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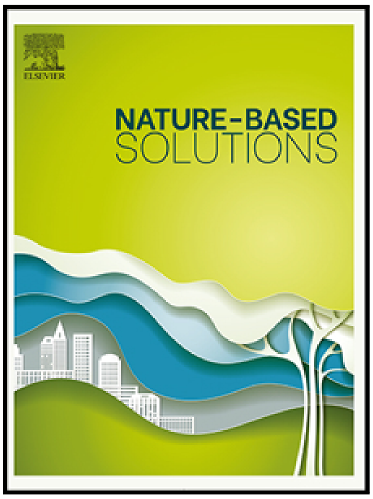

Vegetated roofs as a nature-based solution to mitigate climate change in a semiarid city

Federico O. Robbiati , Cáceres Natalia , Barea Gustavo , Ovando Gustavo , C.Y. Jim , Suárez Mario , Hick Emmanuel , Esteban Rubio , Galetto Leonardo , Imhof Lelia

PII: S2772-4115(23)00021-6
DOI: https://doi.org/10.1016/j.nbsj.2023.100069
Reference: NBSJ 100069

To appear in: *Nature-Based Solutions*

Received date: 3 October 2022
Revised date: 3 March 2023
Accepted date: 16 May 2023

Please cite this article as: Federico O. Robbiati , Cáceres Natalia , Barea Gustavo , Ovando Gustavo , C.Y. Jim , Suárez Mario , Hick Emmanuel , Esteban Rubio , Galetto Leonardo , Imhof Lelia , Vegetated roofs as a nature-based solution to mitigate climate change in a semiarid city, *Nature-Based Solutions* (2023), doi: https://doi.org/10.1016/j.nbsj.2023.100069

- Extensive vegetated roofs (EVRs) sequester c. 0.57 kg C/m^2 in semi-arid Córdoba, Argentina
- EVRs reduce energy consumption by c. 40% through the year, especially in summer
- EVRs reduce CO_2 emissions and offer a sustainable nature-based solution to climate change

Vegetated roofs as a nature-based solution to mitigate climate change in a semiarid city

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Extensive vegetated roofs (EVRs) are effective in storing carbon and suppressing carbon dioxide emissions to reduce energy consumption in buildings significantly. This study aimed to quantify the carbon sequestration capacity of EVRs and estimate their potential in reducing CO_2 emission in Córdoba city in the semiarid region of central Argentina. For carbon sequestration capacity, we sampled plant and soil materials of three EVRs with similar vegetation but different ages and urban environmental stresses. We measured the carbon storage in the aboveground and belowground biomass and the substrate. To estimate the potential of EVRs in reducing energy consumption and thereby trimming CO2 emission, we simulated the energy consumption reduction by a building with EVRs using the EnergyPlus modeling software. We adjusted the actual data of physical parameters obtained in our study to calculate CO_2 emission reduction compared to a control roof. Our results suggested that EVRs in the semiarid climate could sequester carbon in the order of 2.11 CO2eq/m^2 per year The EVRs achieved a reduction in energy consumption of c. 40%, equivalent to decreasing the emission by 68.38 kg CO_2/m^2 per year. Since the EVRs can provide an integrative and multifunctional solution to reduce atmospheric CO_2 in urban ecosystems, they offer a promising sustainable nature-based solution with the potential to mitigate climate change effects.

1. Introduction

Human activities induce changes in atmospheric composition by accumulating greenhouse gasses. Global warming has been related to increased carbon dioxide (CO_2) emissions [1,2]. Urban areas emit a significant amount of greenhouse gasses, including 78% of total CO_2 emissions [3]. Transport, the cooling and heating of buildings, industrial activities and the construction sector are the principal sources of CO_2 and other emissions in urban ecosystems [4], with a significant temperature increase since the end of the last century [5]. Moreover, urbanization can remove large tracts of vegetation cover, degrade soil properties, reduce their ability to sequester and store carbon [6] and perturb biogeochemical and ecological processes [7,8]. Such changes have made the urban environment more vulnerable to climate change. Serious environmental, social and economic problems could be generated due to urban ecosystem degradation [9].

Consequently, it is urgent to develop and implement strategies to reduce atmospheric CO_2 emissions in the urban context [3,10], given that urbanization has drastically intensified worldwide in recent years [6,11]. Energy production harms the environment and contributes to climate change [12,13]. Over 40% of the world's energy is consumed in buildings [14], primarily for indoor cooling or heating [15]. The world needs to develop eco-friendly technologies to reduce building energy consumption [16]. Extensive vegetated roofs (EVRs) offer nature-based solutions that can reduce energy use, enhance energy efficiency, and inform energy-saving strategies [15,16,17]. The EVRs can contribute to this quest by reducing building energy use via multiple pathways, namely shading, insulation, increasing albedo, evapotranspiration [18-23], and suppressing the urban heat island effect [24-25].

