom of the BS that are closest to the entrance need to be the most tolerant to high flow and frequent flooding.

Plants represent a fundamental component of green structures and verifying the scarcity of work aimed at the choice of species, we developed a methodological procedure for selection. This procedure is based on the principles of the functional ecology of plants integrated with their phytoremediative capacities, as shown in Fig. 3. We will use BS as an example of green infrastructure, but the procedure could be used with any other type of structure, such as grass filters or infiltration ditches. Although we are reEFrring to BS, it is important to clarify that other types of IV could use the same reflections.

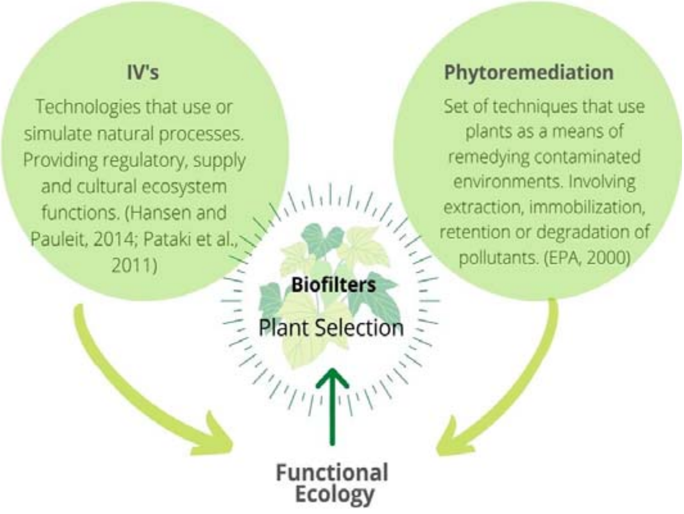


**Fig. 3-**Synthesis of the theoretical basis for PlaSME - Plant selection Methodology based on Funtional ecology

### Design of plant selection methodology based on functional ecology – PlasME applied to a bioretention system

The proposed methodological procedure aimed not only to be a technical contribution, but an alternative to the reductionist paradigm of plant selection for IV's, which were basically based on the questions: Will plants survive variation in humidity? Will they maintain soil infiltration? Are they efficient in retaining contaminants? In this new systemic paradigm, plants enhance SASP and increase the efficiency and effectiveness of green infrastructure, and nature-based solutions. The greatest effectiveness was considered when extending the useful liEF and sustainability of the system with minimal anthropic intervention. For example, when through the association of plants, the system not only retains the contaminants by phytoremediation (it can in the future re-insert contaminants into the soil), but stabilizes the contaminants and re-inserts it in the cycle of a natural ecosystem, in the circular flow of energy, matter, and nutrients.

In **Table 1**, the 5 steps proposed in the methodology are detailed and organized in order of action; within each step, the description of the action is detailed, as well as the main reflection to be carried out before the decision is taken. The methodological procedure proposed by PLasME was composed of 5 levels: 1) diagnosis of the area of contribution and selection of the structure, 2) study of the ecosystem functions of the structure, 3) selection of the species, 4) viability analysis, and 5) planting and management plan for the selected structure. This is an iterative process because it depends on the local characteristics identified at the diagnostic stage and on the viability of acquiring the seedlings. It can also be used to create a database of local species correlated to their functional characteristics.

### Diagnosis of the area of contribution

The first phase (Level 01) was the diagnosis of the area where the structures were implanted, as well as the native soil and local vegetation type. The proposed methodology was applied for the selection of species in a coastal ecosystem located on the Island of Florianópolis, Santa Catarina, southern region of Brazil. The region of Florianópolis is located in an ecosystem with predominant vegetation of Restinga belonging to the Atlantic Forest. The word "Restinga" is used both for geomorphological aspects and for plant formations that cover the coastal sandy plains (Suguio and Tessler, 1984). Restingas are located along the entire Brazilian coast (Lacerda *et al*., 1993). Along the South and Southeast regions, from the boundary with the ocean to the first elevations of the Serra do Mar, Restingas are present (Rizzini, 1997). In 2018–2019, this ecosystem had a 22.4% increase in the deforestation rate per year in the state of Santa Catarina and 27.2% at the national level (encurtador.com.br/ctBD7, accessed at 08/2020), showing that the integration of preservation with urban planning is an emergency. At this phase, the study of BS focus was later implemented.

