Article

Green Roof Design with Engineered Extensive Substrates and Native Species to Evaluate Stormwater Runoff and Plant Establishment in a Neotropical Mountain Climate

Carlos Vicente Rey, Natalia Franco, Gwendolyn Peyre and Juan Pablo Rodríguez *

Environmental Engineering Research Centre (CIIA), Department of Civil and Environmental Engineering, Universidad de los Andes, Bogotá 111711, Colombia; cv.rey1496@uniandes.edu.co (C.V.R.); n.franco253@uniandes.edu.co (N.F.); gf.peyre@uniandes.edu.co (G.P.)

* Correspondence: pabl-rod@uniandes.edu.co; Tel.: +57-133-949-49 (ext. 2804)

Received: 24 June 2020; Accepted: 4 August 2020; Published: 13 August 2020

Abstract: Green roofs are increasingly being implemented in cities for their multiple environmental benefits. Their optimal design requires an appropriate selection of components, including substrates and plant species, to ensure local sustainability in the long term. The present study seeks to assess the runoff quality and quantity of extensive green roofs located in Bogotá (Colombia). The assessment consists of testing different substrates, designed using locally available constituents and a selection of native species. The best performing substrate mixtures, in terms of runoff volume reduction and plant establishment, were jointly evaluated with three native species (i.e., Paepalanthus alpinus, Achryrocline bogotensis and Echeveria ballsii). On average, engineered substrates presented significantly lower concentrations in several water quality parameters (electric conductivity, total phosphorus, phosphates, Total Kjeldahl Nitrogen, nitrates, nitrites, color, biological oxygen demand and chemical oxygen demand) than the commercial extensive substrate used as control. The species Paepalanthus alpinus and Echeveria ballsii showed significant establishment and were considered potentially suitable species for green roofs in Bogotá. The obtained results, therefore, provide recommendations for green roof design in neotropical mountain climate conditions.

Keywords: green roofs; multicriteria analysis; stormwater management; multifunctionality; plant trait approach; substrate composition; native species

1. Introduction

Modern cities keep growing and developing in terms of population and sustainability. In 2030, 61% of the world’s population is expected to live in urban areas, while in Latin American countries, city dwellers should account for 89% of the population [1]. Rapid changes in population density are associated with increasing pollution, loss, fragmentation and reconversion of green spaces. Such impact on green spaces affects the connectivity of urban landscapes and also increases the frequency of flooding, due to the low infiltration rates [2,3]. Due to the growing need to manage the side effects of urbanization, green infrastructure like green roofs (GRs) are a suitable solution for urban stormwater management and native plant species conservation, as well as promoting valuable ecological interactions with pollinators [4–6].

Recent studies suggest that GR implementation should be considered a multi-objective solution [5,7–9], prioritizing the consideration of several criteria including stormwater retention, plant establishment, thermal benefits and runoff quality improvement. In order to achieve these objectives, further efforts should focus primarily on GR design (substrate composition, depth and...
plant species selection), considering the weather conditions and local availability of the materials that will serve as substrate components [5,10,11]. It is expected that substrate composition influences GRs environmental benefits, meaning that the accomplishment of one objective could mean the deterioration of another [12,13]. For instance, maximizing a GR’s plant diversity can cause a reduction in the stormwater retention potential [13]. Otherwise increasing a GR’s stormwater retention through the selection of certain components may compromise thermal benefits [7] or may cause deterioration in runoff quality [10]. Another criterion is substrate depth that has been associated with native species survival; for example, deeper and specifically designed substrates (>10 cm) can improve the establishment of native herbaceous plants without irrigation [14], however, increasing substrate depth can also diminish runoff quality [15]. Therefore, adequate substrate design and plant species selection is required to guarantee the fulfillment of different objectives.

It is necessary to include substrate materials that allow sufficient water holding capacity (WHC) (>20%) and adequate porosity (>10%) to ensure plant establishment, according to the minimum GR requirements established by the German Society of Research on Landscape Development and Landscape Construction (Forschungsgesellschaft Landschaftsentwicklung und Landschaftsbau—FLL) [16]. When designing substrate composition, inorganic materials such as aggregates are normally used in higher volumetric proportions (80–90%) than organic amendments (10–20%) due to their light weight and physical properties that improve stormwater retention [5,7,8,10]. Regarding WHC and stormwater retention, several studies attributed better performance to deeper substrates [10]. Jim and Peng [7] recommended deeper substrates as well as lightweight materials (i.e., compost, perlite, vermiculite and calcined clay). However, others had previously concluded that particle size distribution could be a more significant factor [17]. An adequate selection of both inorganic and organic components must assure the appropriate physical and chemical properties of the substrate to maintain WHC and allow the establishment of vegetation cover, while mitigating runoff pollution.

Vegetation cover of extensive GRs is commonly composed of succulents, small herbs, grasses and mosses due to their overall suitability for shallow substrates and low water retention requirements. It is an important criterion that the selected species have different structural and functional characteristics to avoid allelopathy [18]. Species selection may differ between temperate and tropical climates [10–12]. Succulents such as Sedum species are widely used in temperate climates due to their hardness, relatively shallow roots, water storage capacity and Crassulacean acid metabolism (CAM) photosynthesis, which minimizes water loss [4,19,20]. In tropical climates, native plants with different growth forms including ferns, grasses and vines, are used on GRs along with often non-native succulents [21,22]. Fai et al. [22] evaluated different species in Malaysia and found that native fern Nephrolepis biserrata outperformed other non-native succulent species, namely Sedum mexicanum, in terms of plant coverage and visual appearance when irrigation was provided.

However, in subtropical climates, research on GRs remains limited. Particularly for Bogotá it is important to review successful temperate and tropical case studies, since its climatic conditions are at a crossroads between these two climates due to its latitudinal and altitudinal situation.

As a result of emerging markets, many GR companies have been appearing in most South American countries, but despite recent research efforts, the understanding of GR performance and design under local conditions is still limited. Research on GRs has been carried out in Brazil, Colombia and Ecuador. In Brazil, the studies of Castiglia and Wilkinson [23,24] and Parizotto and Lamberts [25] assessed GRs’ thermal and hydrological performance using different substrates depths, whereas Noya et al. [26] focused on the relative capacity of different substrate compositions to maintain native herbaceous perennial and succulent species. In Ecuador, Jaramillo et al. [27] obtained a broad list of potential native plant species for GRs in Quito using a combined approach of habitat templates and climatic envelopes, recommending the grass (Eragrostis lucida), herbs (Plantago sericea) and shrubs (Lantana canescens). In Colombia, there have been some studies on quantity and quality performances and productive potentials of GRs [28–30], but few on native plant selection [31]. Specifically, in Colombia’s capital, Bogotá, which presents a neotropical mountain climate, GRs are
becoming more and more common, and their use as part of sustainable construction initiatives is being encouraged by the local environmental authority [32]. Through the local guide of GRs and green walls (GWs) [32], constructors can find recommendations of native and non-native species that can thrive in rooftop conditions (i.e., orchids, succulents and ferns), and also recommended volumetric ratios of inorganic components (70–80%) and organic amendments (20–30%). However, the guide does not specify certain substrate mixtures for specific plant traits, which can be a source of relevant information of typical characteristics that are present in plants used in GRs [33,34].

Taking into account the importance of the design process of extensive GRs and the limited research on tropical climates, specifically in neotropical mountain environments, this study focused on three main goals: (i) Evaluate the stormwater retention efficiency of several aided GR designs using local components and native species; (ii) Analyze the GRs’ substrate composition capacity to mitigate runoff pollution; (iii) Identify native species with different growth forms that show complementarity and can successfully establish under the extensive GRs’ conditions without irrigation.

2. Materials and Methods

2.1. Study Site

Several experimental GR modular systems were set up on the rooftop of the Physics Department (5 stories high) of the Universidad de los Andes in Bogotá, Colombia (4°35′56″ N 74°04′51″ W; 2640 m.a.s.l.), where they evenly received permanent natural light. The local climate is characterized as a neotropical mountain, it has a mean annual temperature of 14.5 °C, and an annual rainfall that ranges between 600 and 1200 mm with a bimodal rainfall regime of two dry periods (December, January, February and July, August, September) and two rainy periods (March, April and October, November) during the year [35].

2.2. Experimental Setup

The experimental setup was divided into two phases. The first one consisted of fourteen different extensive GR modular substrates, and the second phase had four substrates selected from the first setup, each one with three replicates, for a total of twelve modular extensive GRs. The first setup was evaluated from November 2016 until February 2017. At this phase, twelve different extensive substrate mixtures (further described in Section 2.3.1) were developed and evaluated together with two commercial substrates (i.e., M1, M2, . . . , M14). One extensive commercial substrate, designed for shallow depths (<15 cm) and the other for deeper substrates (>15 cm), hence referred to here as intensive (Figure 1). The fourteen substrates were planted with three common species: Armeria maritima (Mill.), Festuca glauca Vill., and Gnaphalium antennarioides DC. The purpose of the setup was to preselect four substrates to make further evaluations on the following setup. The second setup was rearranged, using the three best performing substrates from the first setup and the best commercial substrate. Three replicates were made for each substrate. Each modular system was then planted with three native species (further described in Section 3.2) and was evaluated from March to August 2017 (Figure 1).

Each modular system was composed of two plastic recipients of 35 cm × 23 cm and 15 cm tall. One recipient held a filter fabric of 2 mm and a substrate layer of 10 cm that supported the selected species, and the other was used to collect the stormwater runoff (Appendix A). In the second experimental phase the same modular systems were used to hold the preselected substrates and the native species.

Weather data (i.e., rainfall depth, air temperature, relative humidity) were collected throughout the experimental period using a Davis weather station model Vantage Pro 2, in order to evaluate the effect of these variables on the GRs performance. Precipitation depth was measured using a tipping bucket rain gauge with a sampling rate of one second and a 0.2 mm resolution. Rainfall retention was measured as the percentage of the volume of water retained by the substrate layer and intercepted by the vegetated coverage, hence not converting into runoff. Therefore, each module was left to dry...
for 6 hr which was determined to be the time needed for the substrate to drain completely under our specific environmental conditions, as calculated recently by Ferrans et al. [28].

Figure 1. Experimental setup description. Detail of the modular substrate design (vegetation cover, substrate composition) in the two experimental phases with their corresponding monitored variables. Substrates represented with letters BS and CS are the three best performing mixtures and the best performing commercial substrate, selected for Substrate–Plant Evaluation. Three replicates of each substrate were used for the Substrate–Plant Evaluation.