There are several green options for carbon sequestration in urban ecosystems, including urban forests [26], turfgrass [27] and vegetated roofs [1,3]. The EVR is an innovative low-impact development practice [28] that provides notable ecosystem functions where carbon sequestration plays an important role in mitigating climate change [29]. EVRs can realize a modern biophilic technology on a building rooftop, consisting of vegetation growing on a constituted substrate [30-32]. This nature-rich technology could ameliorate various urbanization problems such as the urban heat island effect, stormwater runoff, heat stress, noise and air pollution [32−35]. EVRs are widely employed in bioclimatic architecture to complement traditional materials on flat roofs [1,36-39]. This green technology could contribute to atmospheric carbon reduction in cities in two ways [1]. First, it directly lowers CO_2 in the air by increasing carbon sequestration through photosynthesis [40−42]. Second, it indirectly depresses the building's cooling and heating energy consumption. This passive thermal regulation is attributed to reduced ingress of solar heat in summer and reduced egress of indoor heat in winter [28,32,43,44]. Plants play an important role in atmospheric CO_2 sequestration by fixing carbon into long-lived C pools via photosynthesis [45-48]. Carbon sequestration in EVRs is associated with plants, substrate, green roof structure, and management [47,29,18], especially the substrate's organic carbon content [49]. The plant biomass in an EVR plays a crucial role in passive temperature regulation [50], mainly due to latent energy absorption during transpiration [51]. Additionally, plants can provide cooling by shading and reflecting solar and terrestrial radiant energy, reducing the mean radiant temperature, and improving ambient microclimatic conditions [52].

Based on these findings, we hypothesized that EVRs are efficient in storing CO_2 and reducing emissions due to lower energy consumption. Therefore, our research objective was to assess EVR performance in the semiarid region of central Argentina by: i) quantifying the carbon sequestration capacity of EVRs and ii) estimating EVR potential to reduce CO_2 emission. To quantify their carbon sequestration capacity, we calculated the total carbon storage and total carbon sequestration in three EVRs located in contrasting urban environments. To estimate the

EVR potential to reduce CO_2 emission, we simulated the reduction of energy consumption by the EVRs using the EnergyPlus simulation software. We adjusted the actual data of physical parameters obtained in our trials to calculate the reduction in CO_2 emission. These results are essential to understanding EVR contribution to reducing CO_2 emission in a semiarid region of central Argentina.

2. Materials and methods

2.1. Study sites

The residents of Córdoba City are facing summers and springs with higher temperatures than in the past decades owing to the intensifying urban heat island effect [53,54]. They are exposed to higher concentrations of atmospheric pollutants (i.e., CO_2, NO_x, PM, etc.) [55]. The present study was conducted in three EVRs located in Córdoba city, central Argentina (Fig. 1). The region has a semiarid climate characterized by hot and rainy summer, with wide diurnal and seasonal temperature amplitude, a mean temperature of 26ºC and dry winter with a mean temperature of 10ºC [56]. The mean annual rainfall is 800 mm [57]. The region corresponds to a transition between a warm semiarid (Bsh) and humid subtropical (Cwa) climate according to the Koppen-Geiger Climate Classification [58,59].

The first roof (EVR1) is located in the southwest of the city above a classroom workshop at the School of Architecture of the Catholic University of Córdoba Campus (UCC) (31º28`S, 64º14´W). It was constructed in September 2018, with 78 m^2, at 5 m above ground. The second roof (EVR2) is in the city center on the tenth floor of the City Council Building Palacio 6 de Julio (31º24′S, 64º11′W). It was constructed in April 2019 with an area of 68 m^2. The third roof (EVR3) is located in the city's northwest (31°20'S, 64°15'W). This roof was constructed in October 2019 for a commercial purpose with an area of 78 m^2 (Fig. 1).

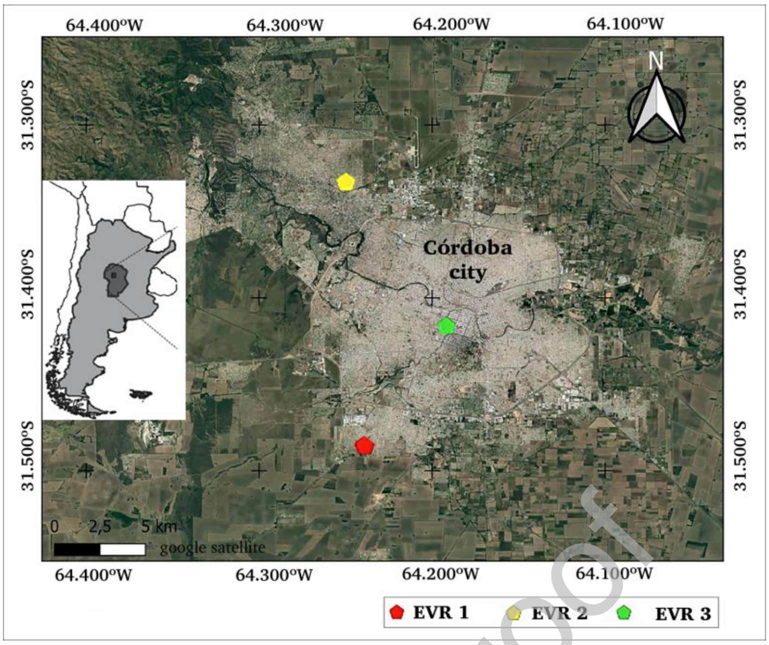

Fig. 1 The locations of the three extensive vegetated roofs chosen for the study in Córdoba city. **EVR1:** School of Architecture at UCC; **EVR2**: City Council Building; **EVR3**: Commercial building.