### Ecosystem functions of the structure and Functional Ecology

### Ecosystem functions

Step 2 consisted of defining the ecosystem functions that the green structure is intended to present. In this work, the terms function and services are adopted according to Costanza *et al*. (1997), where ecosystem functions refer to different habitats, biological, or systemic properties or processes of ecosystems; and services (such as waste assimilation) represents the benefits that human populations derive, directly or indirectly, from ecosystem functions (Pacheco, 2020).

The functions are generally grouped into four primary categories: regulatory function (ability of ecosystems to regulate ecological processes essential to sustain liEF through nutrient cycles, water regulation and supply, soil formation, pollination, and other processes), habitat function (essential to biological conservation, genetic diversity, and evolutionary processes), production function (ability of ecosystems to provide food for human consumption), and information function (ability of natural ecosystems to assist in maintaining human health by providing opportunities for reflection, spiritual enrichment, cognitive development, recreation and aesthetics) (Hall, 2009).

**Table 1.** The 5 steps proposed in the methodology procedure proposed by PLasME

| Level | Actions | Description of Main | Action Reflection | Interdisciplinary Decision Making |
|---|---|---|---|---|
| 1 | Diagnosis of the area of contribution | Characterization of the hydrographic basin: Type of basin, land use and occupation, waterproofing rate, presence of commercial areas and type of businesses, type of vegetation... | What is the ecosystem need for this basin? (Process of physical, hydrological evaluation of the basin and participatory, as the project has to be integrated with local needs). | Linear structures, linear parks, control structures at the source, multifunctional use (Leisure areas, contemplation, and detention). |
|  | Diagnosis of the installation area of the structure | Area characterization study: Height of the water table in relation to the surface, infiltration rate, distance from the urban infrastructure network, presence of heavy traffic roads. Possibility of integration with municipal projects. | How will IV's integrate this ecosystem (from the needs diagnosed in the previous step)? | Type of structure: Detention, retention, infiltration, quantitative regulation qualitative regulation. |
| 2 | Study of the EF structure | Each structure can perform different ecosystem functions, as presented in Fig. 4. At this stage, a survey of the EF of the system is carried out. | What functions can I prioritise to increase the effectiveness of the system (remembering that effectiveness is related to sustainability and resilience)? | Adoption of Phytoremediation.<br>Diagnosis of the types of contaminants.<br>Control of the soil infiltration/collapse process. |
| 3 | Selection of species | From the EF surveyed and prioritized in the previous stage, a survey of functional characteristics of species suitable for the structure are determined. | What are the main functional characteristics for my system (**Table 2**)? | For the selection of the species, determine the dossier of plants with all the functional characteristics (native species, types of growth, types of roots, interaction with other species, redundancy of functions...). |
| 4 | Viability analysis | Access to seedlings, cost value, ease of reproduction of the seedlings, house of vegetation by the municipality, ease of access to native species adopted | The cost of acquiring the plants compensates for the functional and landscape gain? | At this stage the selected species should be reviewed, and if it is not Feasible to return to level 3. Evaluate the possibility of using a non-aggressive exogenous species, if it is more viable |
| 5 | Planting and management plan | This phase is of utmost importance for the sustainability of the post design system. It includes an irrigation plan for the adaptation period of the plants (stress in the moulting phase interEFres with the plant's functionalities in adult liEF) and extraction of aggressive species. | Is my system really integrated with the ecosystem and the local community (review of local consultation and adaptations are needed)? | Will the system be managed by the municipality, or will it be participatory with the local community (the greater the local involvement with the structures, the longer its liEF span, integration with the ecosystem, and lower operating costs)? |