2.3. Substrate and Plant Selection

2.3.1. Substrate Composition

Twelve substrate mixtures were prepared by combining the recommended organic amendments and inorganic aggregates that were locally available, in volumetric ratios of 20% and 80%, respectively [5,7,8,10]. The organic compounds used were, namely, humic soil (So), compost (C), coco peat (CP) and rice husk (R). Organic compounds were used in different proportions within the mixtures (Table 1). Inorganic aggregates were differentiated according to their particle size as coarse, in this instance, coarse pumice (Pu) and expanded clay (EC), and fine, namely zeolite (Z), perlite (P) and sand (S). Aggregates were added in different ratios to the various mixtures (Table 1). Two additional, commercially available substrates were used as a reference to compare the performance of the twelve mixtures. The commercial extensive and intensive substrates had 27.4% and 15.9% of organic matter, respectively.

Table 1. Extensive substrate mixture volumetric ratios (%) of organic and inorganic components.

| Mixture | Compost (%) | Humic Soil (%) | Coco-Peat (%) | Rice Husk (%) | Coarse Pumice (%) | Expanded Clay (%) | Sand (%) | Zeolite (%) | Perlite (%) |
|---------|-------------|----------------|---------------|---------------|------------------|------------------|----------|------------|------------|
| M1      | 20          | 0              | 0             | 0             | 60               | 5                | 5        | 5          | 5          |
| M2      | 20          | 0              | 0             | 0             | 40               | 10               | 10       | 10         | 10         |
| M3      | 0           | 20             | 0             | 0             | 60               | 5                | 5        | 5          | 5          |
| M4      | 0           | 20             | 0             | 0             | 40               | 10               | 10       | 10         | 10         |
| M5      | 0           | 0              | 20            | 0             | 60               | 5                | 5        | 5          | 5          |
| M6      | 0           | 0              | 20            | 0             | 40               | 10               | 10       | 10         | 10         |
| M7      | 5           | 5              | 5             | 5             | 60               | 5                | 5        | 5          | 5          |
| M8      | 5           | 5              | 5             | 5             | 40               | 10               | 10       | 10         | 10         |
| M9      | 10          | 0              | 10            | 0             | 60               | 5                | 5        | 5          | 5          |
| M10     | 10          | 0              | 10            | 0             | 40               | 10               | 10       | 10         | 10         |
| M11     | 0           | 10             | 10            | 0             | 60               | 5                | 7.5      | 0          | 7.5        |
| M12     | 0           | 10             | 10            | 0             | 40               | 10               | 15       | 0          | 15         |
| M13     | Commercial Extensive Substrate |
| M14     | Commercial Intensive Substrate |
2.3.2. Substrate Physical Properties

Particle size of the inorganic aggregates presented the following ranges: Pu (4.8–9.5 mm), Z (1.2–2.4 mm), S (0.6–0.9 mm), EC (4.8–12.5 mm) and P (0.08–2.4 mm). Additionally, the mixtures were evaluated to identify their feasibility in terms of weight, WHC, and bulk density in both dry and water-saturated conditions. Bulk density and WHC were calculated based on a sample of 100 cm$^3$ following the guidelines of the FLL [16].

2.3.3. Substrate Preselection

Preselection was evaluated with common species because it was necessary to have some certainty of the development and performance of these growth forms, before asking for the collection permit that was demanded by the national environmental authority, in order to extract the native species. Two criteria were used to evaluate the mixtures: (i) stormwater runoff retention (evaluating 9 rainfall events, see Table A1), and (ii) plant establishment, measured in terms of appearance and growth rate. From November 2016 to February 2017, during the preselection phase, total precipitation was 690.4 mm, with November being the rainiest month (245.6 mm) and February the driest (121.2 mm). Mean temperature was 15.16 °C throughout this period (Appendix B—Figure A2).

Appearance was determined based on the scale proposed by Monterusso et al. [36], in which 0 represents a dead plant and 5 accounts for a healthy plant. Relative growth rate was measured by calculating the ratio of the difference between the potential approximate volume (assuming a cylindrical shape of the plants by measuring the radius and height of each individual) at the end of the month and at the beginning, to the approximate volume at the beginning of that same month.

2.3.4. Common Plant Species

Three common species available at a local nursery were selected to evaluate plant establishment, after checking that none had an invasive tendency, in the sense of high seed production and effective dispersal [18] whilst not posing a threat to local environments. There was no allelopathy between the commercial species, thus, there was no competition among them. These species were partly chosen because they presented different growth forms, namely herb, turf, and cushion, which are important in evaluating the differences in the establishment of each form and are normally used in gardens and GRs for their ornamental value. The selected species were: *Armeria maritima*, a Plumbaginaceae native to most of the northern hemisphere; *Festuca glauca*, a Poaceae native to Europe, which is often used on GRs in temperate areas; *Gnaphalium antennarioides*, a common Asteraceae native to the northern Andes (Figure 2).

![Figure 2. Common species used for substrate preselection.](image)

2.3.5. Multicriteria Plant Trait Approach

Native plant species were selected using the multicriteria plant trait approach [34], following the methodology used by Van Mechelen et al. [33] that used information of 53 functional traits and 14...
utilitarian aspects that were related to plant adaptation to GR conditions, to find the most frequent characteristics present on these species. This methodology was adapted to the local environmental conditions. A list of 176 different species was obtained by summing up the recommendations of five recent GR guidebooks and manuals that were considered suitable sources for this study case: (i) *Green Roofs and Green Walls, Practical Guide*, Secretaria de Ambiente de Bogotá [32]; (ii) *Ecological gardening and green roofs* [37]; (iii) *Green Roofs in the Caribbean Region* [38]; (iv) *Plant catalogue for green roofs* [39]; (v) *Green Roofs and Green Walls Guide* [40]. To filter the list, information on six exclusion criteria was filled out for each species, based on the methodology proposed by Van Mechelen et al. [33] and the recommendations of the local guide for GRs [32]. Exclusion criteria included the following: (i) root length >15 cm, (ii) life-form: trees, (iii) plant height >80 cm, (iv) little drought tolerance, (v) requirement of nutrient-rich and deep soils, (vi) plant elevation range not centered around 2640 m (Bogotá’s elevation). After filtering with the exclusion criteria, the list was reduced to 98 species. For those resulting species, information was completed using the Colombian plant catalogue [41] and Tropicos [42] search system, for nine functional and three utilitarian traits that were relevant for plant adaptation and for which information was possible to collect (Table 2). Five additional aspects relating plant adaptability to the specific zone of use were found to be relevant as these aspects define physical conditions that are important for plant establishment and were also included after revising the Bolaños and Moscoso [31] tool for native species selection for Green Infrastructure (GR and GW) in Colombia.

**Table 2.** Plant traits and aspects used to evaluate characteristics present in plants used in green roofs (GRs).

| Zone Adaptability | Functional | Utilitarian |
|------------------|------------|-------------|
| Origin           | Leaf area  | Seed dispersal |
| Altitude range   | Leaf shape | Flowering period |
| Climate          | Life form  | Shoot Growth form |
| Soil             | Reserve organ |                |
| Drought tolerance| Photosynthesis |                |
|                  | Strategy   |              |
|                  | Reproduction |            |
|                  | Height     |              |
|                  | Woodiness  |              |

2.3.6. Selection Tool

Using the previous data on the functional and utilitarian traits of 98 species obtained from the consulted literature, a selection tool was developed in order to evaluate native species that might thrive under extensive GR conditions. The resulting evaluation system (Appendix D) was based on the tool developed by Bolaños and Moscoso [31]. Several categories were established for each trait and a score was attributed to each category according to their frequency, so that the most frequent category of each trait had the highest score [33].

2.3.7. Native Plant Species

To select potentially adequate native species to be tested, a list of 45 species was elaborated by gathering information from studies carried out by the José Celestino Mutis Botanical Garden in Bogotá [43,44], the Colombian plant catalogue [41], and further suggestions made by Peyre (pers. com.). To filter the list, some species were discarded by elevation range (not including 2600 m.a.s.l.), plant height (>60 cm) and risk of invasiveness, resulting in 11 species to be evaluated with the selection tool. The final selection identified the three species with the highest scores, and which were most representative of the growth forms of the commercial species used for the substrate preselection. The selected native species did not engage in allelopathy to eliminate neighboring plants and are species that favor their own establishment and survival by interacting with facilitators present in the soil (fungus, bacteria, etc.).
All plants were collected either in Bogotá or at the adjacent Páramo of Las Moyas (4°39'11" N, 74°01'52" W; 3141 m.a.s.l.), which is a little higher than Bogotá and presents common high-Andean grassland vegetation. Twelve mature individuals of each species were collected. One individual of each species was planted in each module and evaluated together with three replicates of the preselected substrates. According to local availability, collected individuals differed in their vegetative and reproductive conditions, which means that none of them had the same size and development state, presenting an initial variability for growth and appearance analysis.

2.4. Metrics for Substrate—Plant Evaluation

Performance of the native species and the preselected substrates was assessed based on the analysis of rainfall retention, plant establishment (appearance and growth) and water quality. Additional information of some of the physical properties (i.e., bulk density, WHC, weight) was already measured for these substrates in the previous phase.

2.4.1. Rainfall Retention

Retained volume was calculated as the difference between the effective rainfall volume and the runoff volume held by a plastic recipient located below each of the mixtures. Rainfall retention was measured for 17 independent events (Table A1) that generated runoff (in order to avoid considering very small events that would not surpass any substrate WHC). The rainfall events occurred between March and August 2017. In this period, the total precipitation depth was 646 mm, with March being the rainiest month (232.8 mm) and July the driest (37.6 mm). Mean temperature of these months was 15.18 °C (Appendix B—Figure A2).

2.4.2. Water Quality Analysis

Water quality analyses carried out in a laboratory were performed for five rain events. Runoff samples were collected from the storage recipients located beneath the modular systems. Two additional rainfall samples, one from a rainfall collection recipient and the other the runoff from a plastic panel installed 5 m from the experimental setup and simulating a conventional roof, were collected and used as reference values to contrast the quality parameter results with those of the GR modular systems. Water quality parameters that were characterized in the laboratory, using a method proposed by Eaton [45], were: total phosphorus (TP), phosphates, Total Kjeldahl Nitrogen (TKN), nitrates, nitrites, ammonia, total suspended solids (TSS), turbidity, color, total coliform, biological oxygen demand (BOD) and chemical oxygen demand (COD). For rainfall events that generated at least 30 mL of runoff (least required module to use the probe), water quality parameters such as pH (10 events) and conductivity (12 events) were measured using portable probes.

2.4.3. Plant Species Test Procedures

Modular systems were evaluated weekly to determine the plant’s appearance and growth. Relative growth rate was determined as the percentage difference between plant volume or height at the end of each month and the initial conditions at the beginning of the same month. Approximate volume was measured assuming a cylindrical shape of the plants by measuring the radius and height of each individual. Appearance was again measured using the scale of Monterusso et al. [36].