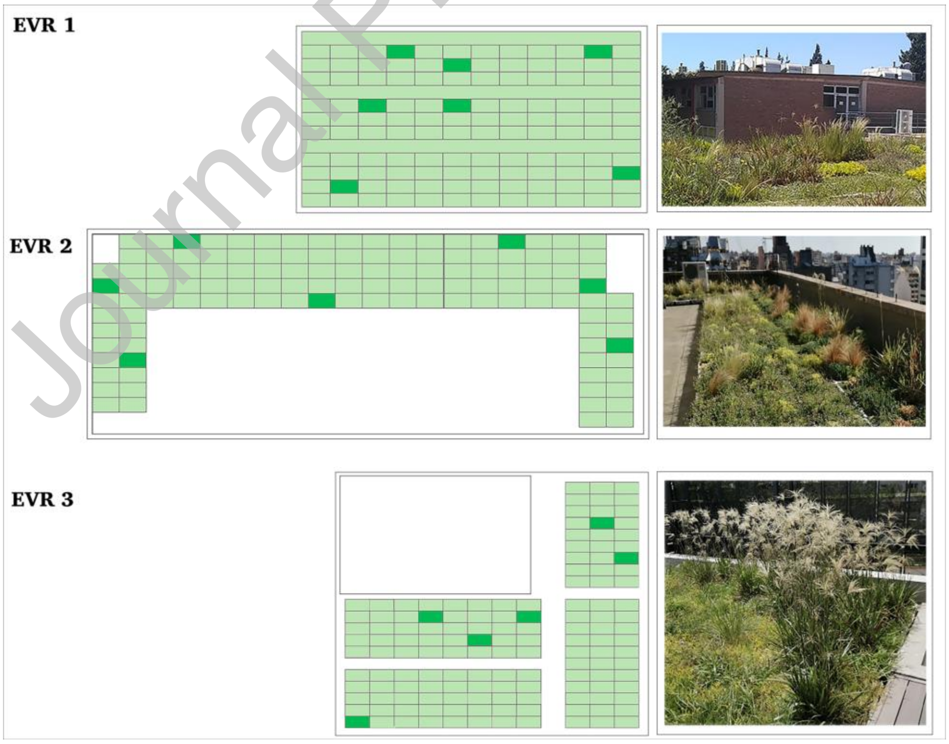

Fig. 2 The layout and plots of the three EVRs. The plots sampled for the vegetation study are shown in dark green. The adjoining photographs illustrate the site conditions.

2.2. Modular system and substrate of the extensive vegetated roofs

An extensive modular system was used for the EVR construction. Each module has an area of 1 m^2 with 0.15 m depth and is made of high-density polyethylene. The substrate was a prepared mixture of construction debris, compost, peanut husks, and perlite (proportion: 3:1:1:1 V/V) with an initial carbon content of 0.32 kgC/m^2. A drip irrigation system (drips at 2h/L) watered each roof twice a week. The excess water was drained through small holes drilled in the base of the module containers (94 holes/m^2); drainage: 94 holes of 8 mm each; water reservoir depth: 35 mm; water substrate weight: 110 kg/m^2.

2.3. Plant materials

The plant material used in the three roofs included assemblages of three life forms: (i) succulents: *Sedum mexicanum* Britton, *S. reflexum* L., *S. lineare* Thunb., and *S. confusum* Hemsl. (Crassulaceae; photosynthetic metabolism CAM); (ii) creeping herbs: *Phyla nodiflora* (L.) Greene, *Glandularia* x *hybrid* (Verbenaceae; photosynthetic metabolism C3); and (iii) graminoids: *Eustachys distichophylla* (Lag.) Nees, *Nassella tenuissima* (Trin.) Barkwoth (Poaceae; photosynthetic metabolism C4 and C3, respectively) (See [32]). These species had been previously characterized, evaluated and selected from experimental monocultures and mixed planting under EVR conditions [31,32,60]. They are evergreen species planted from rooted cuttings and young plants to guarantee a good initial establishment. After two years of plant growth and interspecific interactions, the grass *E. distichophylla* and the succulents emerged as dominants in the three EVRs.

