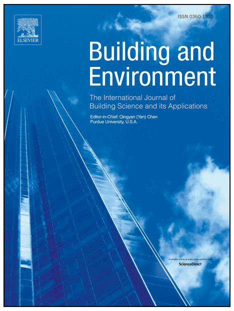

Vegetative and thermal performance of an extensive vegetated roof located in the urban heat island of a semiarid region

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Vegetative and thermal performance of an extensive vegetated roof located in the urban heat island of a semiarid region

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Abstract

Vegetated roofs reduce temperature and heat flow fluctuations on the building's surface mitigating the urban heat island effects and improving other ecosystem services. The objectives of this work were to quantify thermal reduction and to evaluate the performance of vegetated-microcosm treatments during 15 months with different species composition and growth form combinations. Our results showed considerable attenuation of temperature through the whole system of extensive green roofs (EVRs) in both summer and winter periods. The EVRs decreased the outside temperature from 44.6°C to 34.7°C. Temperatures for the EVR showed a lower peak-to-valley-gap and better anti-interference performance during the day and along the year. At the same time, thermal insulation provided by soil and vegetation layers resulted in a negative heat flux (-40 W/m^2) reducing the incoming heat flux during the day. Almost all treatments showed ≥90% of plant survival and ≥60% of coverage after the experimental period. Microcosm treatments with the highest diversity showed the best performance in both the short and long terms (particularly those with the native *Eustachys distichophylla* and the exotic *Sedum* spp.). Consequently, diverse plant arrangements are recommended when designing EVRs in semi-arid climates because they show a better performance in mitigating urban heat island effects by reducing temperature and heat flow fluctuations and also because they provide ecosystem services in urban environments.

Keywords: native germplasm, species combinations, thermal performance, Córdoba city, urban ecosystems

1. Introduction

The increase in urban population growth has led cities to need more space for life and work, which means that more cities are expanding daily [1]. The formation of large waterproof surfaces has exacerbated environmental and energy-related problems in many cities [2]. Energy-related CO_2 emissions from buildings have risen in recent years after flattening between 2013 and 2016. Several factors have contributed to this rise, including growing energy demand for heating and cooling with rising air-conditioner ownership and extreme weather events [3]. Many building envelope techniques have been developed to improve thermal comfort, reduce energy consumption and mitigate the urban heat island **(**UHI) effect [4]. The roof is the component of the building envelope with the highest temperature fluctuations, and significantly contributes to the building energy load. In this sense, passive technologies such as evaporative cooling, reflective materials, insulation, and vegetation can be used to minimize the energy gain from a roof [5]. The extensive vegetated roofs (EVRs) are a modern energy-efficient constructive technology that represents an urban intervention strategy to solve many problems caused by urbanization, including runoff and urban heat island mitigation, thermal regulation, noise and air pollution reduction, and an increase in the longevity of roofing membranes, providing habitat for native biodiversity and adding biological visitors and value to buildings [6, 7, 8, 9, 10, 11, 12]. This technological solution demonstrated to be an efficient and practical tool to reduce energy consumption so it is widely employed in the field of bioclimatic architecture in replacement of the traditional materials used to construct flat roofs [2, 13, 14, 15, 16]. The plant biomass in an EVR plays a key role in moulding these mentioned functions [17] because it allows shading surface, plant transpiration due to latent heat transfer and improves environmental conditions [1, 18].

EVRs are exposed to extreme environmental conditions such as daily variations in temperature, humidity and wind speeds [6, 19]. These environmental factors are further enhanced in arid and semiarid regions, where extreme seasonal temperatures, rainfall and winds are usually present. These extreme environmental conditions have a direct impact on the ecosystem services provided by EVRs [20]. In consequence, plant species selection for an EVR depends on the climatic region, roof types and building uses [21]. Tolerance to drought and high temperatures of different plant species, and their ability to survive in substrates with alternating periods of saturation and water scarcity are desirable characteristics to select materials for an EVR [20, 22]. Other important plant traits to be successful with EVRs are the species establishment capacity under extreme climatic conditions and rapid and high groundcover density [23, 24, 25]. Succulents belonging to the genus *Sedum* L. are widely used in EVRs given their optimal adaptations to stressful conditions mainly due to its Crassulacean Acid Metabolism [26, 27, 25, 28]. The implementation of native plants in urban ecosystems is gaining interest mainly because of their local environmental adaptation. This characteristic allows them to survive under stressful conditions, which means that once established, they will not need pesticides, fertilizers, or large amounts of supplemental irrigation [29, 30]. In parallel, EVRs contribute to biodiversity conservation, restoration and function as biological corridors providing environments for arthropods and bird species because they interact with these native plant species [31, 32, 33, 34, 35].

There is increasing evidence that a biodiverse EVR with a combination of different levels of taxonomic and functional groups, enhances its ecosystem services, resilience and sustainability [36, 37, 38, 39, 40]. For example, diverse arrangements in an EVR improves plant coverage and survival [41, 42, 43]. Investigations showed that more biodiverse EVR systems provide higher functional diversity than those covered only with the widely used *Sedum* species [44].

Upon this background, the objectives of this work were: i) to quantify thermal reduction provided by an EVR (placed on the tenth floor of the Council Building of Córdoba City, Argentina) located in the UHI of a city of a semiarid region; and (ii) to evaluate the performance of plant treatments with different species composition and growth form combinations and then select the best performer combination. We hypothesized that treatments with higher plant richness from different taxonomic groups and diverse growth forms will have better performance (in terms of plant coverage, survival, and health status) than simpler ones in an EVR located in the UHI of Córdoba City. This is the first experimental study in which plant performance was investigated in a real situation of a UHI of a city located in central Argentina, a region with semiarid climatic conditions.

2. Materials and methods

2.1 Experiment characteristics and data analysis

The semi-arid regions of central Argentina (province of Córdoba) are mainly characterized by a wide temperature range (difference between daily maximum and minimum temperatures); for example, winters show a mean seasonal temperature of 12ºC, and summers mean temperatures of 25ºC, with some days with temperatures higher than 40ºC [45]. Precipitations concentrate during the spring-summer period. The autumn-winter season is a dryer and colder period [46]. In particular, the city of Córdoba is located in the boundary between two latitudinal regions [47] the warm and temperate region (sub-humid) with rainy summers, dry winters and winter frosts (Cwa) and the warm semi-arid region (hot arid steppe) (Bsh) according to Köppen- Geiger climate classification. In order to characterize the climate of Córdoba, Fig. 1 shows mean, maximum and minimum monthly temperature and precipitation in a series of 30 years (1981-2010) provided by the National Meteorological Service (NMS) (http://www3.smn.gob.ar), from the meteorological station located at the city´s airport base.

The EVR was laid over a roof terrace of the tenth floor of the Council Building of the City of Córdoba, Palacio 6 de Julio, located in the middle of the city's UHI, surrounded by tall buildings and three squares with scarce green infrastructure next to it (31°24′57″S 64°11′28″W, Fig. 2).

