Analysis of the performance of green roofs in a Mediterranean climate

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Abstract

Green roofs have been increasingly installed on the roofs of buildings, underground car parks and other constructions, as, in addition to contributing to these structures' aesthetic and economic value, they also contribute to minimising problems found to be increasingly recurrent in large cities, such as riverine flooding and the heat island effect.

This paper analyses the behaviour of extensive green roofs in a Mediterranean climate, spanning their hydrological and thermal behaviour, as well as the incorporation of construction and demolition waste (RCDs) in technical substrates and the consequent effect on vegetation development. The effect of varying rainfall intensity and initial substrate moisture content on the performance of green roofing was also analysed.

The addition of RCDs to technical substrates was also analysed to determine whether these soils presented with hydrological and thermal behaviour different from green roof systems made up of technical substrates only.

Keywords: Green roofs in a Mediterranean climate, Hydrological performance, Thermal performance, Addition of RCDs, Vegetation development

Introduction

Nowadays, large cities face increasing urban densities, resulting in green areas being replaced with buildings, roads, and paving, which all impact their initial permeability conditions. Impermeable surfaces hinder the infiltration capacity of urban surfaces, generating an increase in urban surface runoff (Liu et al., 2021). Urbanisation tends to alter the surface hydrology of urban watersheds, leading to the creation of peak flows at extremely short intervals (Paithankar & Taji, 2020). Surface runoff, when caused by heavy rainfall in short periods of time, causes flooding in lower areas of cities. It is therefore vital to rethink city planning practices and the types of materials used in these practices. Solutions such as creating more urban green areas and using more permeable materials can reduce surface runoff, thus mitigating flooding in cities. Another problem resulting from intense urban densification, in addition to flooding, is the heat island effect. The use of materials with relatively low albedo, which present with low incident sunlight reflectivity and high heat absorption capacities, generate an increase in temperatures.

The use of materials or solutions with higher albedo allows for the effect of higher temperatures in cities to be mitigated.

An interesting strategy that allows for the mitigation of both flooding and the heat island effect is the implementation of green roofs - roofs that are totally or partially covered by vegetation. This strategy not only reduces temperatures - through evapotranspiration - and alters albedo but also contributes to reducing air pollutants (through deposition) and carbon dioxide (through photosynthesis) (Gilabert et al., 2021).

Services and performance of green roofs

Types of green roofs

Green structures used on roofs can be classified as extensive, intensive, and semi-intensive depending on the intended use, constructive factors, type of vegetation used and maintenance requirements (Liberalesso et al., 2021).

Extensive roofs are the lightest of the three and can be installed on existing flat or sloped roofs. The depth of substrate used on this type of green roof system ranges from 6 to 20 cm. Succulent plants, mosses or wildflowers can be grown in this type of system thanks to their low maintenance requirements (Manso et al., 2021). Intensive roofing requires a substrate layer that ranges from between 15 and 40 cm, with this deeper substrate layer allowing for a wider variety of plants, shrubs, or even trees to be grown. However, these types of roofs also require more maintenance and irrigation (Manso et al., 2021). Semi-intensive roofing is an intermediate solution between extensive and intensive roofing, requiring a substrate layer with a depth that ranges from between 12 and 25 cm (Manso et al., 2021).

When installing a green roof, several structural factors must be taken into account, such as the material and depth of the substrate, slope, and vegetation to be used (Liu, Feng, Chen, Wei, & Deo, 2019).

Performance in a Mediterranean climate

Variation of surface and coverage temperatures

The use of materials with high thermal inertia, such as concrete, causes heat absorbed to be continuously released by convection during the night. Thus, impermeable surfaces are considered the leading cause of the urban heat island effect, that is, higher temperatures being registered in urban areas of a city when compared to surrounding rural areas (Zhang et al., 2021). The heat island effect has been pinpointed as the cause of about 1/3 of the temperature increase in cities since the beginning of the 20th century (Susca et al., 2011).

Green roofs can be a viable solution for reducing the urban heat island effect, as they reduce surface temperatures through evapotranspiration and increase albedo. That is, they increase urban environments' reflectivity of incident radiation.

Table 1 summarises the average and maximum reductions in temperature in green roof systems when compared to traditional roofs. Both studies were carried out in Mediterranean climates.