2.4. Direct carbon quantification: Sampling and carbon storage estimation

To estimate carbon fixation, the aboveground biomass was determined from the plant communities established on the experimental modules of the three roofs. In each EVR, six to seven sample plots of 0.5 m^2 were randomly chosen (Fig. 2). The sampling was carried out at the end of the growing season (April/May 2022) with the stabilization of the vegetation cover. To quantify the aboveground biomass, all the samples were dried at 105 ºC for eight hours to a constant weight and immediately weighed with a precision balance (0.001 g) (Mettler Toledo PB 19502-S). The biomass carbon stock was determined by multiplying the measured aboveground biomass by an adjustment factor of 0.5 [61]. To estimate the carbon stored in the plant roots, we sampled 10 individuals of the dominant species *Eustachys* and *Sedum* to assess the root mass weight of the module. The root carbon stock was calculated by multiplying the estimated belowground biomass values by an adjustment factor of 0.5 [61]. To determine the percentage of carbon stored in the substrate, we sampled 800 g of the substrate from different locations of the EVR, mixed them, and took representative subsamples of 40 g for instrumental analysis of carbon. The samples were placed in crucibles and heated in a muffle furnace set at 500ºC for four hours to find the loss on ignition value. The weight difference between pre-ignition and post-ignition, minus the soil moisture content, was taken as the equivalent of soil organic matter content. The substrate's organic carbon (%) was calculated by dividing the soil organic matter content by an adjustment factor of 1.8 [62]. Then, we calculated the substrate organic carbon content for each module (kg/kg). To calculate the EVR carbon storage and carbon sequestration, we modified the method proposed by Fan et al. [30]: total carbon storage (TC) = substrate carbon (kgC/m^2) + plant carbon (kgC/m^2). Substrate carbon was calculated as follows: substrate organic carbon (kg/kg) $\times$ substrate bulk density (kg/m^3) $\times$ substrate depth (m). Total carbon sequestration was calculated as: the differences in carbon substrate at the end and the beginning of the experiment + plant carbon at the end of the experiment. To calculate the CO_2 sequestration capability per m^2 of EVR in kgCO_2eq, we multiplied the carbon sequestration value in kgC per m^2 with a conversion factor of 3.66 [63]. Considering that an EVR could reach a steady state at which the carbon stock is stabilized without important additional net direct sequestration [46,47], the attributes were calculated as a one-time value at the end of the green-roof installation year.

2.5. Indirect carbon quantification

2.5.1. EVR energy consumption simulation by *EnergyPlus*

The EnergyPlus is a software commonly used to analyze and simulate the building energy regime. It has been applied to an energy-regulation study by simulating the energy consumption of air-conditioning systems under different structural configurations of EVR in south China with a subtropical monsoon climate [64]. The study required modeling to estimate the thermal behavior of the EVR vegetation cover under experimental conditions. We used the Open Studio Application 1.4.0 software (including the update to OpenStudio 3.4.0) with the EnergyPlus version 22.1.0 calculation engine. EnergyPlus implements an EcoRoof model based on the FASST soil and vegetation models [65,66], allowing the coupling of the green roof energy balance equations to the building. To carry out the simulation, we selected the EVR1 since we had one year of temperature measurement inside the envelope, the control classroom, the data on the construction materials and their occupancy values.

In applying EnergyPlus, the module "Material:RoofVegetation" takes into account the following factors: long-wave and short-wave radiative exchange within the plant canopy; plant canopy effects on convective heat transfer; evapotranspiration from the soil and plants, and heat conduction (and storage) in the soil layer. The simulated building, previously audited on site, was a floor with an interior height of 3 m. Its dimensions were 12.4 m long and 7.23 m wide. Two university classrooms were selected, one with a green roof designated as the treatment plot and the other without (bare roof) designated as the control plot. More details can be found in [35].

Table 1 shows the key attributes of the green roof and the values used to run EnergyPlus. Concepts for the EVR materials and variables were briefly explained, adding a reference for each [67]. Some values were directly obtained from EVR1, some from references indicated for each variable, and others were defined by the model (EnergyPlus). We acknowledge that most biological and physical parameters are not fixed because of variations in the experiment [68]. Thus, we used mean values obtained for the vegetation during the experiment period (Table 1).

Table 1. The extensive green roof (EVR_1) setting values to run the model with EnergyPlus

EVR materials and variables	Property
Height of plants (m) [69]	0.6 (mean value for the different species at the end of the growing season, our date)
Leaf area index (dimensionless) [67]	3 (mean value for the different species at the end of the growing season, our date)
Leaf reflectivity (dimensionless) [70]	0.22 (set EnergyPlus)
Leaf emissivity (dimensionless) [70]	0.95 (set EnergyPlus)
Minimum stomatal resistance (s/m) [71]	282 (from Steifort et al. 2019, Verbena sp. white rs min (s m-1))
Substrate thickness (m) [70]	0.14 (our date)
Conductivity of dry soil (W/m.K) [35]	0.52 (from conductivity of dry soil [35])
Density of dry soil (kg/m^3) [70]	1100 (set EnergyPlus)
Specific heat of dry soil (J/kgK) [70]	1200 (set EnergyPlus)
Thermal absorptance [72]	0.9 (set EnergyPlus)
Solar absorptance [73]	0.7 (set EnergyPlus)
Visible absorptance [72]	0.75 (set EnergyPlus)
Saturation volumetric moisture content of the soil layer [74]	0.3 (set EnergyPlus)
Residual volumetric moisture content of the soil layer [74]	0.01 (set EnergyPlus)
Initial volumetric moisture content of the soil layer [74]	0.1 (set EnergyPlus)

Each classroom had the following lighting installations: 12 pieces of LED main lights with polycarbonate diffusers at 220/240 V, 45 W with warm illumination of 3700 lm; 4 pieces of LED strips with two transformers from 220 V to 12 V that worked all the time when the general lights were turned on. The classroom was occupied by a maximum of 30 students, from 0800–1300 h and 1400–2000 h, Monday through Friday. Infiltrations were set at one air renewal per hour (1 rh) for the whole year. To calculate energy consumption, the thermostats were set between 21ºC for heating and 24ºC for cooling. Outdoor microclimatic attributes were measured *in situ*: dry bulb temperature, wind speed and direction, relative humidity and global solar radiation on a horizontal surface. These measurements were uploaded to a climatic file EPW (TMY3). Direct beam normal radiation was estimated with global horizontal radiation measured using Elements 1.0.6 software developed by Big Ladder Software.