The roof was fully sun-exposed. A meteorological station was placed to record atmospheric conditions during the essay. The total period of measurements was of 515 days. The meteorological station was placed 1.5 m apart from the slab and has sensors to measure environmental conditions: net radiation, wind speed, rainfall, air temperature integrated into the station. Two situations were compared, a conventional roof that was used as control (C, white roof) and a roof with the same constructive conditions but covered by an extensive vegetated roof (EVR) of 68 m^2 each. To measure both situations, temperature sensors were placed at slab level: one on the slab of the control roof and the other on the slab under a module of the vegetated green roof. The sensor to register humidity and temperature substrate was placed in the EVG, inside the substrate. In order to compare the thermal performance of the EVR with respect to the C, thermal conductivity of the construction materials (coefficient of thermal conductivity or k value substrate) was determined by EcoTech analysis at three levels of substrate moisture, with consistent results between the winter and summer seasons [48]. Data of the sensors were obtained with a frequency of fifteen minutes. Details of the instruments and parameters measured are presented in Table 1.

The measured parameters allowed characterizing the thermal performance, the energy efficiency of the extensive vegetated roof (EVR) and the annual dynamic thermal impact in relation to the comfort areas generated by the low-maintenance modular system in the inside space. For net radiation value (W/m^2), rainfall (mm) and wind speed (m/s), Fig. 3 shows values from the weather station for net radiation from 500 W/m^2 and up to 1000 W/m^2; for wind speed the range was from 2 to more than 10 m/s and rainfal from 0 mm to 23.17 mm.

The EVR system used (modular) had the following technical specifications: 1m x 1m x 0.15m dimensions for each module of high-density polyethylene system; resistant to UV rays; water reservoir: 0.013 m^3 with a depth of 35 mm; substrate: 0.12 m^3; and a drain system with 94 holes of 0.008m.

Modules were fitted together allowing an integrated EVR system. The substrate composition was native soil (coarse sandy loam texture with 2.2% of organic matter (Soil Letter, Sheet 3163-13 Jesús María, El Manzano´s Series, http://suelos.cba.gov.ar/JESUSMARIA/index.html), peanut shell, perlite, and equine compost (3:1:1:1 proportions). Chemical properties were determined such as pH: 6.8 and CE: 0.98 dms^{-1} (for more details see [22]).

2.2 Slab temperature, attenuation characteristics and heat flux pattern

The thermal performance was obtained comparing both situations (with and without vegetated roof, EVR and C, respectively). First, the differences between EVR and C were calculated and plotted every fifteen minutes by comparing the following differences for a 30-day period during summer (December 17th, 2019 to January 17th, 2020) and winter time (June 17th, 2020 to July 17th 2020): outside temperature-substrate temperature, outside temperature-control slab temperature, outside temperature-EVR temperature. These differences are shown through position and dispersion statistical measurements by comparing two moments during the day (3 to 4 a.m. and 3 to 4 p.m.) (mean, standard deviation, coefficient of variation of temperature), maximum and minimum values, the difference between them (peak to valley gap) and anti-interference (φ). Statistical comparison were assessed using a Kruskal-Wallis test. The ratio of attenuation (anti-interference ratio, φ) is defined as the relation between the peak-to-valley-gap of slab temperature (control and EVR) and the peak-to-valley-gap of outside temperature. Second, summer cooling and winter heating loads were graphed by calculating heat flux at slab level (control and green roofs situations). A methodology at slab level has been proposed [49] with the formula: $H=(k(T_{GR}-T_O))/d$ for Green Roof and $H=(k(T_C-T_O))/d$ for Control Roof; where H is the heat flux (W/m^2); k is the thermal conductivity at roof slab, which was determined to be of 1.74 (W/m k) of the reinforced concrete on CR and 0.68 (W/m k) of medium humidity substrate; T_{GR} was slab temperature at slab under GR, T_C was slab temperature at slab level

(CR) and T_O was outside temperature; and (d) was the thickness of the roof slab (m) approximately. Heat flux was calculated for summer (December 17th, 2019 to January 17th, 2020) and winter period (June 17th, 2020 to July 17th, 2020).

2.3 Vegetation performance assessment

For the vegetation assessment, five native species were selected from previous studies: three of them were hybrids of the *Glandularia* genus, *Phyla nodiflora* (L.) Greene and *Grindelia cabrerae* Ariza [22, 50], and two correspond to native grasses *Eustachys distichophylla* (Lag.) Ness and *Nassella tenuissima* (Trin.) Barkworth; in addition, three exotic species of *Sedum* (*S. acre* L., *S. lineare* L., *S. reflexum* (L.) Thumb were used for the different combinations (Fig. 4). All the native species had been collected on the basis of the habitat template approach, [36] looking at roadside, rocky environments, shallow and well drained soils, among other habitat features similar to those expressed on EVRs. The herbaceous species have the ability to resprout quickly, presenting adventitious roots; the tall forb *Grindelia cabrerae* and the graminoids, *Eustachys distichophylla* and *Nasella tenuissima*, were observed to reseed [22]. In terms of photosynthetic capability, all the native species used are C3, except *Eustachys distichophylla* which is C4 [51, 52, 53].

The plant material was provided by the "*Laboratorio de Recursos Genéticos y Sustentabilidad Bioclimática*". Plants were asexually propagated from clonal cuttings and mat division, and were cultivated under controlled conditions for approximately a month. After this, all plant materials were arranged in a randomized design in the different modules over the roof. Of the 68m^2, 18 m^2 were used to establish six treatment arrangements (three replicates per treatment of 1m^2). The remaining vegetated meters were planted with the same species that formed the treatments, where the tallest species (grasses and sedums) were planted at the back, next to the building parapet, and the shortest species (creeping herbs, tall forb and sedums) were distributed at the front of the vegetated roof design. Six treatments were established (with three repetitions each), combining different growth forms (succulents; creeping herbaceous; tall forb; and grasses) (Table 2). Implantation date was during the second week, September 2019. Once plant material was established (around a month), the vegetation performance assessment started. Each repetition of a treatment had an area of $1m^2$ and corresponds to a vegetated roof module. Planting density varied between 16 to 24 individuals per repetition per treatment, depending on species and growth forms composition. The treatment variations in the number of individuals of the species were to balance a similar initial coverage percentage. Spontaneous species were removed every two weeks from each plot.

Three variables were evaluated from October 2019 to December 2020: green coverage percentage, survival and health status. The green coverage was defined as the percentage of healthy plants (i.e. without wilting symptoms, stress or some pathology) that cover the module and was determined by taking monthly pictures in a horizontal position over the plant combinations. ImageJ was the digital image processor used for analysis (ImageJ 1.52a NIH, USA, [54]). The coverage dynamics were evaluated analyzing a histogram using the mean monthly coverage values ± the standard deviation. Survival was measured as the quantity of individuals/m^2 at the moment of the measurement with respect to the initial plant density. We compared survival data using the Kruskal-Wallis test implementing the Infostat version 2020 [55]. Dates in February 2020 and in December 2020 were assessed.

Plant health status was determined using a modification of the [26] taking values between 1 and 4 as follows: 1 = considered when plants were dead; 2 = considered for plants with marked stress, brown and with necrotic symptoms on the leaves and branches, 3 = for plants with few symptoms, 4 = for healthy plants, with vigorous growth.