2.5. Statistical Analysis

An analytic hierarchy process (AHP) was conducted for the preselection phase to evaluate and compare the performance of the engineered substrates. This evaluation was realized by formulating three scenarios regarding rainfall retention and plant establishment, (see monitored variables 1 and 3 in Figure 1): The first scenario gave the same weight to rainfall retention (0.5) and plant establishment (appearance: 0.4; relative growth: 0.1). The second scenario granted most of the relevance to the
retention (0.6) followed by plant appearance (0.35) and relative growth (0.05). The third scenario granted a higher relevance to plant establishment (appearance: 0.4; relative growth: 0.15) than to rainfall retention (0.45).

In the second phase, Kruskal–Wallis (K–W) tests were used to determine the effect of the substrate type (i.e., M4, M5, M10 and M13) and rainfall event size on retention efficiency (monitored variable 1), as well as Ordinary Least Squares (OLS) linear regressions to identify the effect of the appearance and size of the plants on the retention efficiency of the GRs. To comply with homogeneity and normality, either Welch tests, ANOVA or K–W tests were used to find differences for each water quality parameter (monitored variable 4) between all substrates and size of rainfall events. In addition, relationships between plant appearance and plant size with water quality were evaluated through spearman correlations. Then plant appearance and relative growth rate (monitored variables 3) were both evaluated through ANOVA and K–W tests to find differences among substrates and species (this last particularly for appearance). Relationships between appearance and relative growth rate with temperature, precipitation and relative humidity were performed through spearman correlations. For some water quality parameters, data were transformed using the natural logarithm to ensure variance homogeneity. When significant differences were found, post-hoc pairwise tests were implemented. All statistical analyses were performed using STATA 15 software.

3. Results

3.1. Substrate Preselection

3.1.1. Physical Properties

Bulk density of the engineered substrates ranged between 0.28 and 0.62 g/cm³ under dry conditions and between 0.48 and 0.86 g/cm³ under saturated conditions (Table 3). Mixture 2 had the lowest WHC capacity with 25.8% and Mixture 5 presented the highest WHC of the engineered substrates with 66.8%, just below the commercial substrates, which presented WHCs of 68.4% and 86.4% for the intensive and extensive substrates, respectively.

Table 3. Physical properties of the mixtures evaluated in the substrate selection.

| Mixture | Weight—Saturated (Kg/m³) | Bulk Density—Dry Weight (g/cm³) | Bulk Density—at WHC (g/cm³) | WHC (%) | Retention Efficiency a (%) |
|---------|--------------------------|---------------------------------|-----------------------------|---------|----------------------------|
| 1       | 86.01                    | 0.62                            | 0.81                        | 30.1    | 40.9 (20.3)                |
| 2       | 107.89                   | 0.59                            | 0.74                        | 25.8    | 56.5 (25.2)                |
| 3       | 88.65                    | 0.54                            | 0.79                        | 45.6    | 51.5 (19.8)                |
| 4       | 106.57                   | 0.50                            | 0.66                        | 32.1    | 66.2 (16.7)                |
| 5       | 92.36                    | 0.50                            | 0.48                        | 66.8    | 68.4 (16.4)                |
| 6       | 95.62                    | 0.58                            | 0.76                        | 30.6    | 56.5 (18.5)                |
| 7       | 85.93                    | 0.49                            | 0.69                        | 40.4    | 53.1 (18.9)                |
| 8       | 101.12                   | 0.57                            | 0.74                        | 30.4    | 59.2 (20.5)                |
| 9       | 80.29                    | 0.4                             | 0.61                        | 51.7    | 43.4 (20.9)                |
| 10      | 96.92                    | 0.54                            | 0.72                        | 33.1    | 63.4 (17.8)                |
| 11      | 88.68                    | 0.48                            | 0.7                          | 46.1    | 54.9 (17.8)                |
| 12      | 95.67                    | 0.56                            | 0.76                        | 35.7    | 39.5 (22.4)                |
| 13      | 65.09                    | 0.28                            | 0.52                        | 86.4    | 50.4 (14.4)                |
| 14      | 68.24                    | 0.51                            | 0.86                        | 68.4    | 45.6 (19.2)                |

a Retention efficiency is presented as the mean percentage of the nine measured rainfall events. Values in brackets show the standard deviation. Values in bold are from the substrates selected to be further evaluated with the native species. WHC, water holding capacity.

3.1.2. Substrate Evaluation

The AHP analysis included information of rainfall retention, plant appearance and plant growth. In order to evaluate how sensitive the results were to changes in the weights given to the evaluating criteria, three scenarios were studied (see Section 2.5).

Mixtures 4 (So20:Pu40:EC10:S10:Z10:P10), 5 (CP20:Pu60:EC5:S5:Z5:P5) and 10 (C10:CP10:Pu40: EC10:S10:Z10:P10) were those within the engineered substrates that appeared repeatedly as the three...
best performing mixtures. M5 and M10 ranked first and second in every scenario, while M4 ranked third in scenarios no. 1 and 3 and tied second in scenario no. 2. The best engineered substrates (BES), were evaluated together with M13 (commercial extensive substrate) that was the fourth best substrate in scenarios no. 1 and 2 and the third best substrate in scenario no. 3 tied with M4. M13 was the best performing commercial substrate (CS) and was used as a control for the BES. All substrates were planted with native species and were evaluated during a 6 months period.

3.2. Species Selection

Using the 17 evaluating traits of the selection tool (Table 2), which scored the potential species from 0 to 72, 11 native species were selected (Table 4). According to the evaluation, *Pernettya prostrata* (59), *Echeveria ballsii* (56) and *Achyrocline bogotensis* (54) obtained the three best scores, and each represented different growth forms as well as a diverse array of functional traits, as part of the experimental scope. However, it was decided that it would be better to change *Pernettya prostrata* for *Paepalanthus alpinus* (52), because its turf growth form was more similar to *Festuca glauca*, the species used in the substrate preselection. The selected species were: *Paepalanthus alpinus* Körn. of the Eriocaulaceae family; *Achyrocline bogotensis* (Kunth.), an Asteraceae; *Echeveria ballsii* E. Walther. a Crassulaceae (Figure 3).

**Table 4.** Native species rank and score according to their evaluation obtained using the selection tool.

| Rank | Name                        | Family            | Score |
|------|-----------------------------|-------------------|-------|
| 1st  | *Pernettya prostrata*       | Ericaceae         | 59    |
| 2nd  | *Echeveria ballsii*         | Crassulaceae      | 56    |
| 3rd  | *Achyrocline bogotensis*    | Asteraceae        | 54    |
| 4th  | *Echeveria bicolor*         | Crassulaceae      | 53    |
| 5th  | *Echeveria quitensis*       | Crassulaceae      | 53    |
| 6th  | *Paepalanthus alpinus*      | Eriocaulaceae     | 52    |
| 7th  | *Sisyrinchium bogotense*    | Iridaceae         | 49    |
| 8th  | *Salvia xeropapillosa*      | Lamiaceae         | 48    |
| 9th  | *Calamagrostis effusa*      | Poaceae           | 48    |
| 10th | *Salvia scutellarioides*    | Lamiaceae         | 47    |
| 11th | *Orthrosanthus chimboraensis* | Iridaceae     | 47    |

Species in bold were those selected for the plant–substrate joint evaluation.

![Figure 3. Native species used for the plant–substrate joint evaluation.](image)

3.3. Substrate–Plant Evaluation

3.3.1. Rainfall Retention

Substrate and Event Size Effect

Results of rainfall retention efficiency were obtained based on the information of 17 rainfall events. Rainfall depth of the monitored events ranged from 3.2 to 84.6 mm. In 82% of those events, rainfall
depth was above 10 mm. Rainfall events were categorized according to their size in small, intermediate and large, according to their characteristics of duration and depth (Figure 4). The mean retention (SD) for small, intermediate and large events, including all the substrates, was 37.37% (28.51%), 61.63% (18.27%) and 30.15% (20.59%), respectively. Regarding the substrate, mean retention values (SD), including all event sizes, were 46.38% (25.20%), 35.67% (26.88%), 41.38% (25.93%) and 42.71% (27.15%) for Mixtures 4, 5, 10 and the commercial extensive substrate, respectively. Figure 4 summarizes the behavior of rainfall retention, grouping data by substrate and event size. K–W test results showed that no statistically significant differences exist between substrates (p-value = 0.554) while event size does have a significant effect on retention (p-value = 0.000). Modular roofs presented a higher retention for intermediate events than for small and large events (p-value < 0.01), since intermediate events are associated with longer antecedent dry weather period (ADWP), and for these events the substrate has more capacity to retain stormwater. Overall results of the multiple tests performed are presented in Table A3.

![Figure 4. Rainfall Retention Box Plot categorized by substrate and event size. Following K–W test, the same capital letters (A, B) show no statistically significant differences between event sizes. (e.g., GRs have significantly higher retention efficiency for intermediate events than for large and small events) (p-value < 0.01). Mean values and (SD) of event size characteristics.](image)

#### Species Effect

For each of the native species, linear regressions were performed in order to identify any effect of the plants’ appearance and size, and the substrate type, on the ability of the GRs to retain rainfall (Table A4). Regardless of the substrates where the plants were growing in, *P. alpinus* and *E. ballsii* showed a significant effect in terms of appearance on the retention efficiency (p-value < 0.01). This behavior shows that as the appearance of both plants improved, retention efficiency decreased. Otherwise, *A. bogotensis* did not show any effect on the retention efficiency (p-value = 0.096). The size of the three species was not found to be relevant for the retention efficiency of the modular GRs (p-value > 0.05).

#### Water Quality

Water quality parameters were measured for each substrate along with reference measurements to rainfall samples and to the runoff from a plastic tile representing a traditional roof. The mean values of the studied quality parameters for each substrate and the average of the two reference points (reference value) are summarized in Table A6.