2.5.2. Model calibration

Calibration is an essential step in developing a useful model. Calibration is achieved by comparing model results with field observations and adjusting the model parameters to generate estimations that agree with valid field observations. Model calibration can reduce parameter uncertainty and, therefore, uncertainty in simulation results. The models were calibrated by modifying indoor space occupancy schedules and opening doors and windows. For the quantification of the concordance between the simulation results and the *in situ* measurements, the following widely used statistical indicators evaluated the model performance: coefficient of determination R^2, d, MAE, RMSE and BIAS [e.g., 75 – 79], calculated (Table 2) using the following equations:

$$R^2 = \left[\frac{\sum_{i=1}^{n} (obs_i - \underline{obs})(sim_i - \underline{sim})}{\sqrt{\sum_{i=1}^{n} (obs_i - \underline{obs})^2 \sum_{i=1}^{n} (sim_i - \underline{sim})^2}}\right]^2$$

$$d = 1 - \frac{\sum_{i=1}^{n} (obs_i - sim_i)^2}{\sum_{i=1}^{n} \left(|sim_i - \underline{obs}| + |obs_i - \underline{obs}|\right)^2}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |sim_i - obs_i|$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (sim_i - obs_i)^2}$$

$$BIAS = \frac{1}{n}\sum_{i=1}^{n} (sim_i - obs_i)$$

Where:
R^2 = coefficient of determination
d = concordance or Willmott index
MAE = mean absolute error
RMSE = root mean squared error
BIAS = mean error
sim_i = simulated values.
est = mean of the simulated values
obs_i = observed values
obs = mean of the observed values
n = sample size

Fig. 3 and 4 compare the internal temperatures estimated by the model and the actual measurements of the classrooms under the treatment plot (EVR) and the control plot (bare roof).

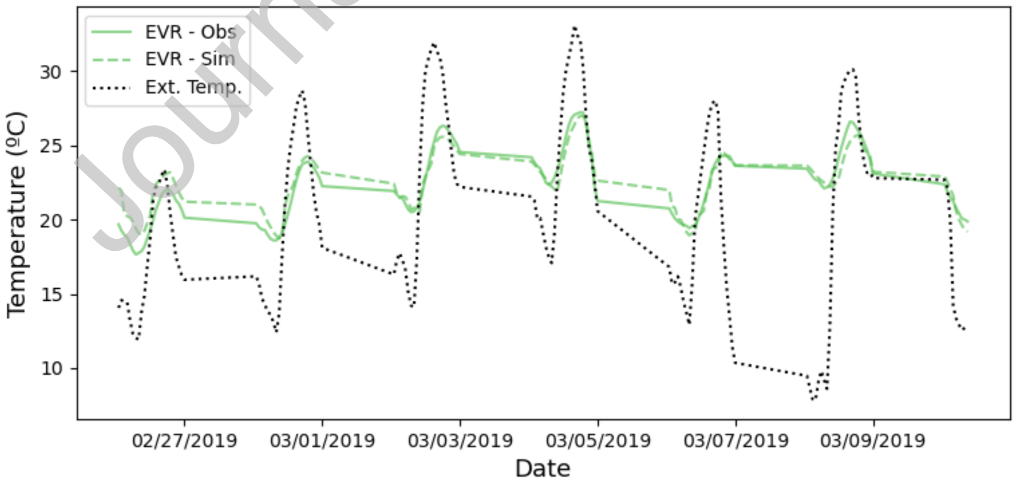

Fig. 3 Internal temperature adjustment in the classroom with EVR (treatment plot) for February 26th to March 4th, 2019.

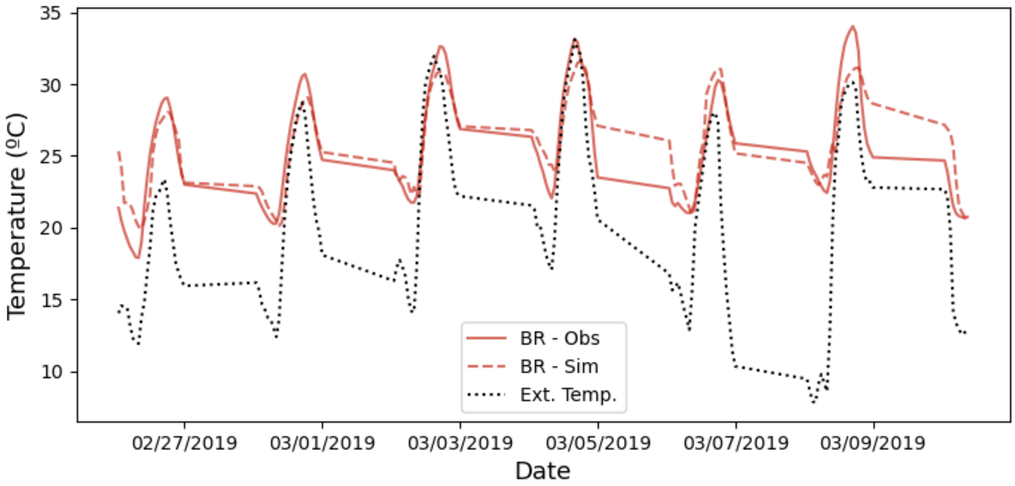

Fig. 4 Internal temperature adjustment in the classroom with a bare roof (control plot) for February 26th to March 4th, 2019.