Table 1 - Average and maximum temperature reductions in green roofs

Reference	Location	Climate	Average reductions	Maximum reductions
(Gilabert et al., 2021)	Barcelona, Espanha	Mediterranean	0.15ºC (during the night) and 0.17ºC (during the day)	1.70ºC (3 pm) and 1.24ºC (7 am)
(Bevilacqua et al., 2017)	Calabria, Italy	Mediterranean	From 0.57 to 0.63 times lower when compared to traditional coverage	For three green roofs, maximum reductions of 29.9°C, 33.4°C and 34.1°C

However, as found in the studies mentioned above, temperature reductions vary depending on the installation location and the material with which the comparison is made. Another factor that significantly influences the surface temperature of a roof is its water content, as the higher the water content, the higher the temperature reduction due to the evapotranspiration effect.

Flow retention

Green roofs provide a range of benefits when used in urban environments, including their ability to retain rainwater, delay peak discharge times, and reduce peak discharge volumes (Liu, Feng, Chen, Wei, & Deo, 2019). As such, they contribute to mitigating flood risks in lower areas of the cities they are used in.

Table 2 contains the results of several studies carried out to determine mean flow retention and peak flow delay.

Table 2 - Retention and peak flow delay

Reference	Location	Climate	Average flow retention	Peak flow delay
(Schultz et al., 2018)	Portland, USA	Temperate, with Mediterranean characteristics	32.9% (substrate thickness of 125mm) and 23.2% (75mm)	-
(Barnhart et al., 2021)	USA	-	Between 30 and 86%	30 minutes
(Liu, Feng, Chen, Wei, Si, et al., 2019)	Gansu, China	Semi-arid	Between 12.68% and 38.02%	-
(Liu, Feng, Chen, Wei, & Deo, 2019)	Gansu, China	Semi-arid	23% (high precipitation intensity) and 33.2% (low intensity)	9.2 minutes (high rainfall intensity) and 21 minutes (low intensity)

Several parameters affect green roof runoff, and consequently, water flow retention, including initial substrate moisture, saturated hydraulic conductivity and depth (Liu et al., 2021).

Use of construction waste in the substrate

The technical substrates used for green roofs have their own specific characteristics. Differing from common soil, they are the main element supporting vegetation growth (ANCV, 2019).

Additions can be made to the inherent properties of technical substrates, such as construction and demolition waste. However, their initial properties must not be significantly altered. Adding RCDs adds weight to the set. As such, the proportion of RCDs to substrate must be well-established in order to avoid generating very dense substrates or harming normal vegetation development.

Several studies are presented in Table 3, in which construction and demolition waste were added to substrate, as well as materials of diverse sources and origins.

Table 3 - Materials and quantities added to technical substrates

Reference	Location	Climate	Materials added to the substrate	Quantity of materials added (%)
(Mickovski et al., 2013)	United Kingdom	Temperate oceanic	Crushed RCDs (diameter < 5mm), containing calcium aggregate (65% by weight) and siliceous aggregate (35% by weight)	20%
(Bates et al., 2015)	Birmingham, United Kingdom	Temperate oceanic	Crushed brick (<75mm); RCDs (<40mm); Solid ash aggregate (<40mm)	Approximately 90%
(Molineux et al., 2015)	London, United Kingdom	Temperate oceanic	Clay; Quarry waste; RCDs; paper ash;	75%
(Eksi et al., 2020)	Istanbul, Turkey	Mediterranean	Crushed concrete (10-20mm); crushed brick (5-10mm); Sawdust; Municipal waste; rocky material of volcanic origin (3-10mm); sheep manure	20% organic material 80% inorganic material
(Eksi & Rowe, 2016)	Michigan, USA	Wet Continental	Municipal compound mixed with RCDs (china and recycled glass)	80%

Recycled materials can be viable additions to green roof technical substrates, improving resilience by increasing vegetation cover and diversity. However, the vegetation selected also plays a key role, as crushed brick was an excellent solution in some of the abovementioned studies, generating significant plant development for some species, though not for others. Therefore, it is important to consider the diversity of plants selected for green roofs so that their compatibility with any additions made to technical substrates can be gauged.