Watering regime (30 minutes 2h.L-1) was applied daily during the spring-summer season (because of higher evapotranspiration rates during these months), and once a week during the cold season (autumn-winter). Spontaneous species were removed every two weeks from each treatment. No additional water support was provided besides the irrigation system.

2.4 Indexes of thermal performance

The indexes of thermal performance previously proposed [56, 57, 2] were used to analyse performance and to characterize the behaviour of the EVR in relation to the UHI phenomenon and energy savings. In particular, we used the STR (surface temperature reduction), which compares the surface mean temperature on EVR with temperature on C, in terms of differences in the average daily temperatures; ETR (external temperature ratio), which is defined as the ratio of the maximum external surface temperature of an EVR to the average temperature of the surrounding air; and TER (temperature excursion reduction), which is defined as the ratio of temperature fluctuation at green roof (EVR) slab level to the temperature at the C slab level. STR represents the sensible heat flow through the EVR and, therefore, of the consumption of energy for heating and cooling in the C. ETR represents the mitigation of the effect of the UHI due to the installation of EVR. TER represents the fluctuation in the external surface temperature.

3. Results

3.1 Pattern of thermal performance, attenuation and heat flux

Surface temperatures measured for EVR and Control roofs during summer (i.e. from middle of December to middle of January) and winter conditions (i.e. from middle of June to middle of July) are presented in Fig. 5. Statistical comparisons of the mean daily temperatures in the periods registered for C and EVR were done using maximum and minimum values and the difference between them within an hour of the minimum (averages between 3 to 4 a.m.) and maximum temperatures (3 to 4 p.m; Table 3). Kruskal Wallis test showed significant differences between C and EVR in all cases (Table 3).

Temperatures for the C roof are higher and with greater oscillations than those registered for the EVR (Fig. 5). A recognizable attenuation of temperature through the substrate and the whole system of the EVR on both cooling and heating periods can be observed (Fig. 5; Table 3). Surface temperatures on bare roofs can reach close to 44.6°C in summer time (in that time slot) as compared to 37.5°C for the EVR. In winter, outside temperature reached values 2.6°C, as well as at the substrate level 2.3°C. At the slab point, none of the situations (C and EVR) showed negative temperature values in winter. By comparison, EVR showed lower peak-to-valley-gap and better anti-interference performance in both daily and seasonal periods (Table 3). In the case of the substrate humidity, winter values were close to zero and constant since irrigation was minimal to cover evapotranspiration needs. Summer values were similar to those from winter, except on January 12th and 13th when rainfall occurred.

C roof experienced heat gains due to the highly heated roof surface during the summer period. This could cause heat gain in the inside space when the heat fluxes reached up to 100 W/m^2. On the contrary EVR showed values from -40W/m^2 to 40W/m^2 (with cooling effects during the day and allowing a positive heat flow inside the building during the night). Delta showed damping of flux between the EVR and C roofs. For the winter period, although the heat fluxes were higher in the C roof than in the EVR, during daytime the EVR showed a cooling effect (negative flow values, up to -49.4W/m^2) but during the night fluxes were positive (values up to 25.1W/m^2). On the contrary, the C roof showed higher positive flux values during the daytime (up to 74.5W/m^2), and during the night heat losses (up to -20.4W/m^2) or slight temperature gains were observed (Fig. 6).

3.2 Vegetal performance assessment

All treatments showed high mean survival values, reaching up to 90% after 15 months of evaluation, except the treatment TD (<75%) because of the losses of *Glandularia x hybrid* individuals (Fig. 7). The succulent species in the treatments TA, TB, TC and TD showed a decrease in individual number in some replicates. The treatment TD displayed significant differences with respect to the rest of the treatment for both periods February 2020 and December 2020 (H = 9.60; p = 0.04 and H = 10.44; p = 0.03, respectively). Almost all the treatments showed optimal plant health status. Only the *Glandularia* specimens in TD and TF displayed a decrease in the amount of foliage and flowering during the first growing season, but they recovered during the beginning of the second growing season.

During the plant establishment period (first month after the planting date) there were already observed differences in green coverage among the treatments (Fig. 8). The treatments TA, TB, TC and TF showed an initial coverage >20% and the treatments TD and TE <20% (Fig. 8). Although, all of them experienced a positive increase in coverage percentage from the planting date to the end of the first growing season (October 2019; February 2020; Fig. 8). At the beginning, treatments TD and TF displayed a decrease in coverage percentage during January and February 2020, but they considerably increased the coverage percentage during the start of the second growing season to reach values higher than 90% (Fig. 8). Also, TA reached the highest coverage percentage during the beginning of the second growing season in December 2020 (Fig. 8). The treatments TB and TC decreased its coverage percentage during the beginning of the second growing season (10-15%) Finally, TE formed by only succulent species showed the lowest coverage percentage from the beginning to the second growing season (71%; Fig. 8), which could have been caused by its initial low coverage.

3.3 Indexes of thermal performance

During summer, the STR thermal value was lower than 1, signifying that both maximum and average external surface temperatures are lower on the EVR compared with the values for the C bare roof

(Table 3). A STR value as 0.872 for all the year round indicates an energy reduction of 12.8% for cooling and heating services (less sensible heat flow through the EVR). The ETR values are constantly higher than 1, ranging from 1.46 to 2.03; this trend denotes that all the plant-substrate configurations reach surface temperatures higher than the outside air temperature. Finally, TER index varied between 0.424 and 0.459, which means an important decrease in temperature fluctuation from the EVR values with respect to those from the control roof (Table 4).

4. Discussion

In this study, we have evaluated the performance of EVR located in the middle of a UHI, analysing thermal performance and adequacy of native vegetated layers, comparing vegetation treatments with different species combinations. Our results showed a notable decrease in temperature at the level of the outside slab under the green roof as well as a marked decrease in the thermal fluctuation with respect to the control roof. In parallel, we assessed the performance of different plant assemblages, with native and non-native species, where the results showed ≥90% of survival and ≥60% of coverage for almost all the treatments after 15 months.

Thermal performance

Buildings have a large proportion of urban space and act as major heat sources [49]. Building greenery systems are a set of innovative construction systems that make it possible to incorporate vegetation into building envelopes providing multiple ecosystem services at both building and city levels [58]. The thermal performance reported in this study for a vegetated roof in the middle of the urban heat island can be compared with previous results obtained for an EVG in the periphery of the city, 9459m apart from each other [48]. Even though there are differences between the UHI and the periphery of the city, showing consistent temperature reduction by EVRs that justify roof greening as an adaptive solution in semiarid areas. For example, we found that surface temperatures registered on bare roofs were higher

(44.6°C in the centre of Córdoba city and 57.6°C in the periphery) with respect to those registered on the EVRs (34.7°C and 37.5°C °C, respectively) [48] and our results. These values are comparable to those registered in Nanjing, China (63.5°C on bare roofs with respect to 34.8°C on extensive green roofs, [49]). Some measurements from EVRs showed a considerable surface temperature reduction at slab level ([59, 60], Basovizza, Trieste, Italy), comparable to the reduction reported here. This reduction of temperature implies energy saving but also influences the durability of the watertight membrane [2] and of the roof materials because EVRs moderate the roof thermal stress.