We present in **Fig. 4** the diagram of ecosystem functions of a bioretention system as a synthesis of this step. BS, or rain gardens, are basically composed of a plant surface over a filter layer, usually with of a mixture of native soil/sand/clay and silt, followed by a transition layer and a drainage layer. Each layer has a regulatory and supporting ecosystem function, i.e. they not only aim to compensate for the loss of infiltration, evapotranspiration, and baseflow areas, but also to solve the pollution problems linked to contaminants carried in the runoff, as well as to provide habitats for micro- and meso- fauna and flora. Within an BS, the treatment is carried out by a variety of unit processes that use the chemical, biological, and physical properties of plants, microorganisms, and soil (filter medium) to remove pollutants from urban runoff (Liu *et al*., 2014), as well as mimicking hydrological functions to reduce surface runoff and assist in flood control.

Superficial vegetation strategically helps to maintain soil permeability by avoiding clogging, in addition to slowing down surface flow and filtering sediment. The roots support microbiological populations that can benefit the degradation of the contaminant and water quality. They have benefits for breaking down pollutants, based on carbon and nutrients, and in absorbing non-biodegradable pollutants, such as metals (Dietz and Clausen, 2005). Plant species vary physiologically, chemically, and morphologically and can also vary considerably in root exudate composition and exudation rates (Read *et al*., 2008), influencing the performance of runoff water treatments.

ASPs have diversified ecosystem functions that generate ecosystem services for the urban environment and, consequently, bring well-being for the city's inhabitants. The plants are directly related to the 4 groups of ecosystem services that can be provided by an BS. They act on the environmental and landscape aspects related to cultural services. They are linked to the processes of regulation as they promote water purification, perspiration, pollutant retention, and reduction of heat islands. At the same time, they participate in nutrient cycling and soil recovery and, thus, act as elements that provide fresh water and natural medicine through the possibility of producing herbal medicines. These ecosystem services are provided from ecosystem functions (**Fig. 2**).

Ecosystem functions that generate ecosystem services can be related to functional ecology. Thus, plant attributes that are related to functional ecology can be used as a targeted way of choosing plants from the role (or function) that they are expected to perform.

## Functional characteristics of plants

The ecosystem functions of green infrastructure provide improvements to the urban environment by addressing issues, such as air and water pollution and flooding. Assessment of the functional characteristics of plants helps in the development of more resilient and sustainable SASP systems. The most commonly used functional characteristics are presented in **Table 2**.