#### Substrate and Event Size Effect

For assessing the substrate effect on water quality parameters, comparisons were established between either substrate types (i.e., M4, M5, M10 and M13) or substrate groups (i.e., BES and CS) and a reference value, in order to determine if GRs are a source of these parameters. Event size was also considered as a possible factor to explain differences in quality parameters (Table 5).
Table 5. Effect of substrate and event size on runoff water quality parameters.

| Parameter | Effect | Transformation | Test | Value | p-Value |
|-----------|--------|----------------|------|-------|---------|
| pH        | Substrate Group * | - | ANOVA | F = 19.58 | 0.000 |
|           | Event Size | - | Kruskal–Wallis | chi² = 8.28 | 0.016 |
| Conductivity (µs/cm) | Substrate Group | Ln | Kruskal–Wallis | chi² = 92.83 | 0.000 |
|           | Event Size | Ln | Welch | W = 3.93 | 0.022 |
| Physical Parameters | Color (PCS) | Substrate Group | Ln | ANOVA | F = 86.23 | 0.000 |
|           | Event Size | Ln | Kruskal–Wallis | chi² = 1.47 | 0.481 |
|           | Turbidity (NTU) | Substrate Group | - | Welch | W = 48.51 | 0.000 |
|           | Event Size | - | Welch | W = 0.19 | 0.829 |
|           | TSS (mg/L) | Substrate Group | - | Welch | W = 22.91 | 0.000 |
| Nitrogen Parameters | TKN (mg/L-N) | Substrate Type | Ln | Kruskal–Wallis | chi² = 47.42 | 0.000 |
|           | Event Size | Ln | Kruskal–Wallis | chi² = 0.74 | 0.690 |
|           | Nitrites (mg/L-N) | Substrate Type | Ln | Kruskal–Wallis | chi² = 29.06 | 0.000 |
|           | Event Size | Ln | Kruskal–Wallis | chi² = 1.49 | 0.475 |
|           | Nitrates (mg/L-N) | Substrate Type | Ln | Kruskal–Wallis | chi² = 32.32 | 0.000 |
|           | Event Size | - | ANOVA | F = 0.09 | 0.913 |
|           | Ammonia (mg/L-N) | Substrate Type * | - | ANOVA | F = 5.76 | 0.001 |
|           | Event Size | - | Kruskal–Wallis | chi² = 3.81 | 0.149 |
| Phosphorus Parameters | Total phosphorus (mg/L-P) | Substrate Type | Ln | Kruskal–Wallis | chi² = 45.63 | 0.000 |
|           | Event Size | Ln | Kruskal–Wallis | chi² = 3.35 | 0.169 |
|           | Phosphates (mg/L-P) | Substrate Type | Ln | ANOVA | F = 84.27 | 0.000 |
|           | Event Size | Ln | Kruskal–Wallis | chi² = 0.45 | 0.798 |
| Organic Matter Parameters | BOD (mg/L) | Substrate Group | Ln | ANOVA | F = 25.94 | 0.000 |
|           | COD (mg/L) | Substrate Group | Ln | Welch | W = 245.16 | 0.000 |
|           | Event Size | Ln | Kruskal–Wallis | chi² = 3.35 | 0.188 |
| Coliform | Total coliforms (MPN) | Substrate Group | - | Welch | W = 5.54 | 0.011 |
|           | Event Size | - | Welch | W = 24.18 | 0.004 |

Substrate Type Effect (M4, M5, M10, M13, reference value). Substrate Group Effect (reference value, best engineered substrates, commercial substrate). Event Size Effect (small, intermediate, large). * Results of substrate group effect on pH and substrate type on Ammonia are presented but did not comply with test assumptions (i.e., normality or heteroscedasticity).

Conductivity and pH were significantly affected by the size of the event. Intermediate events showed a significantly higher pH than large events, while conductivity was significantly higher on large events compared to intermediate and small events. Conductivity was not statistically different between M4, M5 and M10 but showed significant differences among substrate groups. CS had higher mean conductivity than BES, and the latter had higher mean conductivity than reference points. In addition, there were significant differences in pH between BS (7.09), CS (8.05) and the reference value (7.36).

Physical parameters did not present differences amongst event size (TSS was not evaluated for event size effect since all the measured events were large), but they were significantly different between substrate groups. Mean sampled color was significantly higher in CS than in BES and reference values. For turbidity and TSS, mean values of CS and BES were significantly higher than in reference values.

For nitrogen parameters (i.e., TKN, NO₂ and NO₃), events size was not relevant and did not show significant differences, while substrate seems to appear as a source of nitrogen for most measured
parameters (TKN, NO\textsubscript{2} and NO\textsubscript{3}) for which CS had significant higher concentrations. For TKN, BES had also higher concentrations than reference value, however, for NO\textsubscript{2} there were no differences among BES and reference points. For NO\textsubscript{3}, only runoff from M10 was not statistically different from the reference.

When evaluating phosphorus parameters, event size was not a significant factor. In contrast, substrate showed differences in concentrations. For TP, CS mean concentrations were significantly higher than those of M5 and M10 and these two were higher than concentrations of M4 and the reference value. When analyzing PO\textsubscript{4}, the same differences were found although for this parameter M4 concentration was also statistically higher than the reference value.

When evaluating organic matter parameters, event size was not found to be significant for COD. Otherwise, substrate group was significant for both DOB and COB, showing that CS’s have higher concentrations than BES, and the latter higher concentrations than the reference points. Event size effect was not analyzed for BOD, since all the measured events were large.

Total coliforms were also analyzed for both event size and substrate group factors. It was found that BES and CS presented significantly higher values than reference values. In terms of event size, differences were found between large events that presented higher values than intermediate events.

Species Effect

To test the species effect on the water quality parameters, spearman correlations between each species’ appearance and size, and each runoff quality parameter were tested at a 5% significance level. Effects were different across substrates and species. \textit{A. bogotensis’} appearance and size were positively correlated with NO\textsubscript{2} concentrations when growing in substrates M4 and M10, with NO\textsubscript{3} concentrations in M4, with conductivity in substrates M5, M10 and CS, and with turbidity, TKN and COD in CS. Otherwise \textit{A. bogotensis’} characteristics were negatively correlated with pH in M4 and color in M5.

\textit{E. ballsii} characteristics were negatively correlated with conductivity when growing in CS. Plant appearance had a positive correlation with TSS in M4 and a negative correlation with turbidity, NO\textsubscript{2} and TP in M10 and pH in M4. Meanwhile \textit{E. ballsii’s} size, in terms of volume, was negatively correlated with EC, turbidity, TSS, TKN, PO\textsubscript{4} and COD when planted in CS.

Both the appearance and volume of \textit{P. alpinus} were negatively correlated with PO\textsubscript{4} concentrations in M10 substrate, while only the appearance was negatively correlated with turbidity and TKN in M10 and M5, respectively. A positive correlation was also found between \textit{P. alpinus} appearance, conductivity and pH in M10 and CS, respectively.

3.3.3. Plant Establishment

Substrate Type Effect

After 6 months of evaluation, \textit{P. alpinus} showed a 100% survival rate in Mixtures 4 and 5, 66% on Mixture 10, and only 33.3% on the commercial extensive substrate. For \textit{A. bogotensis}, initial adaptation to rooftop conditions was not favorable. From the third to the sixth month, the individual plants’ survival rate was, in the best case, only 66.6% in M5, whereas only 33.3% survived in M4 and M10, and no individuals remained alive on the commercial substrate. \textit{E. ballsii} was the best performing species in terms of survival and 100% of its individuals survived on every substrate.

In all substrates, the appearance of \textit{P. alpinus} dropped in the first two months, followed by a recovery and stable condition at the beginning of the third month. Individuals in M4 and M5 recovered and their mean appearance increased to 3.67. Otherwise, the individual’s appearance in M10 and the CS declined. \textit{A. bogotensis} was not able to establish properly in the first month and showed a large drop in its appearance in all substrates. It was only until the third month that individuals stabilized on the engineered substrates with a very low appearance. \textit{E. ballsii} was the species that suffered the least during its initial adaptation to the rooftop conditions, stabilizing after 2 months. Results showed an optimal appearance of 5 on the CS and a mean value of 2.67, 3.33 and 3.33 for Mixtures 4, 5 and 10.
In terms of plant growth, *P. alpinus* individuals had a marked volume decrease from the beginning, and only individuals in M4 managed to stabilize from the fourth month on. On its natural habitat, *P. alpinus*’s height has a relative increase between 0.011 and 0.064 cm/cm × month and its coverage area between 0.017 and 0.079 cm²/cm² × month [46]. Under GR conditions, height relative growth rate was, on average, −0.089 cm/cm × month and coverage −0.116 cm²/cm² × month, nevertheless, plants in M4 reached the natural growth rate on months 1, 4 and 5 and surpassed it on months 2 and 3. Plants in M5 surpassed the natural growth rate on months 2, 4 and 6, and plants in M10 and CS surpassed the normal growth rate in the second month.

Similarly, *A. bogotensis* suffered a significant height reduction over the first few months. Santos [43] found a mean growth rate of 0.18 cm/month in a close species (i.e., *A. satureioides*). In this study this species was able to grow at a same or even higher rate in M4 in the fifth month, in M5 in months 1, 2, 5 and 6 and in M10 in months 1 and 6. All individuals in the CS died by the end of the third month and did not grow in the period they remained alive.

*E. ballsii* had the best performance in terms of growth and in all the different substrates either stabilized or grew. *Echeveria* spp. can grow approximately at a rate of 2 cm/month [47]. The mean growth rate of this species was 0.167 cm/month; however, it grew only at its normal rate in CS in months 3 and 5 (2.833 cm/month). Figure 5 presents the evolution of each species appearance and growth rates in the four evaluated substrates over the six months of study.

When comparing the mean appearance between the native species through an ANOVA and post hoc Bonferroni tests, it was possible to identify differences between all of them (p-value = 0.000). According to these analyses, *E. ballsii* had the best appearance followed by *P. alpinus* and finally *A. bogotensis* (Figure 6).

Substrate had a significant effect on *E. ballsii*’s appearance (p-value = 0.000), for this species the appearance of the plants in the CS was significantly better than those planted on the engineered substrates (p-value < 0.01). The effect of the substrate for *P. alpinus*’s appearance was only significant under a 10% significance level, between M5 and the commercial extensive substrate which had a lower mean appearance (p-value = 0.081). No effect of the substrate over the appearance was visible for *A. bogotensis* individuals (p-value = 0.179).

Substrate did not have an effect on *P. alpinus* nor on *A. bogotensis* growth rates, as it is possible to see in Figure 5, the growth rate of both species had a similar behavior for all the substrates, and although *P. alpinus* plants growing in M4 and A. bogotensis plants in M5 appear to have a more stable rate, no significant differences are present (p-value > 0.1). For *E. ballsii*, the effect of the substrate was found to be significant, mean growth rate of the plants in CS was higher than the others (p-value = 0.000).