The main effect of the EVR was to decrease daily fluctuation of external building envelope temperatures and, in consequence, the fluctuations of conductive heat fluxes can be reduced, as was previously reported by [61]. In our essay, thermal insulation provided by soil and vegetation layers dampen the incoming heat flux during the day in summer time. Thus, heat fluxes are always negative, indicating that the inside space is cooled by the EVR that disperses heat in the upper layers, similar to those found by [49, 62, 63]. The heat fluxes reached values higher than 100 W/m^2 during the day on the C roof and dampened to less than 40 W/m^2 up to -40W/m^2 on the EVR. In the wintertime, the EVR showed positive flux values during the night (25.1W/m^2) compared to those negative values (or barely positive) in the C; during the daytime, EVR released the heat flux and C flux values showed a marked heating effect (74.5W/m^2). This means a net heat gain of the indoor space during the night and a net heat loss during the day for the EVR. These results revealed that EVRs might be a double-edged sword providing both benefits and drawbacks, but anyway can benefit roof greening practices as a sustainable solution in the long run [48, 49]. Vegetated roofs can help mitigate urban heat because they reduce sensible heat fluxes above the exposed (control) roofs ([48, 64]; our results). This could occur due to the increases in evapotranspiration of the EVG [48, 49, 65, our results] which could also be increased if the EVRs are regularly irrigated [65]. At the same time, thermal conductivity of saturated soils is higher than that of dry soils because air is a better insulator than water [66]. Dry substrate will be more effective at decreasing the conductive heat flux through the EVR but it decreases evapotranspiration, which will increase surface temperature and sensible heat flux [67].

Plant treatment performances

Multiple studies showed that the *Sedum* spp. outperformed the native species (herbs and grasses) in EVRs located in regions with arid climates [26, 68, 69]. Our study showed that the arrangement of the native plants plus the exotic succulents displayed a better performance over the treatment composed only by Sedums, which only reached a coverage area of 71% after 15 months. Even though this could be explained because of the low initial coverage of the treatment (TE). It has been observed that *Sedum acre*, one of the species here, has a slower coverage than native creeping herbs [22], species which doubled the coverage, suggesting that Sedums may have a natural slow growth. In consequence, a desirable option for a quick coverage in EVRs could be using a combination of native plants plus *Sedum* species rather than only non-native *Sedum* spp. In future studies, it would be interesting to compare native and non-native plant species separately (both in monocultures and in mixture arrangements), so we can observe growth patterns in more detail. The treatment including the grass *Eustachys distichophylla* and *Sedum* species was the arrangement that showed the best performance. This result agrees with [22] who showed that *Eustachys retusa* (Lag.) Kunth presented a good coverage performance and also reseeding capacity in a vegetated roof essay. In consequence, *Eustachys* spp. could be considered as valuable species to design biodiverse arrangements for EVRs in semiarid climates. Attributes like high coverage, reseeding capacity, and resprouting contribute to guarantee perpetuation overtime of the vegetated layer of green roofs [23, 24, 25]. The excellent performance of the best combinations in a short period reduces and prevents some common problems of green roofs as substrate erosion or the presence of weeds [25]. In contrast, the treatments with the other grass species

(*Nassella tenuissima* plus succulent; TB) showed the poorest performance. This low performance could be attributed to the response of *N. tenuissima* to the stressed conditions imposed by the EVR in the urban heat island. In the TC treatment (succulents + grasses), interspecific competition between the species of the graminoid growth form (i.e. *E. distichophylla* + *N. tenuissim*a) was observed, and could be the cause responsible for the poor performance of this mixture. Competitive exclusion is a common phenomenon when co-planting species which are phylogenetically related or when they show comparable growth patterns [70, 71].

Comparing the treatments with the highest number of species and growth forms (TD: *Phyla nodiflora* + *Glandularia* x *hybrida* + *Grindelia cabrerae* + *Sedum* spp.; and TF: *Eustachys distichophylla* + *Nassella tenuissima* + *Phyla nodiflora* + *Glandularia* x *hybrida* + *Grindelia cabrerae* + *Sedum* spp.), both showed a very good performance but TF was better than TD. In the case of TF, we attributed these differences to the presence of taller species (*E. distichophylla* or *N. tenuissima)* that provide shade and diminish the substrate temperature, enhancing the performance of the creeping growth species [72]. Besides, optimal survival for individuals of the different species was observed in this treatment. On the other hand, although the TD treatment showed a very good performance, several individuals *Glandularia* x *hybrida* were lost during the evaluation period. This loss could also be attributed to competition between the two creeping herbs (*P. nodiflora* and *Glanduria* hybrids).

Conclusions

Vegetated roofs provide multiple benefits such as reducing energy consumption in urban buildings. Our experimental results support EVR designs with multiple species and growth-forms, even under the extreme microclimatic conditions that characterize roofs over buildings located under the heat island effects of contemporary cities. The EVR is a good option to increase energy saving and provide ecosystem services in urban environments. Nevertheless, new experimental analyses are required to disantangle the components and the mechanisms behind EVRs thermal performance. Consequently, we recommend the use of heterogeneous plant assemblages with native species, particularly grasses as *Eustachys distichophylla* combined with other growth forms to improve the performance of EVR vegetation in both the short and the long term.

Author Contributions

Federico O. Robbiati: Conceptualization, Methodology, Data curation, Formal analysis, Writing- Original draft, Writing- Review & Editing. Natalia Cáceres: Conceptualization; Data curation, Formal analysis, Writing- Original draft, Writing- Review & Editing. Emmanuel C. Hick: Methodology; Data curation, Technical support for roof construction. Mario, Suárez: Data curation, Technical support for roof construction; Silvina Soto: Writing- Review & Editing; Gustavo Barea: Writing- Review & Editing; Evangelina, Mattof: Technical support for roof construction. Leonardo Galetto: Conceptualization, Methodology, Writing- Original draft, Writing- Review & Editing, Supervision, Funding acquisition. Lelia Imhof: Conceptualization, Methodology, Writing- Original draft, Writing- Review & Editing, Supervision, Funding acquisition.

Declaration of Competing Interest

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

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Tables

Table 1. Details of measured parameters and type of sensor used.

Parameter	Sensor	Sensor location
Temperature; Net radiation; Wind speed; Rainfall	Weather Station ATMOS-41 - Meter Group with Datalogger; ZL6 Meter Group	1.5 meter from slab roof (on tenth floor of building) inside weather station
Slab temperature on control roof (C) and slab temperature on EVG green roof	Air temperature sensor with wiring and protection (Decagon Meter Group)	On the surface of slab in two places: directly on slab (control, C) and under EVG system (green roof)
Substrate temperature; Substrate moisture (water content of the substrate)	Substrate temperature and Moisture sensor (TEROS 12 Meter Group)	Integrated substrate temperature and humidity sensor located within the substrate

Table 2. Plant material combinations (growth form), treatment code and initial number of individual plants (n) per module of 1m^2 area of the extended green roof.