Methodology

Pilot installation of green roofs

In this study of green roofs, the main quantities evaluated were the incorporation of construction and demolition waste and the retention capacity and peak rainwater runoff delay. The effect of vegetation on surface temperature regulation was also analysed, as was the development of various types of vegetation in the various substrates monitored.

The study began on the 10th of December 2020 with the installation of four green roofs, the substrates of which did not contain RCDs. However, experimental tests were only carried out from the 24th of March 2021 onwards. Subsequently, the remaining four green roof systems were installed on the 6th of May 2021, with RCDs added to the substrate. The composition of each roof system is presented in Table 4.

Table 4 - Substrates and vegetation of the various green roofs

G1 Substrate: A	**G2** Substrate: A Vegetation: • White stonecrop (*Sedum album*) • *Sedum sexangulare* • Two-row stonecrop (*Sedum spurium*) • Coral reef sedum (*Sedum tetractinum*) • Oregon stonecrop *(Sedum oreganum)* • *Sedum oreganum a)*	**G5** Substrate: A + RCDs Vegetation: Rosemary (*Salvia Rosmarinus*)	**G6** Substrate: A + RCDs Vegetation: • White stonecrop (*Sedum album*) • *Sedum sexangulare* • Two-row stonecrop (*Sedum spurium*) • Tricolor Stonecrop (*Sedum spurium tricolor*) • *Sedum forsterianum*
G3 Substrate: A Vegetation: • Sea Thrift (*Armenia maritima*) • Red Creeping Thyme (*Thymus praecox*)	**G4** Substrate: B Vegetation: • White stonecrop (*Sedum album*) • *Sedum sexangulare* • Two-row stonecrop (*Sedum spurium*) • Coral reef sedum (*Sedum tetractinum*) • Oregon stonecrop *(Sedum oreganum)* • Tricolor Stonecrop (*Sedum spurium tricolor*) • *Sedum oreganum a)*	**G7** Substrate: A + RCDs Vegetation: • Sea Thrift (*Armenia maritima*) • Red Creeping Thyme (*Thymus praecox*)	**G8** Substrate: B + RCDs Vegetation: • White stonecrop (*Sedum album*) • *Sedum sexangulare* • Two-row stonecrop (*Sedum spurium*) • Tricolor Stonecrop (*Sedum spurium tricolor*) • *Sedum forsterianum*

Eleven precipitation tests were carried out, the first of which was used to calibrate shower precipitation intensity, as a precipitation intensity registered was much higher than that of a storm, as well as precipitation time. The shower flow rate was estimated using a five-litre bottle, with the rate calculated based on the time it took to fill the bottle. Precipitation intensity was then calculated from the flow in order to assess the intensity of the simulation.

AutoCAD software was used to monitor the development of vegetation and expansion of the green area on the roof by measuring the area occupied by each species, as can be seen in Figure 1 and Figure 2.