Species and Climate Effect

Native species appearance and relative growth rate were analyzed together with some climatic variables (temperature, precipitation and relative humidity) in order to identify which variables are important for their establishment. For each species, *P. alpinus* and *E. ballsii* appearance was positively correlated with the relative growth rate. Additionally, *P. alpinus* appearance and relative growth rate were also positively correlated with temperature, and its growth rate has also a positive correlation with precipitation. Appearance of *A. bogotensis* was positively correlated with precipitation and relative humidity, while its relative growth rate depended more on temperature, which increased when the mean temperature dropped. Meanwhile, *E. ballsii*’s establishment was not significantly correlated with any of the evaluated climatic variables (p-value > 0.05).
Figure 5. Monthly average and standard deviation of plant appearance for (a) \textit{Paepalanthus alpinus}, (b) \textit{Achyrocline bogotensis} and (c) \textit{Echeveria ballsii}, presented by substrate. The appearance scale represents the following characteristics: 5: No stress, all leaves are healthy; 4: Minor stress, more than 50% of leaves are green; 3: 50% of the leaves are green; 2: Stress, less than 50% of the leaves are green; 1: Severe stress, few leaves remain green; 0: Plant is dead and completely dried. Monthly average and standard deviation of plant volume or height for (d) \textit{Paepalanthus alpinus}, (e) \textit{Achyrocline bogotensis} and (f) \textit{Echeveria ballsii}, presented by type of substrate. Bars represent standard errors.

Figure 6. Effect of the substrate and standard deviation on the native species appearance. The same capital letters (A–C) show no statistically significant differences between species (ANOVA) (e.g., \textit{Echeveria ballsii} has a significantly higher appearance than \textit{Paepalanthus alpinus} and \textit{Achyrocline bogotensis}). Differences were tested under 5% significance level.
4. Discussion

Byformulating several engineered extensive substrates for GRs and proposing native species as vegetated coverage, this study has contributed some possible solutions to the challenges of water management in cities using GRs. This research provided a better understanding of the properties that affect extensive substrate efficiency in terms of stormwater retention, water quality and plant establishment and the possible trade-offs between these criteria. It also provided a general outline of the characteristics needed for a plant to thrive in GR conditions, taking into account that there is an adjustment process that varies with each species, which can be more deeply evaluated by implementing further long-term monitoring.

4.1. Rainfall Retention

All engineered substrates in this study showed that an appropriate ratio between organic amendments and inorganic materials favors moderate weight (80–120 Kg/m²) and WHC values of 20–65%, which made mixtures suitable for GR use according to the recommendations of FLL [16]. The presence of components such as coarse pumice and zeolite contributes to the improvement of the physical properties of the substrate, increasing the porosity which is important for rainfall retention, while aggregates such as sand can increase the bulk density and decrease the ks [5]. This allows us to establish that, as in temperate regions, under a neotropical mountain context, a greater use of coarse amendments (e.g., pumice and expanded clay) increases WHC, which explains the higher WHC value of M5, that was composed of 65% coarse amendments, compared with M4 and M10 that were composed of 50% coarse amendments. (Table 3).

As some studies suggest, it is difficult to compare rainfall retention values between studies, since substrate composition and depth, study length and climate conditions are not homogeneous [28,48]. Therefore, taking into account that only events that generated runoff were measured, the retention values that range between 35.76% and 46.38% are lower than the ones reported in other studies. Brandao et al. [6] measured a median retention that ranged between 55 to 100%, however, over one third of the measured events did not produce runoff. Under the same neotropical mountain climate, in a study on the Universidad de los Andes campus, Ferrans et al. [28] measured a mean retention of 85% for an experimental modular GRs with different vegetation coverages and a 6 cm substrate layer.

In this study, substrates did not present differences in retention, though the size of the event and the antecedent dry weather period (ADPW) were important variables. In contrast to other studies’ findings, larger events, in terms of rainfall depth and duration, are associated with smaller retention efficiencies [28,48]. In this study, the retention of intermediate events was significantly higher than for small and large events. Nevertheless, it was found that more than the size effect, a complementary effect of the soil moisture explained this behavior, as intermediate events were associated with the longest ADWP (Figure 4). In accordance with Stovin et al. [49], these results reflect that the substrate hydrologic performance is strongly influenced by its initial moisture.

4.2. Water Quality

Some studies suggest that GRs can be a source of nutrients that may diminish runoff quality. These reductions in water quality can be attributed to the composition and depth of the substrate and also to the magnitude of the rainfall events [3,15,50]. According to Beecham and Razzaghmanesh [15], low organic matter content in the substrate and the presence of vegetated coverage are crucial factors for a better water quality outcome, however, there is a larger effect associated with substrate than that of plants [28,51]. Regarding event magnitude, lower concentrations of many quality parameters can be associated with larger events [50]. Hence, substrates were design in order to mitigate runoff pollution.

Although pH values differed among substrates, ranging between 6.70 and 8.05, these values do not affect the quality of receiving water bodies and are within the permitted limits of the local normativity (5–9) [52]. As Beecham and Razzaghmanesh [15] explain, the presence of vegetation on
GRs is very important since the root activity helps to increase the pH; nonetheless, at pH above 5.5 some nutrients are insoluble and cannot be absorbed by plants, ending up in the runoff. Otherwise, it was found that pH was significantly higher in intermediate events that are associated with long ADWP, in agreement with Buffam et al. [50] findings that associated higher pH with events following dry antecedent conditions.

Results of other quality parameters, showed that GRs’ runoff had significantly higher concentrations than the reference values (i.e., conductivity, TSS, turbidity, TKN, PO₄, COB, BOD and coliforms) confirming other study results that reported higher concentrations of TN, TSS, EC and turbidity on GRs [15,53]. Nevertheless, in some cases BES runoff quality (i.e., color, NO₂, NO₃ and TP) was not statistically different from that of the reference values, which can be attributed to low organic ratio and the presence of vegetation. For all BES, mean concentrations of NO₂ and NO₃ reported in this study are below the local limit for domestic use, which are, respectively, 1mg/L-N and 10mg/L-N [52]. As for CS, it was found that it can be promising for some species establishment, but it can also be a greater source of pollutants in the runoff [51]. Therefore, though it is challenging to avoid increasing nutrient concentrations on GRs’ runoff, results show that it is possible in some cases to find a balance where there are enough nutrients available for plant uptake and no significant excess is leached.

### 4.3. Plant Establishment

A variety of inorganic materials were used, as it is understood that the use of multiple inorganic aggregates in substrate composition can increase plant abundance and diversity in GRs [54,55]. Additionally, a proper selection of inorganic constitutes that increase the hydraulic conductivity (ks) and help proper plant establishment were included [5].

The selected native species showed different establishment successes depending on the initial adaptation they achieved under the new conditions, taking into account that no irrigation or fertilization was applied throughout the monitoring period. Although transplanting had obviously a negative impact on the immediate development and adjustment, which differed between the species, the surviving individuals of *A. bogotensis* and *P. alpinus* showed their adaptive potential in the engineered substrates. Sarmiento and León [56] found that *P. alpinus* and *Achyrocline* spp. grow in shallow and porous soils with a low content of nutrients and are exposed to intense solar radiation for long periods during dry seasons. These conditions resemble at some level the physical properties of the engineered substrates that presented a limited depth and a low proportion of organic matter, unlike growing in nutrient rich soils like the commercial extensive substrate that had 27.4% of organic matter and presented higher concentrations of TKN and TP in the leachate than the engineered substrates. Hence, establishment on commercial substrates was not successful, indicating that these species thrive better under specific conditions. These two species also showed correlation with climatic factors, particularly *A. bogotensis* that performed better with high precipitation rates and high relative humidity. A more generalist species like *E. ballsii* showed that it could establish on both engineered and commercial substrates. Although it did not present significant growth in engineered substrates, it managed to adapt under restrictive conditions and were not dependent on specific climatic conditions. These results strengthen the recommendation to use Crassulaceans, due to their ability to adapt to harsh conditions like GRs with poor substrates [4,19,20].

It was possible to notice that using three native species belonging to different growth forms (i.e., herb, cushion and rosette), worked as a strategy to limit competition and enable them to grow together and establish [19,36]. However, only one individual of each species was planted per module, therefore variability could be partly explained by intrinsic variation instead of specific responses to the climatic and edaphic conditions. It is important to mention that plants grow differently depending on the species surrounding them, whether animal, vegetal or fungal. Some studies have found that diverse plant communities where no invasive nor competitive species are used, can ensure the survival of some species by increasing the availability and diversity of pollinators and creating convenient
and diverse interactions \[19,54,57\]. The three species present complemen tal dispersal mechanisms, for instance, *E. ballsii* is pollinated by hummingbirds, *P. alpinus* and *A. bogotensis* by flying insects and all species use the wind as a disper sal mechanism, amplifying the possibilities of survival of the plant simplicis t community.

Through this study it is possible to recommend *E. ballsii* and *P. alpinus* as appropriate native plants for GRs in Bogotá. In the particular case of *A. bogotensis*, though being native, it is sensitive to GR conditions and did not adjust well. Recommendations are to use similar taxa that are more common and plastic, such as *A. satureioides*, used in other studies for GW and GRs \[44\] or *G. antennarioides*, which was used in the preselection phase; or other species from the list that are compatible with the two species recommended previously. Besides this GR design, larger combinations of plant species should be tested in order to maximize biodiversity and help adapt GRs to local climatic conditions as well as to wind, sun exposure, pollution, and so on. Further analysis should be carried out over a longer period of time to observe a more complete development of the species. Additionally, in the case of engineered mixtures, composition of the substrates could be modified in order to increase the organic amendments to promote plant growth.

Other approximations using climate and habitat variables for finding suitable species for GRs constitute an important reference for enlarging the GR’s native plant list proposed in this study. From the list of potential native species for GRs proposed by Jaramillo \[27\] for Quito, some herbs were also native to Colombia and are present in the rural region of Bogotá (e.g., *Castilleja fissifolia*, *Plantago sericea*, *Oreomyrrhis andicola*). Therefore, similar studies developed in the Andes biogeographic region are primordial to expand the plant list.

5. Conclusions

Several extensive substrate mixtures that presented the appropriate physical properties were developed, namely, Mixtures 4 (So20:Pu40:EC10:S10:Z10:P10), 5 (CP20:Pu60:EC5:S5:Z5:P5) and 10 (C10:CP10:Pu40:EC10:S10:Z10:P10). These had favorable bulk densities and WHCs and were capable of retaining considerable amounts of rainfall. Components such as coarse pumice, and zeolite were found to be suitable for GRs in that they fulfill the GR’s weight requirements and have adequate physical properties for the substrates.

Comparing the runoff quality of the three mixtures with that of a commercial extensive substrate, it was possible to determine that engineered substrates had significantly lower concentrations for most of the parameters, however, they are still a source of TSS, turbidity, TKN, PO4, COD, BOD and coliforms. For some parameters, such as NO2, NO3, TP and color, at least one engineered substrate did not present significantly different concentrations than those of reference samples, which state that for these parameters, engineered substrates do not diminish rainfall quality.