Code/ Plant name	*Eustachys distichophylla*	*Nassella tenuissima*	*Phyla nodiflora*	*Glandularia x hybrida*	*Grindelia cabrerae*	*Sedum spp.*	n
TA	x					x	12
TB		x				x	12
TC	x	x				x	15
TD			x	x	x	x	18
TE						x	16
TF	x	x	x	x	x	x	24

Table 3. Temperature measures in Control and in EVR: mean, coefficient of variation (CV), minimum value, maximum value, peak to valley gap (PV=the difference between maximum and minimum) and their fluctuations (φ) Values were taken for summer and winter periods at two moments of the day (between 3 and 4 a.m; and between 3 and 4 p.m). Kruskal Wallis tests with a common letter were not significant (p>0.05).

	Outside temperature	**Control slab temperature**	**Green roof slab temperature**	**Substrate temperature**	**Kruskal-Wallis test**
Summer 3 a.m					
Mean ± SD	20.71^{A}±3.11	22.87^{A}±2.82	23.22^{B}±2.19	20.49^{B}±3.2	H=22.20; p<0.0001
PV = (M) – (m)	15.2	12.8	10.3	15.5	
(φ)		0.84	0.68		
Summer 3 p.m					
Mean ± SD	30.91^{A}±4.95	35.11^{B}±4.74	27.68^{C}±3.3	34.13^{C}±6.33	H=36.11; p=<0.0001
PV = (M) – (m)	20.9	20.4	15.1	25.1	
(φ)		0.97	0.72		
Winter 3 a.m					
Mean ± SD	8.03^{A}±3.03	7.63^{A}±2.68	10.75^{A}±1.98	7.17^{B}±3.07	H=28.76; p<0.0001
PV = (M) – (m)	13	12.6	8.5	14.4	
(φ)		0.96	0.65		
Winter 3 p.m					
Mean ± SD	15.26^{A}±3.37	13.73^{AB}±2.88	12.81^{AB}±2.24	13.79^{B}±2.89	H=9.72; p<0.0211
PV = (M) – (m)	13.7	12.3	8.6	11.4	
(φ)		0.89	0.63		

*means with a common letter were not significantly different (p>0.05); M=maximum value; m=minimum value

Table 4. Values for the indices of thermal performance during the year and for summer and winter seasons when comparing the extensive green roof in the urban heat island of Córdoba City with the control roof. STR (surface temperature reduction), ETR (external temperature ratio), TER (temperature excursion reduction).

Indexes thermal performance	**All year**	**Summer**	**Winter**
STR (surface temperature reduction)	0.872	0.892	1.058
ETR (external temperature ratio)	1.71	1.46	2.03
TER (temperature excursion reduction)	0.45	0.424	0.459

Figure captions

Fig. 1. Climagram of the City of Córdoba. Series of 30 years (1981-2010) of monthly mean, maximum and minimum temperature (°C) and precipitation (mm) (NMS).

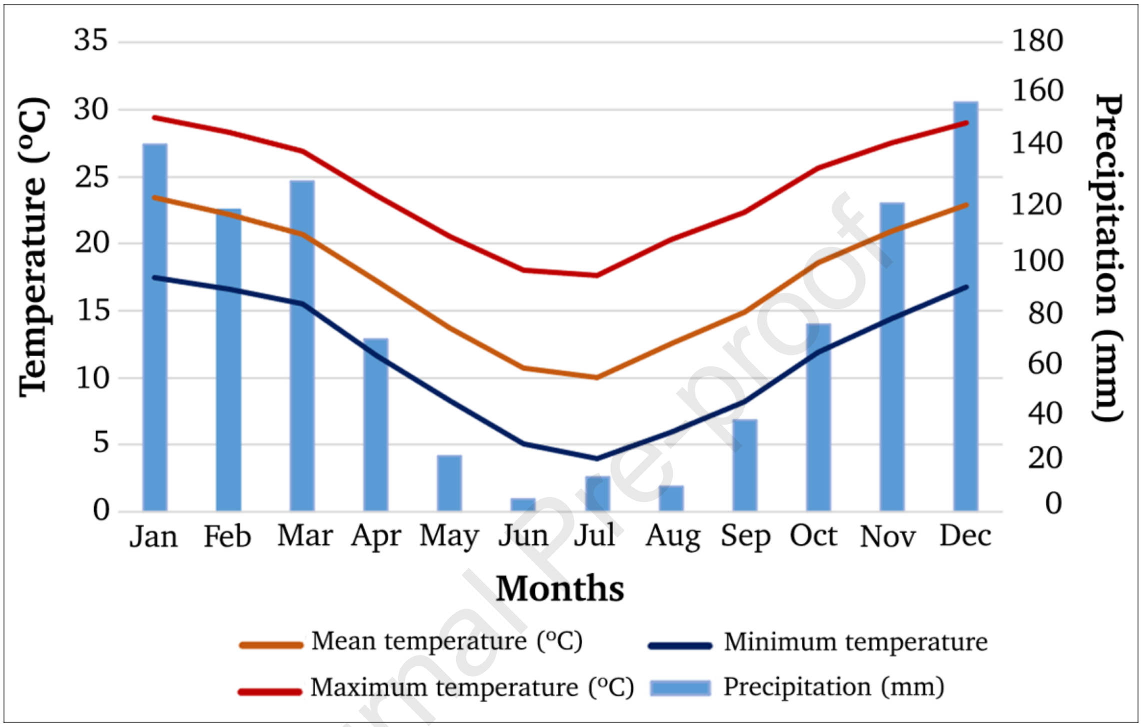


Fig. 2. Location of the essay on the tenth floor of the Córdoba Council Building, a) Google Map Image of the study site; b) an overview of the vegetated roof at the building top with a parapet of 0.5 m of height; c) technical scheme showing treatments distribution over the extensive green roof. TA = *E. distichophylla* + *Sedum* spp.; TB = *N. tenuissima* + *Sedum* spp.; TC= *E. distichophylla* + *N. tenuissima* + *Sedum* spp; TD = *P. nodiflora* + *Glandularia* x *hybrida* + *G. cabrerae* + *Sedum* spp.; TE: *Sedum* spp.; TF: *E. distichophylla* + *N. tenuissima* + *P. nodiflora* + *Glandularia* x *hybrida* + *G. cabrerae* + *Sedum* spp.