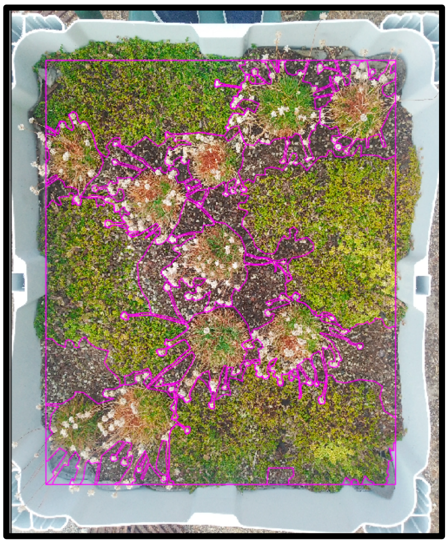


Figure 1 - Tracing of polylines in each plant

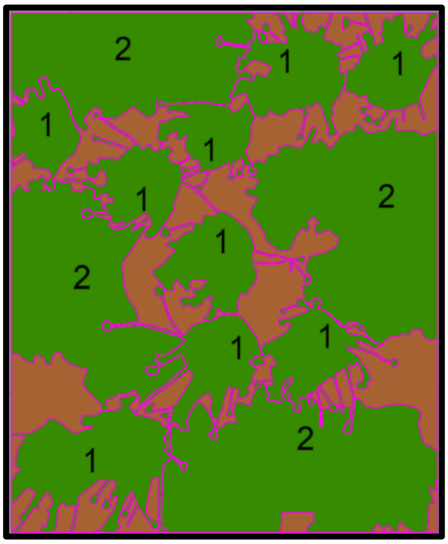
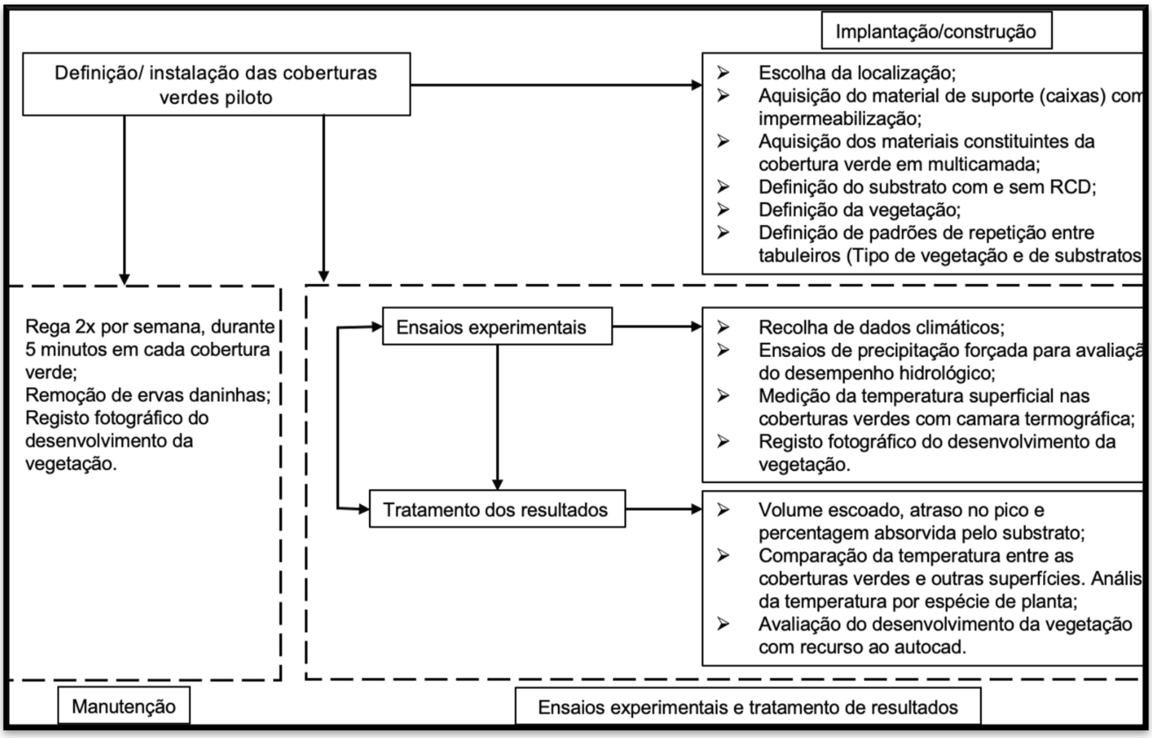


Figure 2 - Occupation of plants on the roof

Figure 3 presents a summary of the workflow applied to the pilot green roofs installed, as well as the measurements carried out.



- Escolha da localização;
- Aquisição do material de suporte (caixas) com impermeabilização;
- Aquisição dos materiais constituintes da cobertura verde em multicamada;
- Definição do substrato com e sem RCD;
- Definição da vegetação;
- Definição de padrões de repetição entre tabuleiros (Tipo de vegetação e de substratos

Rega 2x por semana, durante 5 minutos em cada cobertura verde;
Remoção de ervas daninhas;
Registo fotográfico do desenvolvimento da vegetação.

- Recolha de dados climáticos;
- Ensaios de precipitação forçada para avaliaçã do desempenho hidrológico;
- Medição da temperatura superficial nas coberturas verdes com camara termográfica;
- Registo fotográfico do desenvolvimento da vegetação.

- Volume escoado, atraso no pico e percentagem absorvida pelo substrato;
- Comparação da temperatura entre as coberturas verdes e outras superfícies. Anális da temperatura por espécie de planta;
- Avaliação do desenvolvimento da vegetação com recurso ao autocad.