When analyzing the establishment of the selected native species, it was possible to determine that initial adaptation was very difficult for *Paepalanthus alpinus* and *Achyrocline bogotensis*. *P. alpinus* started to stabilize after the fifth month in Mixtures 4 and 5. *A. bogotensis* showed a deficient performance in all substrates and is not recommended to be used in rooftop conditions. *Echeveria ballsii* had the best performance, it maintained a good appearance and grew significantly under the commercial extensive substrate conditions, and also had an outstanding establishment on the engineered substrates. It is recommended to extend the joint evaluation of substrates and native species in order to reach a better understanding of plant establishment and assure that water quality improvement and stormwater retention remains over time. Mixtures must be further analyzed, rearranging volumetric ratios, including a drainage layer and trying other recycled materials such as crushed brick, in order to develop better conditions for *P. alpinus* and other species with different life-forms that can coexist with the successful species and help to increase biodiversity. Sporadic maintenance and a deeper substrate can improve the appearance and growth of *P. alpinus* and *E. ballsii* under the conditions of Mixtures 4, 5 and 10.
Author Contributions: Conceptualization, C.V.R., N.F., G.P., and J.P.R.; Monitoring, C.V.R., and N.F.; Data Analysis, C.V.R., and N.F.; Supervision, G.P., and J.P.R.; Writing—Original Draft Preparation, C.V.R.; Writing—Review and Editing, C.V.R., G.P., and J.P.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Departamento de Ingeniería Civil y Ambiental, Universidad de los Andes; Fondo de Apoyo para Profesores Asistentes, Universidad de los Andes and Departamento Administrativo de Ciencia, Tecnología e Innovación (COLCIENCIAS).

Acknowledgments: We thank David Rodríguez for his collaboration and instructions with some of the laboratory analyses, Groncol for providing the commercial substrates and Maria Elsa Correal for her orientation with some statistical analyses.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Appendix A

![Figure A1](image1.png)

**Figure A1.** Extensive Green Roof modular system. (a) Modular system used in substrate preselection phase, planted with common species. (b) Modular system used in the Substrate–Plant Evaluation phase, planted with native species.

Appendix B

![Figure A2](image2.png)

**Figure A2.** Rainfall and temperature conditions for experimental evaluation, comprehending the period between November 2016 and August 2017.
Table A1. Rainfall events used for the analyses in the two experimental phases *

| Date                  | Experimental Phase | Precipitation (Mm) | Duration (Min) | ADWP ** (Days) |
|-----------------------|--------------------|--------------------|----------------|-----------------|
| 26 November 2016      | I                  | 60                 | 1685           | 2.62            |
| 1 December 2016       |                    | 15.8               | 158            | 3.71            |
| 3 December 2016       |                    | 8.6                | 893            | 1.32            |
| 9 December 2016       |                    | 31                 | 259            | 0.13            |
| 11 January 2017       | I                  | 78.4               | 504            | 0.82            |
| 18 January 2017       |                    | 26.4               | 446            | 0.43            |
| 19 January 2017       |                    | 27                 | 288            | 0.68            |
| 21 February 2017      |                    | 32.6               | 216            | 0.98            |
| 24 February 2017      |                    | 61.2               | 3110           | 1.91            |
| 19 March 2017         |                    | 23                 | 2520           | 2               |
| 21 March 2017         |                    | 12.2               | 2258           | 0.43            |
| 25 March 2017         |                    | 79.6               | 3684           | 1               |
| 8 April 2017          |                    | 11.8               | 1584           | 7.79            |
| 12 April 2017         |                    | 15.8               | 3009           | 1.75            |
| 20 April 2017         |                    | 13.4               | 1599           | 1.63            |
| 22 April 2017         |                    | 17.2               | 58             | 1.19            |
| 26 April 2017         |                    | 3.2                | 87             | 3.38            |
| 3 May 2017            | II                 | 22                 | 749            | 1.09            |
| 11 May 2017           |                    | 84.6               | 4335           | 1.19            |
| 15 May 2017           |                    | 8.2                | 360            | 0.58            |
| 6 June 2017           |                    | 21.2               | 732            | 1.69            |
| 8 June 2017           |                    | 18.8               | 403            | 0.97            |
| 9 June 2017           |                    | 7.6                | 475            | 0.79            |
| 11 June 2017          |                    | 45.8               | 2491           | 0.89            |
| 18 August 2017        |                    | 18.8               | 605            | 0.79            |
| 19 August 2017        |                    | 14.6               | 2578           | 0.42            |

* Events in bold were measured for water quality analyses. ** Antecedent dry weather period (ADWP).

Appendix C

Table A2. Native species selection tool showing traits categories and scores.

| Type               | Variable                      | Categories                                      | Score |
|--------------------|-------------------------------|------------------------------------------------|-------|
| Adaptability       | Origin                         | Native                                         | 6     |
|                    |                               | Naturalized and/or Adventitious                  | 3     |
|                    |                               | Cultivated                                      | 0     |
|                    |                               | Exotic                                          | 0     |
|                    | Altitude Range (m.a.s.l.)     | 2500–2700                                      | 6     |
|                    |                               | 2000–4500                                      | 3     |
|                    |                               | The range does not include the altitude of the zone | 0     |
|                    | Climate                        | Temperate                                      | 6     |
|                    |                               | Dry                                            | 4     |
|                    |                               | Tropical                                       | 2     |
|                    |                               | Cold                                           | 0     |
|                    |                               | Polar                                          | 0     |
|                    | Soil                           | Requires shallow and poor soils                | 6     |
|                    |                               | Requires shallow and rich soils                | 3     |
|                    |                               | Requires deep soils                            | 0     |
|                    | Hydrologic Stress Tolerance   | Drought tolerant                               | 6     |
|                    |                               | Requires low water supply                      | 0     |
|                    |                               | Requires high water supply                     | 0     |
Table A2. Cont.

| Type                        | Variable                          | Categories                  | Score |
|-----------------------------|-----------------------------------|-----------------------------|-------|
| Functional Characteristics   |                                   |                             |       |
| Leaf Area (mm²)             | 0–71                              | 4                           |       |
|                             | 72–142                            | 3                           |       |
|                             | >352                              | 2                           |       |
|                             | 143–213                           | 1                           |       |
|                             | 214–352                           | 0                           |       |
| Leaf Shape                  | Ovate                             | 4                           |       |
|                             | Linear                            | 3                           |       |
|                             | Lanceolate                        | 2                           |       |
|                             | Scale-like                        | 1                           |       |
|                             | Other                             | 0                           |       |
| Life Form                   | Chamaephytes                      | 4                           |       |
|                             | Hemicryptophytes                  | 3                           |       |
|                             | Geophytes                         | 2                           |       |
|                             | Therophytes                       | 1                           |       |
|                             | Other                             | 0                           |       |
| Reserve Organ               | Water reservoir (Leaves and Stems)| 4                           |       |
|                             | Nutrients reservoir (Rizhomes or Bulbs)| 2                   |       |
|                             | No organ                          | 0                           |       |
| Photosynthetic Metabolism   | CAM                               | 4                           |       |
|                             | C3                                | 3                           |       |
|                             | C3-C4                             | 2                           |       |
|                             | C4                                | 1                           |       |
|                             | Other                             | 0                           |       |
| Type of Strategy            | Stress Tolerant                   | 4                           |       |
|                             | Competitor and Stress Tolerant    | 2                           |       |
|                             | Ruderal and Stress Tolerant       | 1                           |       |
|                             | Competitor, Ruderal and Stress Tolerant | 0                   |       |
| Reproduction                | Vegetative/Sexual                 | 4                           |       |
|                             | Sexual                            | 2                           |       |
|                             | Asexual                           | 0                           |       |
| Typical Height (cm)         | <60                               | 4                           |       |
|                             | >60                               | 0                           |       |
| Woodiness                   | Semi-Fibrous                      | 4                           |       |
|                             | Not Fibrous                       | 2                           |       |
|                             | Fibrous/Woody                     | 0                           |       |
| Utilitarian Aspects         | Birds, Insects and Wind           | 2                           |       |
|                             | Insects                           | 1                           |       |
|                             | Birds                             | 1                           |       |
|                             | Wind                              | 1                           |       |
|                             | Other                             | 0                           |       |
| Flowering Period            | 9–12 months                       | 2                           |       |
|                             | 6–9 months                        | 2                           |       |
|                             | 3–6 months                        | 1                           |       |
|                             | 0–3 months                        | 0                           |       |
| Shoot Growth Form           | Erect                             | 2                           |       |
|                             | Semi-erect                        | 1                           |       |
|                             | Prostrate                         | 0                           |       |
Appendix D

Table A3. Statistical ANOVA and Kruskal–Wallis test results for the effect of substrate type (i.e., M4, M5, M10 and M13), event size (i.e., small, intermediate and large) and species (i.e., *P. alpinus*, *A. bogotensis* and *E. ballsii*) on rainfall retention and plant establishment.

| Response Variable | Effect         | Test      | Value   | p-Value |
|-------------------|---------------|-----------|---------|---------|
| Rainfall retention| Substrate Type| Kruskal–Wallis | $\chi^2 = 2.09$ | 0.554   |
| Rainfall retention| Event Size    | Kruskal–Wallis | $\chi^2 = 18.21$ | 0.001   |
| Appearance        | Species       | ANOVA     | $F = 151.66$ | 0.000   |
| *P. alpinus*      | Substrate Type| Kruskal–Wallis | $\chi^2 = 4.91$ | 0.179   |
| *A. bogotensis*   | Substrate Type| Kruskal–Wallis | $\chi^2 = 3.57$ | 0.311   |
| *E. ballsii*      | Substrate Type| ANOVA     | $F = 24.29$ | 0.000   |

Table A4. Linear regressions (Ordinary Least Squares) to evaluate the effect of plant appearance and growth rate, and substrate, on rainfall retention.

| Species | Variable | t     | p-Value   | Num obs |
|---------|----------|-------|-----------|---------|
| *P. alpinus* | Appearance | -2.76 | 0.008 | 68 |
|          | Size     | -1.52 | 0.133 | $F(3,64) = 3.31$ |
|          | Substrate | 1.48  | 0.144 |  |
|          | constant  | 5.07  | 0.000 |  |
| *A. bogotensis* | Appearance | -1.69 | 0.096 | 68 |
|          | Size     | 1.79  | 0.078 | $F(3,64) = 3.31$ |
|          | Substrate | 0.39  | 0.695 | p-value = 0.025 |
|          | constant  | 3.33  | 0.001 |  |
| *E. ballsii* | Appearance | -3.67 | 0.001 | 68 |
|          | Size     | 0.30  | 0.766 | $F(3,64) = 3.31$ |
|          | Substrate | 1.04  | 0.303 | p-value = 0.025 |
|          | constant  | 5.76  | 0.000 |  |
Table A5. Spearman correlations between plan establishment characteristics and water quality parameters.