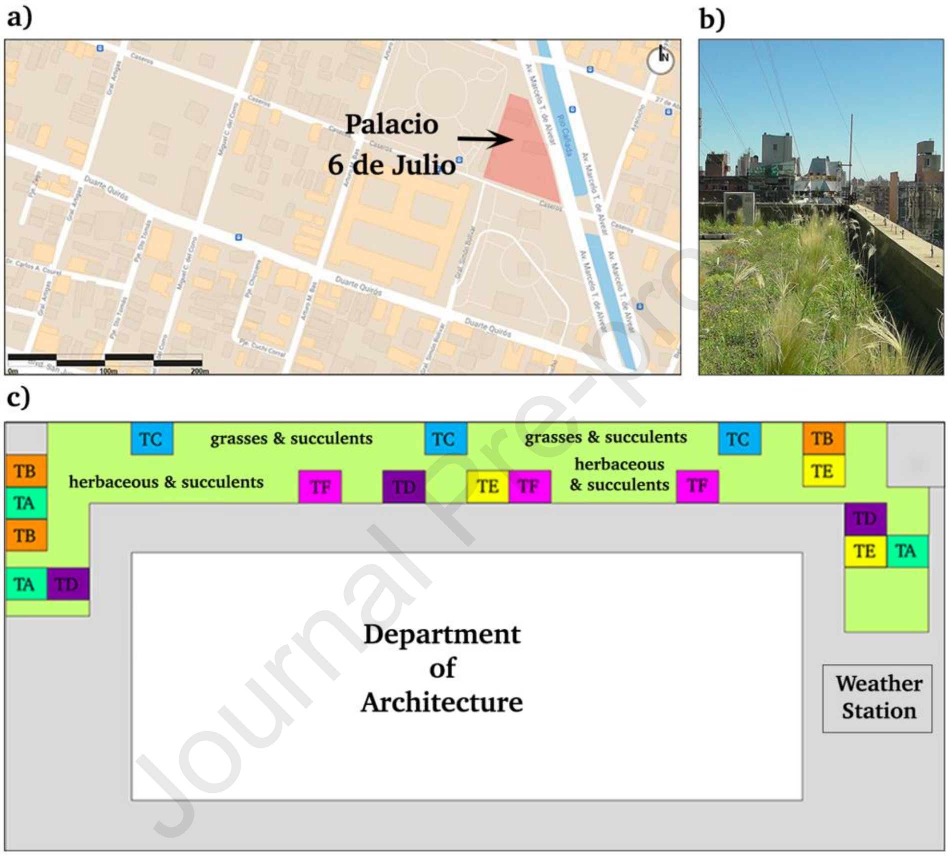


Fig. 3. Net radiation (W/m2), Wind Speed (m/s) and Rainfall (mm) values recorded by a weather station from 17/7/2019 to 17/12/2020 (from the week #29 of the year 2019 to the week #50 of the year 2020). In a) Wind Speed (m/s) b) Net radiation (W/m2), and c) Rainfall (mm).

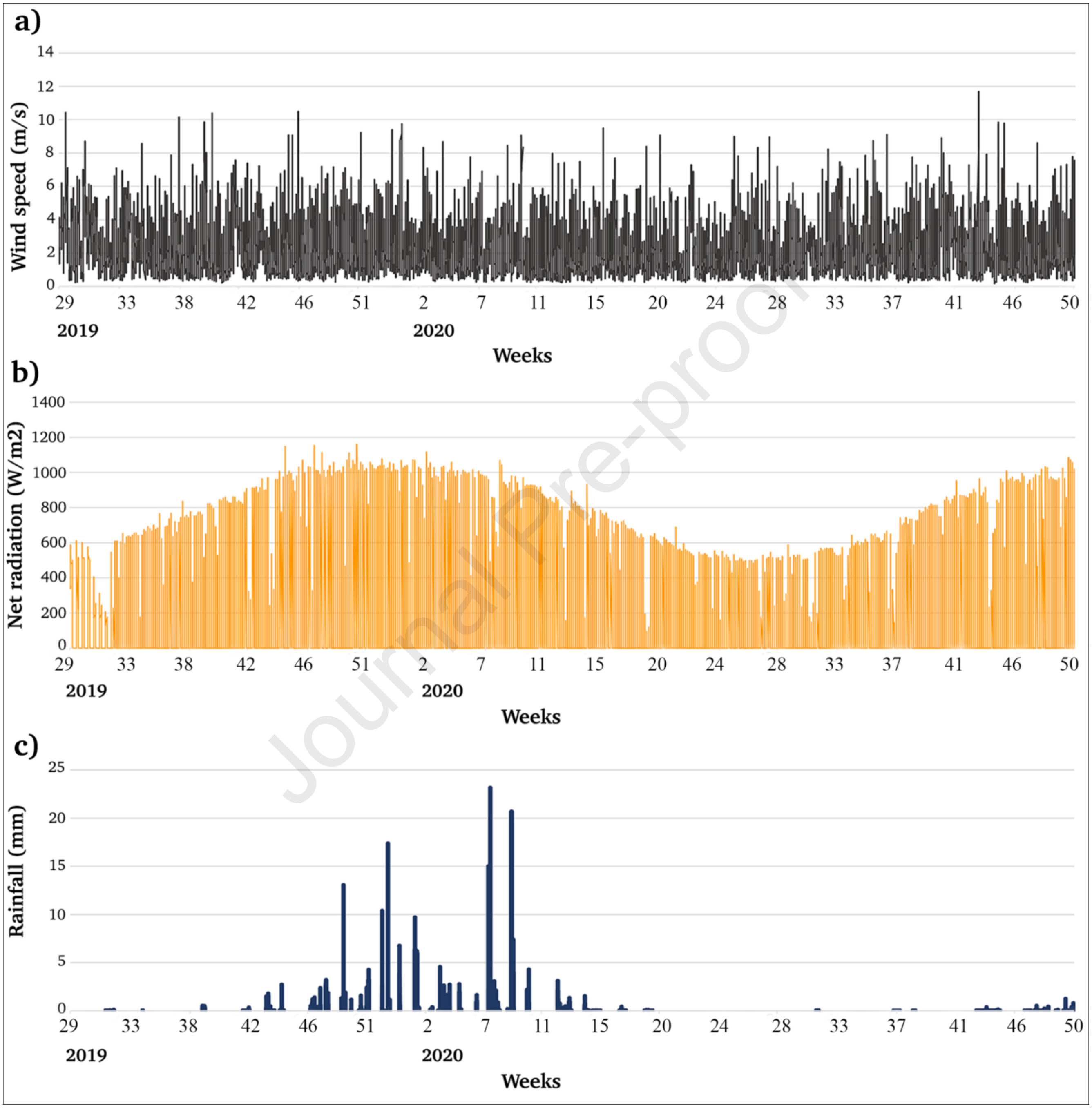


Fig. 4. Growth forms and species used for the performance assessment.

Fig. 5. Temperatures (on a 15-minute basis) for the air temperature (outside, slab level at control roof and vegetated roof and substrate level) and humidity of substrate (15-minute based) for a 30-day period during a) the summer (December 17th, 2019 to January 17th, 2020; week # 51, 2019 to week # 3, 2020) and during b) the winter (June 17th, 2020 to July 17th 2020; week # 25 to week # 29, 2020).