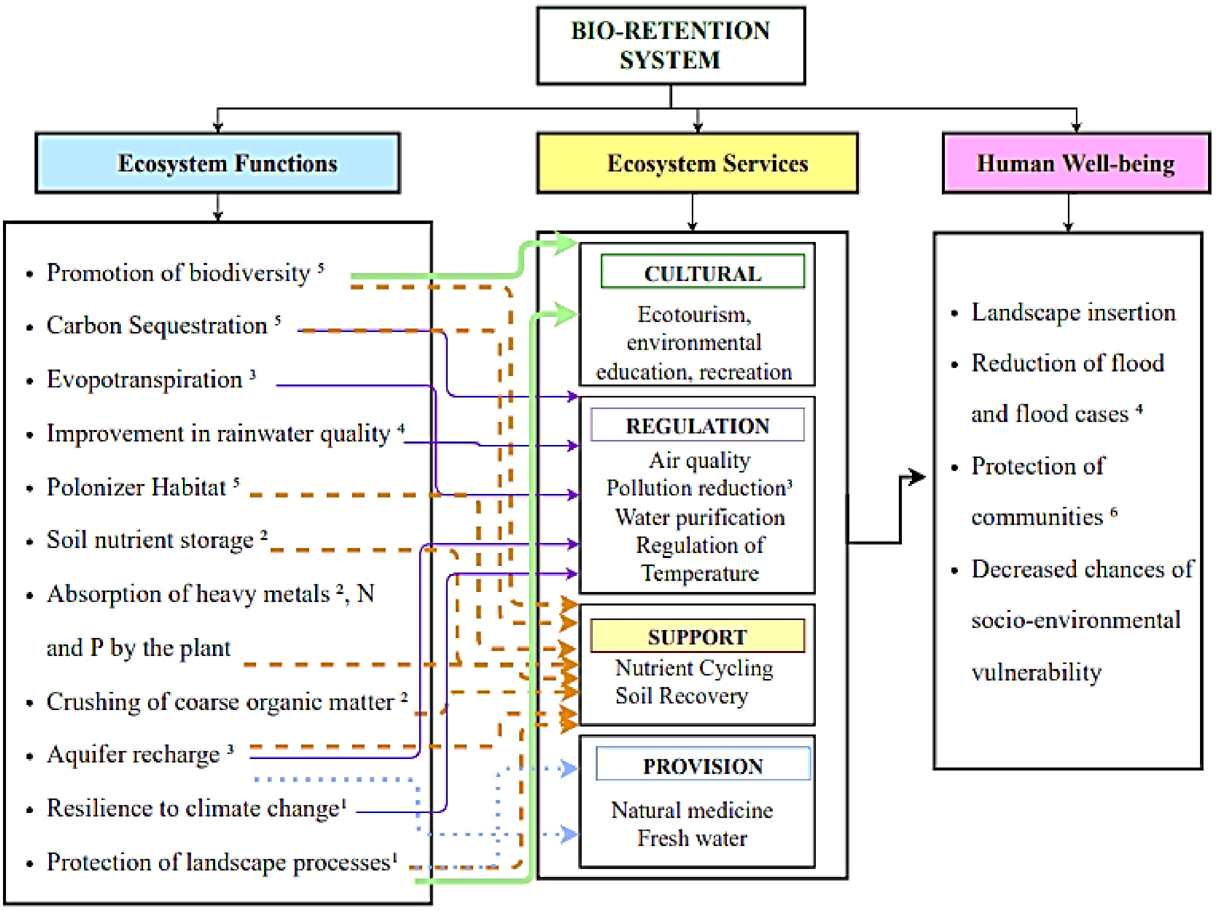


**Fig. 4** Ecosystem functions provided by the Bioretention Systems. (1: Ihimatsu *et al*., 2017, 2: Mehring *et al*., 2016, 3: Hsieh e Davis 2005; Davis 2008; Thompson *et al.* 2008; Carpenter e Hallam 2010 apud Nocco, 2016, 4: Bondar, 2014, 5: Ambrose, 2015; 6: Carvalho, 2015

**Table 1.** Functional characteristics and methods of production

| **Functional characteristics** | | **Analysis methods** |
|---|---|---|
| Sheets | Surface Area | (a) Sheets surface area. The total area of each sheet (FAD), in cm², was calculated by:<br>FAD = MST * ATD * MSD-1 (1),<br>Where: MSD is the dry mass of the discs, ATD, the total area of the discs, and MST, the total dry mass of the sheets (Maldaner *et al.*, 2009)<br>(b) Sheet length and width product method (HF = C x L), length (C) and width (L) measurement, scanning and processing in image, portable leaf area integrator method, bench top leaf area integrator method, square method, fresh leaf disc mass method, and dry leaf disc mass method (Zeist *et al.*, 2014) |
| Roots | Depth of roots | (c) Square method, proposed by Marsh (1971), Tennant (1975), apud (Filho *et al.*, 2004)<br>(d) Scanning (Partelli *et al.*, 2006) |
| | Density of the root system | (e) Scanning<br>Quant Root v. 1.0 (Guimarães *et al.*, 2013): Win Msc Rhyzo", versão 3.8. (Beulter and Centurion, 2004) |
| | Relative growth rate | (f) Growth measurements were made with the aid of a measuring tape. According to the equation:<br>$TA = \left( \frac{C^2}{T^2} - \frac{C^1}{T^1} \right)$<br>Where:<br>TA = growth rate (cm d-1);<br>C2 and C1 = average leaf length at times 1 and 2 (cm);<br>T2-T1 = interval between collections (days) (Esteves, 1998; Tostes *et al.*, 2013) |
| | Thickness of roots | (g) Program "QuantRoot" (Freitas *et al.*, 2004):<br>(h) FFScanning<br>The wall thickness was obtained with the aid of micrometric eyepieces. To measure the thickness of the cortex, style and total thickness of the roots, a projection microscope with an increase of 5/0,25μm. (Tostes *et al.* (2013) |