| Substrate | M4 | M5 | M10 | M13 |
|-----------|----|----|-----|-----|
| Variable | Appearance | Size | Appearance | Size | Appearance | Size | Appearance | Size |
| Species | $P.\ alpinus$ | $A.\ bogotensis$ | $E.\ ballsii$ | $P.\ alpinus$ | $A.\ bogotensis$ | $E.\ ballsii$ | $P.\ alpinus$ | $A.\ bogotensis$ | $E.\ ballsii$ | $P.\ alpinus$ | $A.\ bogotensis$ | $E.\ ballsii$ |
| pH | $-0.051$ | $-0.648^*$ | $-0.575^*$ | $0.265$ | $-0.626^*$ | $0.241$ | $0.112$ | $0.655^*$ | $0.617^*$ | $-0.591^*$ | $-0.464^*$ |
| Conductivity | $-0.005$ | $0.158$ | $0.259$ | $0.296$ | $0.234$ | $0.118$ | $0.535^*$ | $0.417^*$ | $0.086$ | $0.068$ | $0.118$ |
| Turbidity | $-0.058$ | $-0.309$ | $-0.231$ | $-0.273$ | $-0.307$ | $-0.152$ | $0.535^*$ | $0.417^*$ | $0.086$ | $0.068$ | $0.118$ |
| TSS | $-0.136$ | $0.161$ | $0.770^*$ | $-0.691$ | $0.229$ | $-0.527$ | $-0.011$ | $0.065$ | $0.042$ | $0.110$ | $0.086$ |
| Color | $0.065$ | $0.355$ | $0.291$ | $0.427$ | $0.304$ | $0.153$ | $0.112$ | $0.075$ | $0.043$ | $0.110$ | $0.086$ |
| TKN | $0.114$ | $0.318$ | $-0.129$ | $-0.085$ | $0.256$ | $0.260$ | $0.535^*$ | $0.417^*$ | $0.086$ | $0.068$ | $0.118$ |
| NO$_2$ | $-0.188$ | $0.614^*$ | $0.174$ | $-0.070$ | $0.672^*$ | $-0.087$ | $0.535^*$ | $0.417^*$ | $0.086$ | $0.068$ | $0.118$ |
| NO$_3$ | $-0.162$ | $0.708^*$ | $0.457$ | $-0.375$ | $0.656^*$ | $-0.171$ | $0.535^*$ | $0.417^*$ | $0.086$ | $0.068$ | $0.118$ |
| TP | $-0.155$ | $0.353$ | $-0.065$ | $0.010$ | $0.415$ | $0.068$ | $0.535^*$ | $0.417^*$ | $0.086$ | $0.068$ | $0.118$ |
| PO$_4$ | $0.023$ | $-0.362$ | $-0.378$ | $-0.168$ | $-0.391$ | $-0.045$ | $0.112$ | $0.655^*$ | $0.617^*$ | $-0.591^*$ | $-0.464^*$ |

* $p$-value < 0.05.
| Mixture | pH * | Conductivity * | Apparent Color | Turbidity | Total Suspended Solids ** | Nitrates ** | Nitrites | Ammonia | Total Kjedhal Nitrogen | Phosphates | Total Phosphorus | BOD ** | COD | Coliforms |
|---------|------|----------------|----------------|-----------|--------------------------|-------------|---------|---------|------------------------|------------|---------------------|---------|-----|----------|
|         | (µs/cm) | (UPC) | (NTU) | (mg/L) | (mg/L-N) | (mg/L-N) | (mg/L-N) | (mg/L-N) | (mg/L-N) | (mg/L-P) | (mg/L-P) | (mg/L-P) | (mg/L-P) | (MPN) |
| M4      | 6.70 | 196.126 | 17.6 | 6.95 | 2.39 | 1.102 | 0.020 | 0.143 | 0.927 | 0.237 | 0.236 | 2.26 | 27.5 | 30,513 |
|         | (0.56) | (268.818) | (6.6) | (4.22) | (0.73) | (0.454) | (0.022) | (0.251) | (0.501) | (0.154) | (0.386) | (1.09) | (6.9) | (48,304) |
| M5      | 7.20 | 303.208 | 148.3 | 28.05 | 9.68 | 0.946 | 0.016 | 0.102 | 1.092 | 1.924 | 0.986 | 2.87 | 39.6 | 2733 |
|         | (1.23) | (637.577) | (63.7) | (11.77) | (5.67) | (0.382) | (0.007) | (0.114) | (0.352) | (1.015) | (1.124) | (1.32) | (13.5) | (35,37) |
| M10     | 7.37 | 249.354 | 113.3 | 23.67 | 8.70 | 0.789 | 0.024 | 0.057 | 2.123 | 0.964 | 0.433 | 2.94 | 49.2 | 11,207 |
|         | (0.36) | (509.529) | (24.8) | (7.60) | (3.96) | (0.235) | (0.025) | (0.059) | (1.515) | (0.435) | (0.420) | (1.02) | (15.0) | (31,307) |
| M13     | 8.05 | 1062.997 | 1073.3 | 32.96 | 16.23 | 7.879 | 0.073 | 0.208 | 9.445 | 12.256 | 6.621 | 5.82 | 279.8 | 26,449 |
|         | (0.33) | (2186.882) | (628.5) | (25.42) | (12.44) | (4.479) | (0.032) | (0.101) | (4.184) | (4.454) | (3.112) | (2.69) | (91.7) | (41,341) |
| Reference | 7.36 | 25.155 | 9.4 | 2.43 | 1.03 | 0.563 | 0.019 | 0.381 | 0.512 | 0.058 | 0.110 | 1.11 | 8.9 | 143 |
|         | (0.82) | (21.284) | (3.0) | (1.71) | (0.60) | (0.249) | (0.014) | (0.301) | (0.395) | (0.042) | (0.110) | (0.42) | (5.9) | (320) |

* Conductivity and pH were analyzed for 10 and 12 rainfall events, respectively; ** For total suspended solids, nitrates and biological oxygen demand (BOD), only 3, 4 and 3 rainfall events were analyzed in the laboratory, respectively. The other parameters were analyzed for 5 rainfall events.
Table A7. Spearman correlations between plant establishment characteristics and climatic variables.

| Variable         | Appearance | Growth Rate |
|------------------|------------|-------------|
|                  | P. alpinus | A. bogotensis | E. ballsii | P. alpinus | A. bogotensis | E. ballsii |
| Precipitation    | 0.046      | 0.297 *      | 0.031      | 0.240 *    | −0.004       | 0.188      |
| Temperature      | 0.285 *    | 0.088       | 0.143      | 0.424 *    | −0.228 *     | 0.066      |
| Relative Humidity| −0.058     | 0.319 *     | −0.007     | 0.023      | 0.023        | 0.014      |
| App. P. alpinus  | 1.000      | 0.065       | −0.166     | 0.485 *    | −0.114       | −0.066     |
| App. A. bogotensis| 0.065    | 1.000       | −0.177     | 0.078      | 0.195        | −0.151     |
| App. E. ballsii  | −0.116     | −0.177      | 1.000      | −0.069     | −0.158       | 0.349 *    |
| GR P. alpinus    | 0.458 *    | 0.078       | −0.069     | 1.000      | −0.170       | −0.070     |
| GR A. bogotensis | −0.114     | 0.195       | −0.158     | 0.349 *    | 1.000        | 0.035      |
| GR E. ballsii    | −0.066     | −0.151      | 0.035      | 1.000      |

*p-value < 0.05.

References

1. United Nations. World Urbanization Prospects. The 2014 Revision; United Nations: New York City, NY, USA, 2015.
2. Bates, A.; Sadler, J.; Greswell, R.; Mackay, R. Effects of recycled aggregate growth substrate on green roof vegetation development: A six year experiment. Landscape and Urban Planning. 2015, 135, 22–31. [CrossRef]
3. Kuoppamäki, K.; Lehavavirta, S. Mitigating nutrient leaching from green roofs with biochar. Landscape and Urban Planning. 2016, 152, 39–48. [CrossRef]
4. Butler, C.; Butler, E.; Orians, C.M. Native plant enthusiasm reaches new heights: Perceptions, evidence, and the future of green roofs. Urban. For. Urban. Green. 2012, 11, 1–10. [CrossRef]
5. Liu, R.F.; Fassman-Beck, E. Effect of composition on basic properties of engineered media for living roofs and bioretention. J. Hydrol. Eng. 2016, 21, 06016002. [CrossRef]
6. Brandão, C.; Cameira, M.D.R.; Valente, F.; De Carvalho, R.C.; Paço, T. Wet season hydrological performance of green roofs using native species under Mediterranean climate. Ecol. Eng. 2017, 102, 596–611. [CrossRef]
7. Jim, C.; Peng, L.L. Substrate moisture effect on water balance and thermal regime of a tropical extensive green roof. Ecol. Eng. 2012, 47, 9–23. [CrossRef]
8. Ondoño, S.; Martínez-Sánchez, J.; Moreno, J. The composition and depth of green roof substrates affect the growth of Silene vulgaris and Lagurus ovatus species and the C and N sequestration under two irrigation conditions. J. Environ. Manag. 2016, 166, 330–340. [CrossRef]
9. Vijayaraghavan, K. Green roofs: A critical review on the role of components, benefits, limitations and trends. Renew. Sustain. Energy Rev. 2016, 57, 740–752. [CrossRef]
10. Vijayaraghavan, K.; Raja, F.D. Design and development of green roof substrate to improve runoff water quality: Plant growth experiments and adsorption. Water Res. 2014, 63, 94–101. [CrossRef]
11. Chow, M.F.; Abu Bakar, M.F.; Wong, J.K. An overview of plant species and substrate materials or green roof system in tropical climate urban environment. In Proceedings of the AIP Conference, Ho Chi Minh, Vietnam, 29–30 April 2018; AIP Publishing: Melville, NY, USA; 020004.
12. Rowe, D. Green roofs as a means of pollution abatement. Environ. Pollut. 2011, 159, 2100–2110. [CrossRef]
13. Bates, A.; Mackay, R.; Greswell, R.; Sadler, J. SWITCH in Birmingham, UK: Experimental investigation of the ecological and hydrological performance of extensive green roofs. Rev. Environ. Sci. Bio/Technol. 2009, 8, 295–300. [CrossRef]
14. Licht, J.; Lundholm, J. Native Coastal Plants for Northeastern Extensive Ans Semi-Extensive Green Roof Trays: Substrates, Fabrics, and Plant Selection. In Proceedings of the 4th Annual Greening Rooftops for Sustainable Communities Conferences, Boston, MA, USA, 11–12 May 2006.
15. Beecham, S.; Razzaghmanesh, M. Water quality and quantity investigation of green roofs in a dry climate. Water Res. 2015, 70, 370–384. [CrossRef] [PubMed]
16. Forschungsgesellschaft Landschaftsentwicklung und Landschaftsbau e.V. (FLL). Richtlinien für Die Planung, Ausführung und Pflege von Dachbegrünungen. Richtlinien für Dachbegrünungen (Guideline for the Planning Execution and Upkeep of Green-Roof Sites); Selbstverlag: Troisdorf, Germany, 2008.
17. Graceson, A.; Hare, M.; Monaghan, J.M.; Hall, N. The water retention capabilities of growing media for green roofs. *Ecol. Eng.* 2013, 61, 328–334. [CrossRef]

18. Dunnett, N. Green roofs for biodiversity: reconciling aesthetics with ecology. In Proceedings of the 4th Annual Greening Rooftops for Sustainable Communities, Boston, MA, USA, 11–12 May 2006.