Table 2. Statistical indicators showing the relationship between simulated and measured roof temperature of the classroom with EVR and bare roof

Statistic	Classroom with EVR (treatment plot)	Classroom with a bare roof (control plot)
R^2	0.90	0.83
d	0.96	0.94
MAE (ºC)	0.63	1.34
RMSE (ºC)	0.81	1.67
BIAS (ºC)	0.19	0.22

2.5.3. Energy consumption to CO_2 conversion

To analyze the reduction in CO_2 emission through energy savings, we applied the Simple Operation Margin Emission Factor (SOMEF). It was calculated as the average weight of the CO_2 emission per unit of electricity generation (tCO_2eq/MWh) of all the power plants that operate in the Argentinean system. We excluded the generation plants with low-cost/must-run, defined as those with a low marginal generation cost or dispatched regardless of the daily or seasonal system load. The value employed was 0.446 tCO_2eq/MWh, obtained by averaging 2018 and 2019 SOMEF values [80].

3. Results

3.1. Direct carbon quantification

The plant carbon stock and total carbon sequestration are presented in Table 3. The aboveground carbon stocks for EVR1, EVR2 and EVR3 were 0.27, 0.16 and 0.57 kgC/m^2, respectively. The belowground biomass was 12% of total biomass, at 0.04, 0.02 and 0.12 kgC/m^2 for EVR1, EVR2 and EVR3, respectively. The total carbon plant stock ranged between 0.18 to 0.69 kgC/m^2. The EVR3 held the greatest total plant biomass, followed by EVR1 and EVR2. The carbon fixed in the substrate was about 10% of the total C on the most recent roof (EVR3). With time, it began to exceed the value fixed in the substrate with respect to the carbon plants stored (EVR1). The total carbon fixed was the greatest in EVR3 (northwest periphery of the city), followed by EVR1 (southwest periphery of the city) and EVR2 (city center and center of the urban heat island), with an average of 0.57 kgC/m^2. The CO_2 sequestration capability of the EVRs varied from 1.13 $kgCO_2eq/m^2$ to 2.74 $kgCO_2eq/m^2$ (Table 3). The average value of total C sequestration by the vegetation was 2.11 $kgCO_2eq/m^2$ after the first growing season, and then this value stabilized in the ensuing years.

Table 3. Total plants and soils carbon stocked, total carbon storage and sequestration, and CO_2 sequestration during the first growing season

Extensive vegetated roof (EVR)	Total plant C (kgC/m^2)	Substrate C (kgC/m^2)	Substrate C fixed (kgC/m^2)	Total C storage (kgC/m^2)	Total C sequestration (kgC/m^2)	CO_2 sequestration during the first growing season (kgCO_2eq/m2)
EVR1	0.31	0.68	0.36	0.99	0.67	2.45
EVR2	0.18	0.45	0.13	0.63	0.31	1.13
EVR3	0.69	0.38	0.068	1.07	0.75	2.74
Average	0.39	0.50	0.18	0.89	0.57	2.11

3.2. Indirect carbon quantification: Energy consumption simulation and conversion to CO_2 emission

Fig. 5 compares the EVR1 and bare roof in relation to monthly energy consumption for heating and cooling the classroom. The graph highlights the green-roof positive effects vis-a-vis the bare roof. The green roof maintained higher ceiling temperatures in winter and lower ones in summer. The EVR1 achieved an annual reduction in energy consumption by 41.96% (365.33 kWh/m^2 for bare roof and 212.01 kWh/m^2 for EVR). The peak demand for indoor cooling occurred in January and February, with the highest ambient air temperatures. The notable differences in cooling loads demonstrated an 80–90% energy saving each summer month. On the other hand, during the winter indoor heating period, the classrooms with EVR1 and bare roof had almost the same energy consumption.

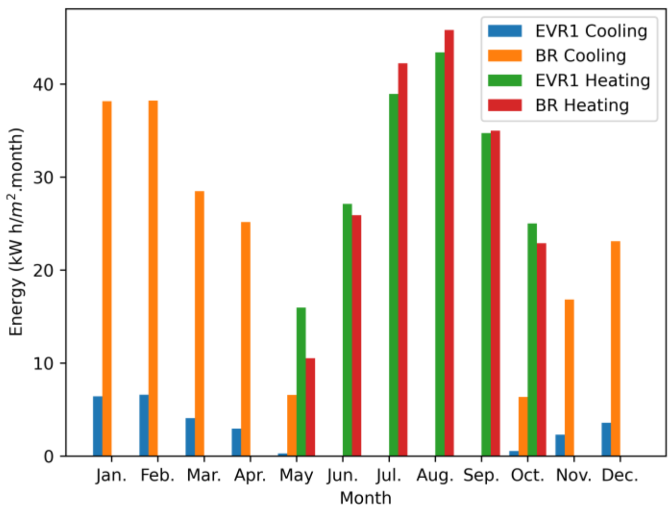

Fig. 5. Monthly energy consumption variations for heating and cooling the classroom under the extensive vegetation roof (EVR1) and the bare roof (BR) plots.