Root characteristics, such as depth, directly influence the infiltration rate of the filter medium, as the greater the depth of the roots, the greater the infiltration rate (Stuber, 2012;Palmer *et al.*, 2013). Additionally, long and thin roots improved nitrogen removal (N) (Payne *et al.*, 2018;). However, thick roots can negatively influence nitrogen (N) retention by creating preferred pathways and not allowing the necessary time of contact with soil microorganisms. Ideal plants for bioretention systems are plants with high above-ground biomass and thick and extensive roots (to improve the removal of pollutants, increase perspiration, and prevent clogging of the environment) (Winfrey at al, 2018). This information strongly suggests that plant species with large root masses with larger diameter roots and root hairs are most effective in removing N and phosphorus (P) from rainwater runoff in BS. Plants for BS should have high nutrient absorption to maximize the benefits of pollution control. Leaf characteristics, such as specific surface area (SSA), influence perspiration and conversion of contaminants. Nutrient uptake can be achieved through high N and P fractions in biomass and/or high total biomass. According to Palmer (2013), the greater the efficiency of water use, the greater the conversion of perspired water into biomass, and the lower the concentration of leached contaminants in the underground environment. The increase in the growth rate generates an increase in biomass, which helps in the removal of pollutants (Di Luca *et al.*, 2018).

**Table 2.** Degree of influence of the interface of Functional Characteristics of plants and Ecosystem Functions of BS

| BIO-RETENTION ECOSYSTEM FUNCTIONS | | FUNCTIONAL CHARACTERISTICS OF PLANTS | Depth of roots $^{(1)}$ | Root density $^{(1,2)}$ | RGR $^{(3)}$ | RRT $^{(4)}$ | Surface Area $^{(5)}$ | Contour $^{(6)}$ | Planting Density |
|---|---|---|---|---|---|---|---|---|---|
| Ecosystem Regulatory Services (7) | Hydraulic regulation | Interception | | | | | ■ | ■ | ■ |
| | | Flow Regulation | ■ | ▨ | ▨ | ▨ | ░ | | ■ |
| | | Infiltration Modification | ■ | ■ | | ▨ | | | ■ |
| | | Perspiration | | | | | ▨ | ▨ | ■ |
| | | Erosion Control | ▨ | ■ | ▨ | ▨ | | | ■ |
| | Purification | Organic Matter | | | ■ | | | | ■ |
| | | Nitrogen ($NH_4$, $NO_2$, $NO_3$, N) | ■ | | ■ | ░ | | | ■ |
| | | Phosphorus | | | ▨ | ▨ | | | ■ |
| | | Heavy Metals (Nutrients) | | | ■ | | | | ■ |
| | | Heavy Metals (Toxic) | | | ▨ | | ■ | | ■ |
| | | Pathogens | | ■ | | ■ | | | ■ |

| Level of influence | ■ | ▨ | ░ | |
|---|---|---|---|---|
| | High | Average | Negative | None |

RGR: Relative Growth Rate; RRT: Relative Root Thickness (1, 4, 5, 6) Wifrey (2018); (1) Payne (2018) and Palmer(2013); (2) Read (2007); (3) Di Luca *et al.* (2018); (7) Muedter (2018)

Serrated leaves (leaf contour) have more ASE than rounded leaves, as well as increased interception for water control (Winfrey at al, 2018). Regarding pathogens, plants with associated mycorrhizal fungi have higher assimilation of P (Palmer, 2013), and the decrease in the infiltration rate has a negative impact on the removal of pathogens (Winfrey, Hatt and Ambrose, 2018).