19. MacIvor, J.; Lundholm, J. Performance evaluation of native plants suited to extensive green roof conditions in a maritime climate. *Ecol. Eng.* 2011, 37, 407–417. [CrossRef]

20. Durhman, A.K.; Rowe, D.B.; Rugh, C.L. Effect of substrate depth on initial growth, coverage, and survival of 25 succulent green roof plant taxa. *Hort. Sci.* 2007, 42, 588–595. [CrossRef]

21. Johari, J.; Rasidi, M.H.; Said, I. Planting Technology of Green Roof for Building in Tropical Cities: A Review on Plant Selection. In Proceedings of the 5th South East Asian Technical University Consortium Symposium, Hanoi, Vietnam, 24 February 2011.

22. Fai, C.M.; Bakar, M.A.; Roslan, M.A.A.; Fadzailah, F.A.; Ismail, N.F.; Sidek, L.M.; Basri, H. Hydrological performance of native plant species within extensive green roof system in Malaysia, ARPN. *J. Eng. Appl. Sci.* 2015, 15, 6419–6423.

23. Feitosa, R.C.; Wilkinson, S.J. Modelling green roof stormwater response for different soil depths. *Landsc. Urban. Plan.* 2016, 153, 170–179. [CrossRef]

24. Feitosa, R.C.; Wilkinson, S.J. Attenuating heat stress through green roof and green wall retrofit. *Build. Environ.* 2018, 140, 11–22. [CrossRef]

25. Parizotto, S.; Lamberts, R. Investigation of green roof thermal performance in temperate climate: A case study of an experimental building in Florianópolis city, Southern Brazil. *Energy Build.* 2011, 43, 1712–1722. [CrossRef]

26. Noya, M.G.; Cuquel, F.L.; Schäfer, G.; Armingo, R.A. Substrates for cultivating herbaceous perennial plants in extensive green roofs. *Ecol. Eng.* 2017, 102, 662–669. [CrossRef]

27. Jaramillo, M.L. Plant Selection for Green Roofs in Quito, Ecuador. Master’s Thesis, Faculty of Science, University of Melbourne, Melbourne, Australia, 2016.

28. Ferrans, P.; Rey, C.; Pérez, G.; Rodríguez, J.; Díaz-Granados, M. Effect of Green Roof Configuration and Hydrological Variables on Runoff Water Quantity and Quality. *Water* 2018, 10, 960. [CrossRef]

29. Escobar, N.O.; Torres, A. Hydric Attenuation and Hydrological Benefits for Implementing Productive Green Roof in Soacha, Colombia. *Ingeniería y Universidad* 2014, 18, 291. [CrossRef]

30. Molina, S.G.; Torres, A.; Rengifo, P.; Puentes, A.; Cárcamo-Hernández, E.; Méndez-Fajardo, S.; Devia, C. The benefits of an eco-productive green roof in Bogota, Colombia. *Indoor Built Environ.* 2016, 26, 1135–1143. [CrossRef]

31. Bolaños, T.; Moscoso, A. Guía de Selección de Especies Para Ecoenvolventes; Universidad Piloto de Colombia: Bogotá, Colombia, 2011.

32. Secretaría Distrital de Ambiente. Guía de techos verdes y jardines verticales. Secretaría Distrital de Ambiente de Bogotá: Bogotá, Colombia. Available online: http://www.ambientebogota.gov.co/c/document_library/get_file?uuid=f807042d-064e-4a7a-adf1-75e1e4b7aaaa&groupId=1015 (accessed on 30 September 2016).

33. Van Mechelen, C.; Dutoit, T.; Kattge, J.; Hermy, M. Plant trait analysis delivers an extensive list of potential green roof species for Mediterranean France. *Ecol. Eng.* 2014, 67, 48–59. [CrossRef]

34. Rayner, J.P.; Farrell, C.; Raynor, K.J.; Murphy, S.M.; Williams, N.S. Plant establishment on a green roof under extreme hot and dry conditions: The importance of leaf succulence in plant selection. *Urban. For. Urban. Green.* 2016, 15, 6–14. [CrossRef]

35. Instituto de Hidrología. *Estudio de la Caracterización Climática de Bogotá y Cuenca Alta del Río Tunjuelo;* Instituto de Hidrología: Bogotá, Colombia, 2013.

36. Monterusso, M.A.; Rowe, D.B.; Rugh, C.L. Establishment and persistence of sedum spp. and native taxa for green roof applications. *HortScience* 2005, 40, 391–396. [CrossRef]

37. Uesseler, H. Diplomado: Sistema LEED Certificación en Construcción sostenible. Available online: https://docplayer.es/17519726-Diplomado-sistema-lead-certificacion-en-construccion-sostenible-modulo-uso-eficiente-del-agua-jardineria-ecologica-y-cubiertas-verdes-por.html (accessed on 15 October 2016).

38. Rivera, C. Cubiertas Vegetales en la Región del Caribe. Available online: https://upcommons.upc.edu/bitstream/handle/2099.1/25659/memoria.pdf?sequence=1&isAllowed=y (accessed on 15 October 2016).
39. Soto, M.S.; Lorena, B.; Coviella, M.A.; Stancaelli, S. Catálogo de plantas para techos verdes. Instituto Nacional de Tecnología Agropecuaria. Available online: https://inta.gob.ar/sites/default/files/script-mp-inta_-catlogo_de_plantas_para_techos_verdes.pdf (accessed on 15 October 2016).

40. Impulsemillas. Catálogo Techos Vivos. Available online: https://issuu.com/pamil243/docs/catalogo_techos_vivos_mayo_2013 (accessed on 15 October 2016).

41. Bernal, R.; Gradstein, S.R.; Celis, M. Catálogo de plantas y lúquenes de Colombia. Instituto de Ciencias Naturales, Universidad Nacional de Colombia, Bogotá. Available online: http://catalogogplantasdecolombia.unal.edu.co. (accessed on 15 October 2016).

42. Tropicos. Sepecimen Search Engine. Available online: https://www.tropicos.org/SpecimenSearch.aspx (accessed on 20 November 2016).

43. Santos, D. (Jardín Botánico José Celestino Mutis: Bogotá, Colombia). Evaluación de seis especies nativas (Salvia scutellaroides Kunth, Bidens andicola Kunth, Scutellaria ventenati Hook, Senecio formosus Kunth, Salvia cuatrecasana Epling y Slavia xeropapillosa Fern. Alonso) y un sustrato para ser utilizados en ecoenvolventes arquitectonicos. Personal communication, 2014.

44. Santos, D. (Jardín Botánico José Celestino Mutis: Bogotá, Colombia). Evaluación de cuatro especies nativas (Achyrocline satureioides, Brachyotum stringosum, Niphogeton sp, Lupinus sp) y un proceso de fertilización orgánica con potencial para ser utilizados en muros verdes. Personal communication, 2015.

45. Eaton, A.D. Standard Methods for the Examination of Water and Wastewater, 21st ed.; American Public Health Association: Washington, DC, USA, 2005.

46. Castiblanco-Álvarez, F. Control de pastos exóticos mediante sombreado artificial y reubicación de especies nativas como estrategias para la restauración ecológica del páramo andino (PNN Chingaza-Colombia). Departamento de Biología 2012, 55. [CrossRef]

47. United States Plant Patent. Echeveria Plant name ‘Apus’. Available online: https://patentimages.storage.googleapis.com/20/18/81/0ce21ca9b980ed/USPP26229.pdf (accessed on 15 April 2020).

48. Carpenter, C.M.G.; Todorov, D.; Driscoll, C.T.; Montesdeoca, M. Water quantity and quality response of a green roof to storm events: Experimental and monitoring observations. Environ. Pollut. 2016, 218, 664–672. [CrossRef]

49. Stovin, V.; Vesuviano, G.; Kasmin, H. The hydrological performance of a green roof test bed under UK climatic conditions. J. Hydrol. 2012, 414, 148–161. [CrossRef]

50. Buffam, I.; Mitchell, M.E.; Durtsche, R.D. Environmental drivers of seasonal variation in green roof runoff water quality. Ecol. Eng. 2016, 91, 506–514. [CrossRef]

51. Chen, C.F.; Kang, S.F.; Lin, J.H. Effects of recycled glass and different substrate materials on the leachate quality and plant growth of green roofs. Ecol. Eng. 2018, 112, 10–20. [CrossRef]

52. Ministerio de Agricultura. DECRETO No. 1594 DEL 26 DE JUNIO DE 1984; Ministerio de Agricultura: Bogotá, Colombia, 1984.

53. Liu, W.; Wei, W.; Chen, W.; Deo, R.; Si, J.; Xi, H.; Feng, Q. The impacts of substrate and vegetation on stormwater runoff quality from extensive green roofs. J. Hydrol. 2019, 576, 575–582. [CrossRef]

54. Molineux, C.; Gange, A.; Connop, S.; Newport, D. Using recycled aggregates in green roof substrates for plant diversity. Ecol. Eng. 2015, 82, 596–604. [CrossRef]

55. Nektarios, P.A.; Amountzias, I.; Kokkinou, I.; Ntoulas, N. Green roof substrate type and depth affects the growth of the native species Dianthus fruticosus under reduced irrigation regimens. HortScience. 2011, 46, 12081216. [CrossRef]

56. León, O.A. Transición bosque-páramo. Bases conceptuales y métodos para su identificación en los Andes colombianos; Instituto de Investigacion de Recursos Biologicos Alexander von Humboldt (IAVH): Bogotá, Colombia, 2015.

57. MacIvor, J.S.; Margolis, L.; Puncher, C.L.; Matthews, B.J.C. Decoupling factors affecting plant diversity and cover on extensive green roofs. J. Environ. Manag. 2013, 130, 297–305. [CrossRef] [PubMed]