Under the bare roof scenario, the per year energy consumption corresponded to the emission of 162.94 $kgCO_2eq/m^2$ per year. The EVR simulation returned 94.56 $kgCO_2eq/m^2$ per year. With this lower energy consumption, an emission reduction of 68.38 $kgCO_2eq/m^2$ per year was estimated. The EVR1 offsets CO_2 by 68.38 $kgCO_2eq/m^2$ for emission reduction and 2.45 $kgCO_2eq/m^2$ for sequestration capacity. The total CO_2 offsets using the green roof construction system was 70.83 $kgCO_2eq/m^2$ (Table 4) during the first year of the EVR implantation.

Table 4. Average rooftop offsets versus building energy offsets during the first growing season of the vegetation of EVR1

CO_2 offsets	Value on EVR1	% of total CO_2 savings
Sequestration capability ($kgCO_2/m^2$/during the first growing season)	2.45	3.46
Emission reduction ($kgCO_2/m^2$/yr)	68.38	96.54
Total CO_2 offsets ($kgCO_2/m^2$/during the first growing season)	70.83	100.00

4. Discussion

In this study, we examined the contributions of three EVRs located in a semiarid region of central Argentina to building energy savings and CO_2 emission reduction. Our results showed that the EVRs are essential in reducing carbon sequestration and energy consumption in an urban context. In particular, EVRs in the semiarid climate could sequester carbon once in the order of 2.11 $kgCO_2eq/m^2$ when herbaceous vegetation achieves the maximum coverage during the first year. At the same time, EVR1 can reduce energy consumption by c. 40%, equivalent to decreasing the emission by 68.38 kg CO_2/m^2 per year.

4.1. Carbon sequestration on green roof

Our study showed an average carbon plant storage of 0.39 kgC/m^2. The three sites displayed a range of 18 kgC/m^2 in the center of the urban heat island (EVR2), 0.31 kgC/m^2 in the southwest periphery of the city, and 0.69 kgC/m^2 (EVR1) in the northwest periphery (EVR3). These values are similar to other vegetated roofs installed in different climatic zones; (i) arid and semiarid regions such as Iran (0.14–0.61 kgC/m^2) [48] and Greece (0.3–1.5 kgC/m^2) [81]; (ii) in a cool humid climate such as Michigan (0.27 kgC/m^2) [46]; and (iii) in hot humid areas such as Maryland (USA), Ciudad de México (México), DuJiangyan (China) (0.1–0.68 kgC/m^2; 0.16 kgC/m^2, and 0.73–3.83 kgC/m^2, respectively) [46,82,83]. The results are also related to watering [84], as the findings highlighted irrigation as a strong driver of plant growth in vegetated roof systems, including the more humid climate [85]. Rainfall increases the water supply to the EVR system, bringing faster growth and higher CO_2 sequestration [6]. Arid and semiarid conditions with very low or contrasting seasonal rainfall and wide diurnal and seasonal temperature amplitude can suppress plant biomass accumulation [86,87].

This study showed that the more recently installed EVR3 had the highest plant biomass. Generally, the viable plants would experience rapid growth in the first year. In the youngest EVR3, the plants were larger with better vigor than in other sites. Several studies suggested that extensive green roofs store new net carbon during the first few years of life [46,47]. Once the plants mature, net carbon sequestration will reach an equilibrium where the decomposition of organic matter will equal sequestration [11,88–92]. Carbon storage of plants is closely related to biomass [91-93] and plant growth (and then biomass). It is influenced by environmental factors [94], substrate conditions and human activities [95]. ERV2 had the lowest carbon sequestration in comparison to EVR1 and EVR3. This result could be explained by the relatively more stressful city-center environment with a more intense urban heat island effect than city-periphery conditions [32]. The carbon storage capacity of EVRs is highly dependent on plant type and substrate properties [46, 47, 96]. The root system's proliferation plays an important role in C cycling and soil organic C stabilization [97,98], and root decomposition adds particulate organic matter to the soil [99]. It was found that the aboveground plant material and root biomass stored an average of 0.168 kgC/m^2 and 0.107 kgC/m^2, respectively [46]. These values are similar to our results.

In a vegetated roof, the substrate layer is an essential component that significantly influences EVR performance [100, 101]. Its physical properties and water content can help to enhance the urban environment [91]. Our results showed that the substrate layer stored 31.5% of the total carbon sequestration, compared with 57.8% in the aboveground biomass and 10.5% in the root biomass. In our EVRs, the older green roof accumulated more carbon in the substrate. This result suggests that although the aboveground biomass accumulation in a green roof reaches a limit in the first few years, the substrate continues to function as a carbon sink. Most biomass is allocated to the shoots, but roots can produce CO_2 by respiration and decomposition [84].