Figure 3 - Flowchart of the development of green roofs

Presentation and discussion of results

The influence of initial moisture content on the performance of green roofs

The initial moisture content of a substrate affects its capacity to absorb any water that falls on it. A substrate's initial humidity is related to local climatic conditions, such as relative air humidity, recent precipitation, and the temperature itself, as higher temperatures can dry out substrates. Once the interstitial spaces are filled, the amount of excess water that percolates onto the substrate will be discharged by the substrate directly, as it can no longer retain water.

Initial substrate moisture content has been proven to influence green roof temperatures. The higher the initial substrate moisture, the lower the green roof surface temperature, a trend that can be seen across practically all roofs. More water in the substrate stops roof surface temperatures from rising, producing a cooling effect on this upper layer.

The initial moisture in the substrate influences the time interval until runoff occurs.

It was found that the greater the initial moisture content in the substrate, the shorter the time interval between precipitation and runoff from the roof. As the soil is wetter, that is, the soil pore spaces are filled with water, any excess water from precipitation will percolate through the soil at a quicker rate, generating flow in the roof outlet pipe. This behaviour was observed across the various roofs, except in cases where there was no runoff or when the precipitation intensity was so high that substrate moisture had little influence.

Influence of precipitation intensity on the performance of green roofs

It appears that the greater the intensity of precipitation, the greater the volume drained by the green roof, as the substrate starts to become fully saturated, losing its retention capacity. As such, all excess water causes flow in the roof exit tube.

Another important relationship to interpret is that between precipitation intensity and the percentage absorbed by the substrate. The greater the intensity of precipitation, the lower the soil's ability to absorb water due to high intensities of precipitation creating strong downward vertical flows in the substrate, with a significant portion discharged by the roof's outlet pipe, resulting in significantly reduced absorption by the substrate.

An identical relationship can be witnessed between the intensity of precipitation and the instant in which flow begins, as the more significant the intensity of precipitation, the shorter the time interval for the flow to begin from the roof. As mentioned previously, an increase in precipitation intensity results in a substrate's lowered absorption capacity and a shortened timeframe before flow is registered.

A similar conclusion can be drawn regarding the intensity of and delay in peak flow. High rainfall intensities will result in shorter peak runoff delays for the reasons mentioned in the previous paragraph.

Vegetation development

Having monitored the development of the vegetation over time, it was found that the G6 system reached the most extensive coverage in terms of area, occupying about 94.15%. Though it was implemented well after systems G1 to G4, G6 presented with greater spatial occupation due to the fact that the plants were more developed than those in other groups. The remaining G5, G7 and G8 plants did not follow the same pattern of development as the G6, as they were made up of different species. It should be noted that the substrate on the roof with the largest covered green area consisted of substrate A and RCDs. Covers G1 and G5 were made up of the same type of vegetation (rosemary), differing only in the constitution of their substrates, as G5's technical substrate incorporated RCDs. By comparing these two systems, it can be concluded that the RCDs roof presented with a higher rate of green coverage.

Surface temperatures on green roofs and other surfaces

Surface temperatures on the green roofs were consistently lower than those on other surfaces used for comparison, such as earth, asphalt, paving stones, and concrete. It is worth noting that the weather conditions directly influenced the temperature of each surface on the day the temperature was taken. It was found that a reduction in ambient temperature did not cause a reduction in the surface temperature of green roofs, except for roof G3; contrary to expectations. However, this effect may be related to the temperature readings not having been taken consistently at the same time of day.

Significant temperature reductions were achieved when compared to other surfaces (Table 5), with a maximum reduction of 32.1°C registered.

Table 5 - Temperature differentials between green roofs and other surfaces

Date	**Temperature difference (ºC)**			
	Earth	**Asphalt**	**Paving stones**	**Concrete**
09/06/21	26.9	18.6	11.8	15.8
29/06/21	32.1	17.1	8.2	11.6

Figure 4 and Figure 5 present the difference in temperatures on the various surfaces using a thermographic camera. Figure 5 displays the surfaces used for comparison: earth, degraded asphalt, paving stones, and concrete, respectively.