Thus, from the literature review, the ecosystem functions of Bioretention Systems were systematized and related to the functional characteristics of the plants (**Table 3**) and the degree of influence between the parameters, that is, the main ecosystem functions of BS and the enhancement of these functions from the functional characteristics of the species. This table can be used in the design phase of new SASP-based system projects, according to the objective of using the structure.

From the conclusions of phase 2, the biofilter in question could be deployed to comply with regulatory and cultural ecosystem services by prioritising the following ecosystem functions of BS (Fig. 4): evapotranspiration, improved water quality, soil nutrient storage, adsorption of heavy metals, nitrogen and phosphorus, and promotion of biodiversity.

## Plant selection

In phase 3 (level 03), a survey of sandbank plants associated with the Atlantic Forest Domain were determined for multifunctional BS (detention, infiltration, water regulation, and purification), complemented by adoption of the principles and use of phytoremediation systems. A survey of native plants that were resistant to climate variations, humidity variations, and that were already used by the municipality for urban landscaping (this point was not determinant but it facilitated the process of acquiring the seedlings) was carried out.

For phase 3, the functional characteristics of the plants and whether they were native to the Atlantic Forest, systematization of the literature on these species, and a survey of arboreal species suggested by the Municipal Environmental Agency and Floram-Fundação Municipal do Meio Ambiente, were prioritized as selection criteria for urban landscaping. The following species were selected: Jasmim-catavento (Tabernaemontana catharinensis), Carobinha (Jacaranda puberula), Lantana camara, Douradinha (Tibouchina asperior), Algodoeiro da praia (Androtrichum trigynum), Cipó da praia (Ipomoea pes-caprae L.), Bromélia (Dyckia encholirioides), and Bromélia (Aechmea lindenii). This set of information was used to create a bibliometric survey similar to evidence-based surveys, widely used in health and medicine (Conforto *et al.*, 2011; Jesus, 2013; Cohen, 2017)

In the second stage of the selection, the bibliometry of the pre-selected plants was performed in the CAPES, Scopus, and Web of Science journals (**Table 4**), and the identification of the main scientific areas of application were in Biological Sciences and Agriculture. The bibliometry is important to identify species that have already been used in phytoremediation and if they have some contraindication in the adoption of some exogenous applications, investigating if it is an aggressive species in the context to be used. In this case and in the proposal to develop a system of Bioretention applied in a control system at the source (functional focus), one arboreal, 3 herbaceous, and one shrub plant were selected, considering the characteristics presented in **Table 1**. A greater number of herbaceous species were prioritized due to sandy soil and roots that contain soil erosion, i.e. very thick and deep, which was indicated for plants that perform the treatment, optimizing the treatment and preventing contamination of the aquifer.

Of the selected species, the only one that was not identified for use in phytoremediation was Vrisia friburguense, but records were found for the use of species of the Bromeliaceae family for phytoremediation of Cs and Sr (Zheng, Pemberton and Li, 2017) and Radon absorption (222Rn), with a positive correlation with the leaf surface area (Li, Pemberton and Zheng, 2015). The species Plumeria rubra was among the plants with one of the highest rates of Air Pollution Tolerance (APTI), considering the following parameters: amounts of ascorbic acid, chlorophyll, relative water content, and pH of leaf extract. *Typha domingensis* was the best documented of all species studied for use in wetland systems, as well as Bioretention systems. Plant Lantana presented detailed studies of the translocation of the following metals in the plant to Cu and Zn leaf> stem, to Cr and Mn, leaf> stem, to Ni root> stem and to Pb root> stem respectively (Pandey and Bhattacharya, 2018).

## Viability study

The viability study (phase 4) aimed to identify if there were any impediments or difficulties in the application of the selected plants. In our methodology, we started from the following reflection in decision making: Does the cost of acquiring the plants offset the functional and landscape gain? From this stage, we identified the challenges that make the use of the selected plants unEFasible, and phase 3 was carried out again.