A comparison of ground-level ornamental landscapes with vegetated roofs showed that carbon sequestration was higher in ground landscapes [47]. It is because the former commonly used woody plants and shrubs (65.67, 78.75, and 62.91 kgC/m^2) [47], as well as herbaceous perennials and grasses (68.75 and 67.70 kgC/m^2 for the in-ground and green roof sites, respectively) [47]. Comparing our results (0.57 kgC/m^2) to other urban green infrastructures, such as urban parks and other urban green sites, indicates that EVRs can serve as a complementary urban greening tool. In addition, the EVR carbon sequestration capability could be increased by incorporating a layer of shrubby vegetation and increasing the depth of the substrate to allow more extensive root development.

4.2. Energy saving in buildings

In our study, the energy saving was 41.96%. The indirect carbon fixation refers to the reduction in CO_2 emission following green roof retrofitting on an existing building, estimated by the energy saving [37]. In Mediterranean cities such as Palermo (Italy), the vegetated roof provided a yearly energy saving of approximately 23%, compared with the control bare roof [102]. In Catania (Italy), energy savings was 31–35% for cooling and 2–10% for heating [37]. The EVR in Portugal, with a low insulation level, was able to reduce 20% of the energy demand [103]. In the warm climate of Tenerife (Canary Island, Spain) and Seville (Spain), vegetated roofs trimmed energy consumption by 10.8% and 11%, respectively. In the mild climate (Rome and Amsterdam), the reduction was 8.2% and 8.5%, respectively. For the cold climate (Oslo), the annual energy saving was around 5.9% [104,105]. For semiarid climates such as Córdoba city, energy savings are significant and with higher values than the other cities mentioned. Implementing this technology on a larger scale is considered necessary as a mitigation tool in the current context of climate change.

It was found that a 33% reduction in annual energy consumption with a green roof and 10,300 kWh of energy saving is equivalent to a decrease of 203.4 kg CO_2 [37]. Translated to our results, a yearly decline of 153,32 kWh/m^2 of consumption means a reduction of 68.38 kg CO_2eq/m^2/yr. Energy consumption could not be calculated in EVR2 and EVR3 as the full range of building information and temperature data inside the envelope needed to run the model were unavailable. In future studies, it is important to simulate and compare the energy savings provided by EVR in different situations, such as urban heat island, and with different vegetation assemblage and coverage. On the other hand, this study revealed that EVR carbon sequestration capability by the vegetation is low compared with the energy savings of the building mediated by the green roof. Maintaining a permanent vegetation coverage with larger plant biomass could increase annual energy savings and carbon sequestration. To cope with climate change caused by greenhouse gas (GHG) emissions, national CO_2 emission reduction targets have been widely set [106]. One of the most valuable ecosystem services for climate change mitigation by green infrastructure such as EVR is carbon storage and sequestration in the aboveground biomass and substrate [42]. The GHG inventory of Córdoba city (2014) indicated that each inhabitant would emit 3.62 t CO_2eq/m^2. On average, 1 m^2 of green roof in Córdoba, including the sequestered carbon and avoided CO_2 emission, could achieve 70.83 kgCO_2eq/m^2 during the first year of implementation of the EVR or 708.3 t CO_2eq/ha of reduction. We could infer that 1 ha of green roof in Córdoba would mitigate the carbon emitted by approximately 195 people per year.

5. Conclusions

Extensive vegetated roofs have the capacity for carbon sequestration and to reduce CO_2 emissions through energy savings. Our results suggested that EVRs in a semiarid region could sequester carbon in order of 0.57 kgC/m^2, equivalent to reducing atmospheric CO_2 by 2.11 kg CO_2eq/m^2. This attribute was calculated as a one-time value because vegetation savings (i.e., carbon sequestration) are only accrued in the year of EVR installation. The comparison between EVRs and a bare roof through EnergyPlus simulations successfully demonstrated the indoor thermal variations under green and bare roof covers. The findings allowed the prediction of a classroom's heating and cooling energy savings covered by a vegetated roof. The substantial energy savings reached a peak of c. 40%, which would vary considerably throughout the year, being more important in summer cooling than winter heating. An EVR offsets 70.49 kgCO_2eq/m^2 in the first year. It comprises an annual 68.38 kgCO_2eq/m^2 emission reduction and a one-off 2.11 kgCO_2eq/m^2 sequestration in the first year. Consequently, most CO_2 emission reductions by EVRs are contributed by energy consumption savings rather than biomass-cum-substrate carbon accumulation. Finally, our findings provide objective data to help governments and decision-makers to estimate the building roof surface with extensive vegetated roofs necessary to mitigate carbon emission targets in semiarid cities such as Córdoba.

Acknowledgments

The authors thank MSc. Evangelina Matoff, Dr. Silvina Soto and members of INTA Argentina for their help. MSc. Matoff collaborated with installing the vegetated roofs and plant material maintenance and Dr. Soto in trial management. The authors appreciate the collaboration of

Graciela Bolatti (Forage Laboratory of the School of Agricultural Sciences (Universidad Católica de Córdoba). This work was supported by the Agencia Nacional Promoción Investigación, Desarrollo Tecnológico e Innovación (Foncyt-PICT, BID-PICT 2019-01920), SECyT (UNC), and the Consejo Nacional de Investigaciones Científicas y Técnicas through the PIP fund (Multiannual Research Projects, CONICET).

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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.