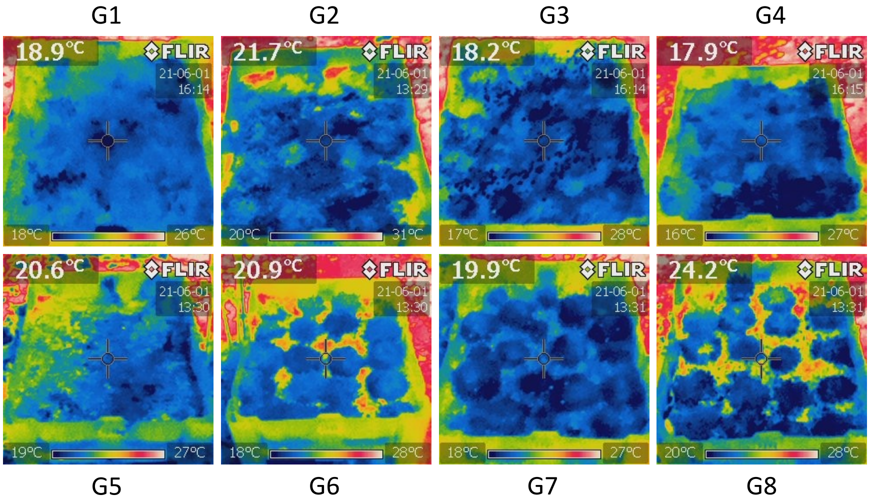


Figure 4 - Thermographic analysis of green roofs

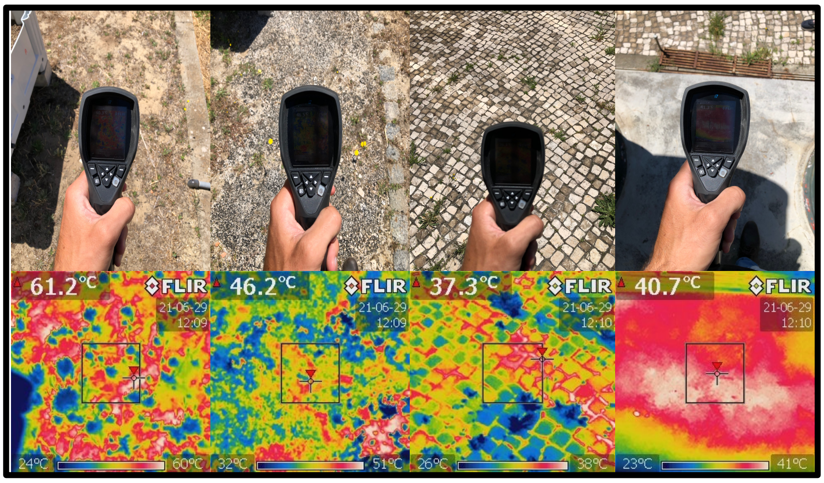


Figure 5 - Thermographic analysis of other surfaces

It should be noted that by reducing surface temperatures, green roofs reduce heat island effects in large cities, rendering them a viable solution to reduce this negative effect.

Conclusions

Green roofs prove to be a viable solution to be implemented on the roofs of buildings, underground car parks or any other constructions that may allow for their implementation. The variety of possible green roof solutions available, from intensive, extensive to semi-intensive, allows for practically any type of vegetation to be used, whether creeping plants or even sizeable trees. These roofs can be made accessible to create leisure areas, as well as contributing to any construction's aesthetic and economic value.

The results obtained from the various experimental tests run allow for a conclusion to be drawn that green roofs are a viable solution thanks to their efficiency in retaining water from precipitation, reducing the heat island effect in cities and incorporating new materials in technical substrates, such as RCDs, which make the solution more eco-friendly overall. Aesthetically, the solution adds value wherever it is installed.

The intensity of precipitation and initial humidity content of green roofs are parameters that influence their performance. High intensity precipitation reduces a substrate's absorption capacity, advances the onset of runoff, and increases runoff volume. These effects result from the soil's reduced capacity to absorb large amounts of water in short periods of time, therefore generating more runoff. It should be noted that green roof systems in which RCDs were incorporated in the substrate did not register significant differences from those that only contained technical substrate.

Green roofs proved to be effective in reducing surface temperatures when compared to other surfaces, with differences of around 32ºC being recorded. Green roofs have a higher albedo when compared to other surfaces, increasing their reflectivity and therefore lowering surface temperatures.

In short, all the results obtained in this pilot experiment of green roofs can be generalised, though it must be taken into account that the climate in which they are installed and the local weather conditions can influence roof performance.

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