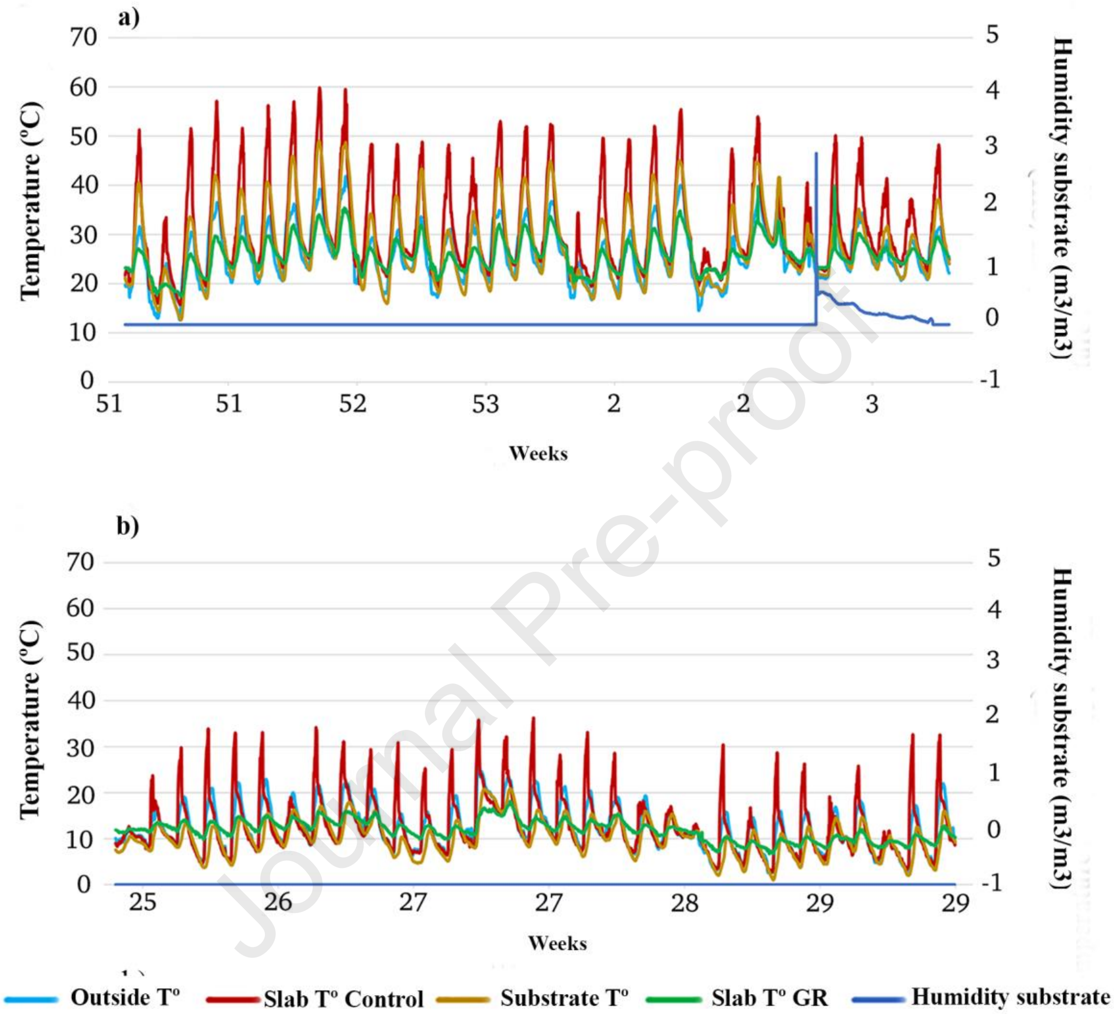


Fig. 6. Heat flux patterns at slab level during the essay comparing Heat flux on C roof and on extensive vegetated roofs and Delta value (515 days; Delta = (fluxGR: heat flux at slab level under the green roof- fluxCR: heat flux at slab level on control roof)); a) summer time (December 17th, 2019 to January 17th, 2020; week # 50, 2019 to week # 3, 2020) and b) winter time (June 17th, 2020 to July 17th 2020; week # 33 to week # 38, 2020).

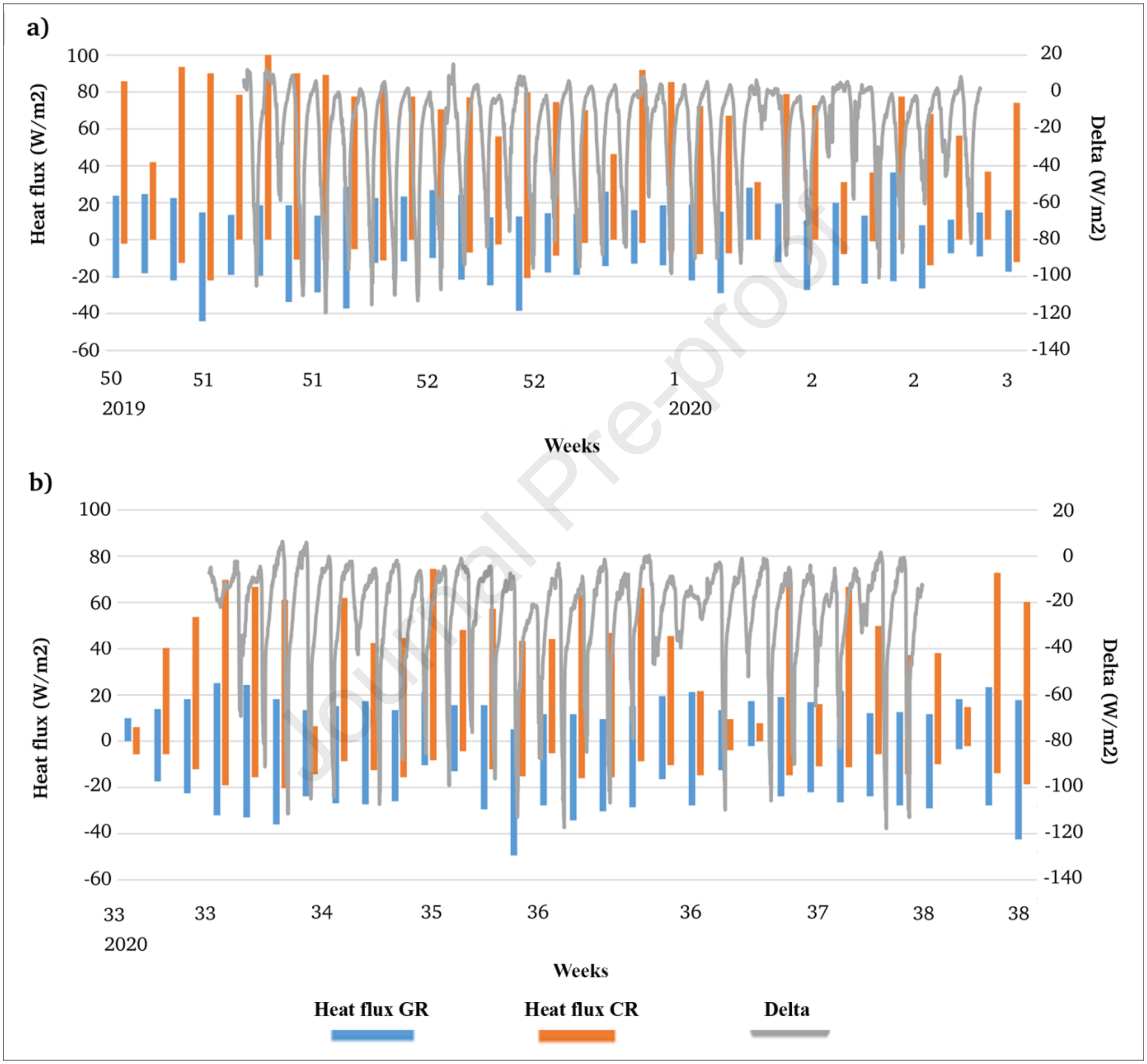


Fig. 7. Plant survival values (percentage) comparing the initial measurements (October 2019), the end of the first growing season (February 2020), and during the middle of the second growing season (December 2020) for the different treatments measured in an extensive green roof placed at the urban heat island of Córdoba City. Dissimilar letters show significant differences between survival values among treatments, at p<0.05 Kruskal-Wallis test. Treatments: TA = *E. distichophylla* + *Sedum* spp.; TB = *N. tenuissima* + *Sedum* spp.; TC= *E. distichophylla* + *N. tenuissima* + *Sedum* spp; TD = *P. nodiflora* + *Glandularia* x *hybrida* + *G. cabrerae* + *Sedum* spp.; TE: *Sedum* spp.; TF: *E. distichophylla* + *N. tenuissima* + *P. nodiflora* + *Glandularia* x *hybrida* + *G. cabrerae* + *Sedum* spp.