**Table 3.** Bibliometry and the dossier of the selected species

| *Specie*<br>**Family** | **NC** | **Functional Characteristics** |
|---|---|---|
| *Plumeria rubra*<br>Apocynaceae | 173<br>India<br>(+40)<br>1961 | Typical tree, perennial and ornamental plant of South America. It has large and wide leaves that fall in the winter season and in periods of prolonged drought, contributing to soil management with the high production of biomass and maintenance of soil moisture in periods of drought. Its roots are long and thin. |
| *Myrcia palustris*<br>Myrtaceae | 5<br>Brazil<br>2010 | Pivot-rooted tree, globular crown and perennial leaves, pioneer species, typical of Restinga forests, indicated for the recovery of degraded areas. Its growth is slow, and seedlings are easy to produce. It likes full exposure to the sun and sandy or clay soil. (Floram, 2017). Species with ornamental and environmental restoration potential, as well as important bird food sources (Leonhardt, Calil and Fior, 2010). |
| *Lantana sp*<br>Verbenaceae | 109<br>India<br>(+30)<br>1967 | It is a very branched bush, always green, from 30 cm to 2(3) m or a little higher. Opposite leaves, very thick, rough, ovate or cordiform, with a sawn edge, aromatic. Fascinated root. Root formed by several axes, branched or simple, more or less equal in thickness and length. It has rapid growth, high biomass, strong perspiration rate, high tolerance to stress (Agamuthu, 2019). It can grow in extreme conditions, resistant to long periods of drought or heavy rainfall (Jusselme *et al*., 2012). |
| *Sphagneticola trilobata/*<br>Asteraceae | 65<br>Brazil<br>(+20)<br>1996 | Herbaceous, stoloniEFrous, and perennial. It has a prostrate stem with roots along the knots of ascending branches, capable of forming dense populations. Simple leaves, opposite crossed often trilobed, yellow flowers, interlaced superficial roots that act in erosion control (Luciana *et al*., 2017). |
| *Vrisia Friburguenses*<br>Bromeliaceae | 1646<br>Brazil<br>(+750)<br>1933 | The reduced size body, rhizomatous habit,<br>photothermic stem (biological tanks), trichomes for foliar absorption, xeromorphic adaptations (Prado, 2012). The leaves are arranged in rosette, lanceolate, wide, with parallel ribs, usually fibrous, rarely fleshy, with smooth edges. |
| *Typha domingensis*<br>Typhaceae | 541<br>USA<br>(+150)<br>1911 | It is a perennial, herbaceous, rhizomatous, aquatic plant, which can reach up to 3 m in height and exhibits propagation by both seeds and vegetation (Cruz, 2017). |

NC = Number of studies/Country/year.

In our case, the criteria for the use of native species that already had commercial sales, or that were already reproduced by municipal nurseries, was inserted due to the technical difficulty of obtaining the species. Therefore, we carried out phase 3 twice; the first time, we selected the following species: Jasmim-catavento (*Tabernaemontana catharinensis*), Carobinha (*Jacaranda puberula*), Lantana camara, Douradinha (*Tibouchina asperio*r), Algodoeiro da praia (*Androtrichum trigynum*), Cipó da praia (Ipomoea pes-caprae L.), Bromélia (*Dyckia encholirioides*), and Bromélia (*Aechmea lindenii*).

All were native to Restinga forests, but the only ones produced by the municipal nursery and marketed were Lantana and Bromeliads. Thus, we repeated phase 3 and validated the following species: *Myrcia palustres*, *Lantana spp*., *Sphagneticola trilobata*, *Plumeria rubra*, *Vrisia Friburguenses*, and *Typha domingensis*. These were produced by the municipal nursery, except *Pluméria rubra*, which were bought in floricultures.