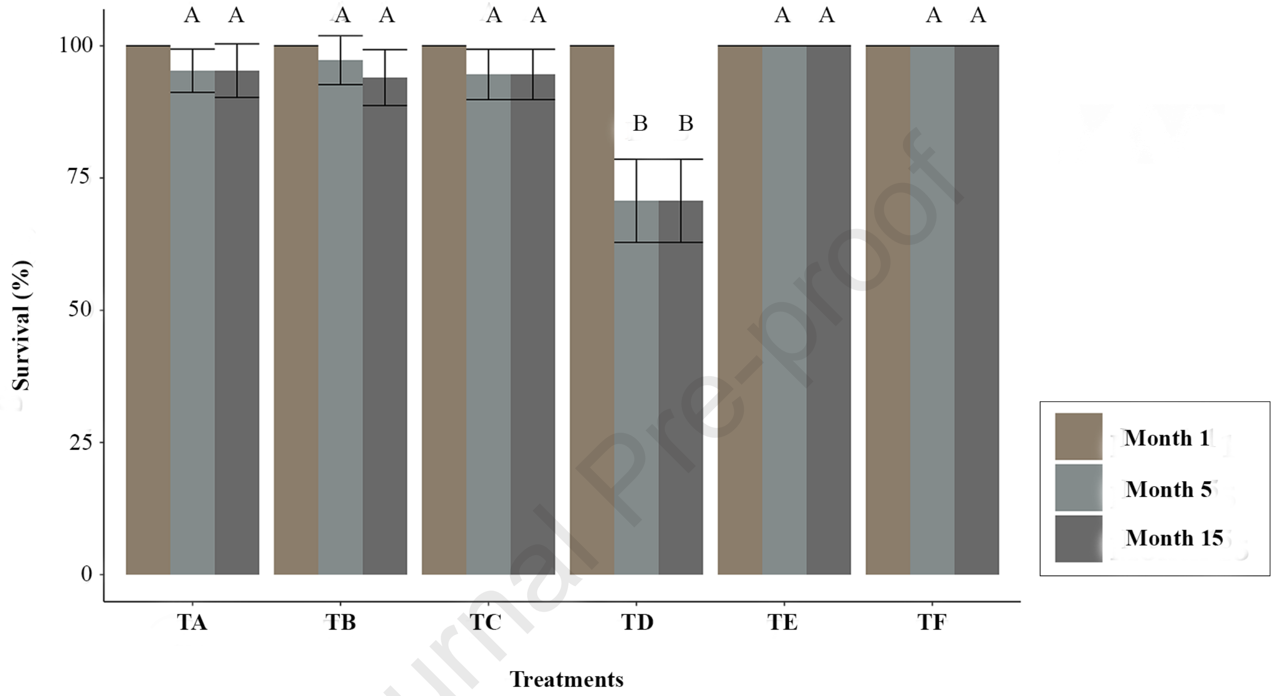
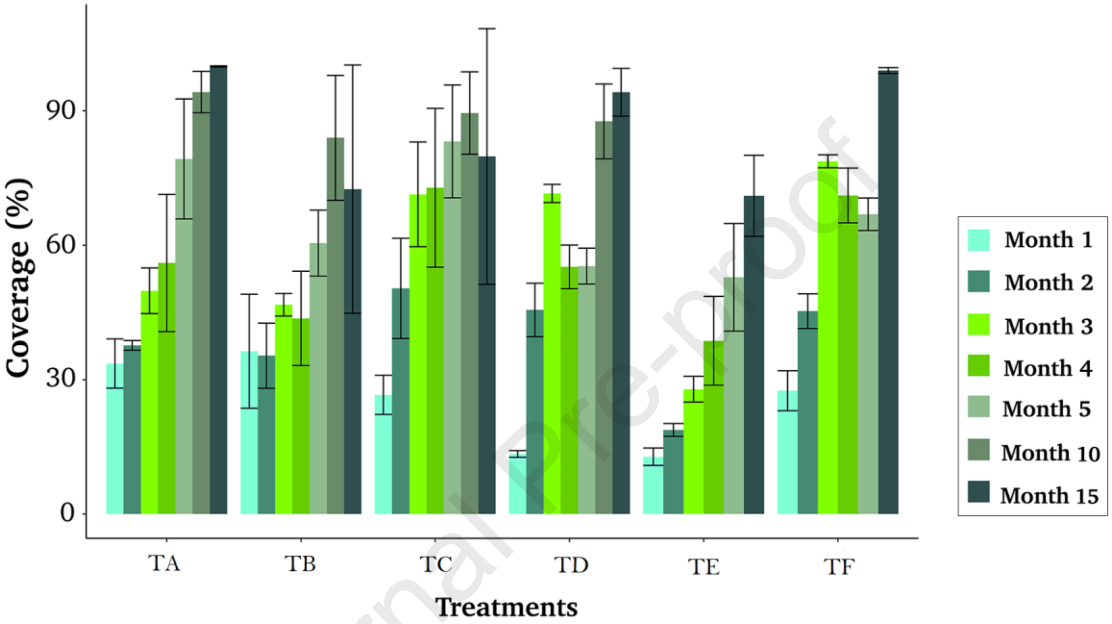


Fig. 8. Dynamics of coverage area (%) over 15 mouths evaluated for each vegetation treatment placed in an extensive vegetated roof in the urban heat island of Córdoba City. Values are the means ± standard deviation of three replicates for each treatment. Treatments: TA = *E. distichophylla* + *Sedum* spp.; TB = *N. tenuissima* + *Sedum* spp.; TC = *E. distichophylla* + *N. tenuissima* + *Sedum* spp; TD = *P. nodiflora* + *Glandularia* x *hybrida* + *G. cabrerae* + *Sedum* spp.; TE: *Sedum* spp.; TF: *E. distichophylla* + *N. tenuissima* + *P. nodiflora* + *Glandularia* x *hybrida* + *G. cabrerae* + *Sedum* spp.



Highlights

-Extensive vegetated roofs (EVRs) reduced the temperature in the urban heat island.

-Combinations of native and Sedums species showed better performance in EVRs.

-A diverse plant assemblage enhances EVRs performance and ecosystem services.

Declaration of Competing Interest

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