## Planting and management plan

Phase 5 corresponded to the management and planting plan, and we based our reflection on the following: Is my system really integrated with the ecosystem and the local community? (review of local consultation and adaptations are needed). Thus, the project was presented to the Campeche District Residents' Association and a participatory decision making process was initiated to select the public spaces that could be used for the installation of the project, but this phase was interrupted due to legal issues in the selected area.

In the organization and planting, some of the plants were considered resistant and tolerant to humidity, and met the needs for the speed of growth and the guidelines cited in Topic 3. They could also control aggressive weeds by means of natural mechanisms, using native forage to Sphagneticola Trilobata, which helped in soil cover, erosion control, and clogging.

## CONCLUSIONS AND RECOMMENDATIONS

The main objective of this paper was to revisit the species selection process from an ecological perspective, not focusing on being just a selection tool but a proposal to break the paradigm with an in-depth, holistic and interdisciplinary look at the implementation and selection of vegetation species for green infrastructure. With this focus, it was important to highlight that in the process of applying the systemic and interactive process, the researcher created another link with the object studied. In recognizing and valuing local potential in the maintenance, recovery, and resilience of the of the studied ecosystem.

In this proposal, it was important to change the urban environment and develop the capacity to appreciate these places from the perspective of being an organisational form of an ecosystem (circular flow of energy, matter, and nutrients). The IV's were already structures based on forest systems that when implemented, converged their ecosystem functions with the functional ecology of plants and expanded the capacity for self-regulation and sustainability of the Urban Ecosystem. The natural cycles of the forest were improved by assimilating nutrients, pollutants, and metals through interactions between plants, soil, organic layer, and fauna. Thus, we saw how green infrastructure technologies intrinsically possess this potential for ecosystem recovery and can be used to improve the urban environment.

Functional ecology improved the plant selection process by using the characteristics present in different local species in an experiential way. Within the focus of the article, which prioritized the experience of the selection process with the creation of linkage and admiration of local vegetation (provided in the construction of the dossier), there was evolution from the perspective of urban infrastructure planning, leaving it more systemic.

When the functional characteristics of the plants in PLasME and the methodology for BS were considered, it was possible through step 3 (iterative systemic process) to optimize the multifunctionality of the system because the bibliometry and the dossier of the plants directly influenced the decision making of the choice of species. Another experience with this approach to the dossier was with the selection of fodder species (plants of great importance for the control of erosion in the support medium of the plants), when carrying out the dossier a fodder plant was selected not only because it was native but also because it was a phytoremediary plant. This fact could only be verified after the application of the iterative systemic process of plant selection, as well as its multifunctionality.

The main contribution of this article was to reflect on the current paradigm of rainwater management and to enhance the design of green infrastructure through the bias of urban ecosystem recovery systems. In addition, to deepen the use of functional attributes (root depth, root system density, relative growth rate, root thickness, leaf surface area) as a procedural tool for species selection. From the in-depth study of the ecological functions of plants in SASP, a more sustainable proposal could be verified, which included the selection of an interdisciplinary process, prioritizing greater effectiveness for the sustainability of the Urban Ecosystem.

From a theoretical discussion, the selection of species for BS directly influenced the ecological functions of regulation and purification of BS, as well as its interface with the ecosystem services offered by the structure to the urban ecosystem, influencing the processes of infiltration, evapotranspiration, retention, and inactivation of contaminants and pollutants in soils.

The development of the dynamic and iterative process provided a new perception about the role and functionality of the Bioretention Systems for the Urban Ecosystem, extending to a more interdisciplinary and integrated process of the structures to the urban space. In the application of the methodological procedure, it was possible to verify the optimization of the process by expanding the multifunctionality of the species, reducing the cost and feasibility of installation. It can be used as an inspiring and motivational tool for urban planning and design, as well as in the development of new projects for monitoring and deepening the BS and in the design of other green infrastructures.

**Acknowledgment** The authors are very grateful to CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) for scholarship grants, CNPQ (Conselho Nacional de Pesquisa) for supporting research activities, and Municipal Prefecture of Florianópolis for the partnership in this research.

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