Field experiment on transpiration from isolated urban plants

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Abstract:

The effect of pot plant density on plant transpiration rate was examined in a series of field experiments. Three spatial densities were created using 203 nearly homogeneous pot plants; the ratios of plant separation to plant height were 0·25, 0·5, and 3 for the 'high,' 'medium,' and 'low' groups respectively. The daily transpiration rate of 55 pot plants was measured for 28 days. During that period, the plants were randomly rotated each day to statistically eliminate individual characteristics and to successfully ascertain the effect of plant spatial density on the transpiration rate. As a best-case scenario, the soil for each plant was saturated at the start of each experiment. The results showed that the transpiration rate of potted plants in the 'low' group was about 1·5 times greater than that of the 'high' group. On the basis of the transpiration rate per unit of vegetation area projected on a horizontal plain, which is a general index used in meteorological modeling, the plants in the 'low' group evaporated 2·7 times as much water as those in the centre of the 'high' group. These results indicate the need for modified models that can consider the relative increase in evapotranspiration from vegetation in small-size plants or low spatial density of vegetation to estimate latent heat flux in urban areas. Copyright © 2007 John Wiley & Sons, Ltd.

INTRODUCTION

An accurate evaluation of water balances in urban areas is necessary to understand their hydrological cycle and climate. In particular, the latent heat flux from urban vegetation has an ameliorating thermal effect in hot summers (e.g. Spronken-Smith and Oke, 1998). Thus, the estimation of latent heat flux is important in understanding urban microclimates.

According to previous field measurements, evapotranspiration from urban vegetation is strongly affected by local and micro-advection. For example, Oke (1979) showed that actual evapotranspiration from an irrigated suburban lawn (approximately 160 m^2) was about 1·3 times greater than the potential evaporation set by Priestley and Taylor (1972) and greater than that from an irrigated rural pasture. Spronken-Smith *et al.* (2000) also reported a large latent daytime heat flux from an urban park. The observed latent heat flux was greatest at the upwind edge and decreased with distance from the edge to 20 m inside the park.

For the last several decades, much attention has been paid to developing accurate models of evaporation rates from finite wet surfaces. Most of this research has focused on the regional, local, or micro-scale advection of sensible heat. Brutsaert and Yu (1968) investigated mass transfer coefficient relational equations, which incorporate the size of the evaporating surface and wind speed as explanatory variables based on experimental data.

Brakke *et al*. (1978) presented a modified Bowen ratio–energy balance method that incorporates horizontal gradients of air temperature and vapour pressure to estimate local and regional advection of sensible heat. Brutsaert and Stricker (1979) proposed an advection-aridity model to calculate actual regional evapotranspiration based on the symmetric hypothesis of Bouchet (1963). Parlange and Katul (1992) presented an advection-aridity model that includes the effect of atmospheric stability.

In contrast with regional, local, or micro-scale advection effects, the 'clothesline effect' (Rosenberg, 1974; Oke, 1987) has not been well investigated. The clothesline effect prevails in small isolated areas of vegetation or along the upwind edge of a vegetation canopy surrounded by lower roughness. It causes high rates of evapotranspiration because the lack of obstacles to both solar radiation and wind results in large inputs of radiation and sensible heat (e.g. van Bavel *et al*., 1962).

Most current urban climate models estimate the spatially averaged latent heat flux from estimated values for each type of ground surface using surface coverage ratios, which are usually deduced from aerial photographs (e.g. Akbari *et al*., 2002). Isolated and small areas of vegetation, e.g. hedges, garden plants, and roadside trees, that are thought to be susceptible to the clothesline effect account for a considerable proportion of urban vegetation. Based on field measurements from a residential district in Tokyo using the eddy correlation method, Moriwaki and Kanda (2004) pointed out that estimates of aerial latent heat flux in urban areas based on present procedures are probably underestimated. Grimmond and Oke (1991) presented a model for calculating evapotranspiration from

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urban and suburban areas. The model includes a surface resistance concept to account for surface water availability for vegetation; however, the characteristics of evapotranspiration from small urban vegetation were not discussed.

Therefore, we focused on the transpiration rate of small-scale vegetation, which is affected not only by micro-scale advection effects, but also by the clothesline effect, to further understand the latent heat flux of urban isolated vegetation. We ran a series of idealized field experiments using numerous pot plants and investigated the relationship between transpiration rates per unit biomass and horizontal density of biomass. Urban trees vary in species, biomass, and age, but such diversity is difficult to control experimentally. We used even-aged plants of the same species and defined a pot plant by its unit biomass. Three vegetation groups with different horizontal biomass densities were created by varying inter-pot distances. As latent heat flux from urban vegetation is affected not only by the horizontal density of biomass, but also by the type of ground surface (such as pavement, bare soil, lawn) and the amount of water in the soil to simplify the analysis, all experimental conditions except the horizontal biomass density were fixed.

EXPERIMENTAL DETAILS

Alignment of potted plants

The experiments were carried out in Saitama, Japan (36°01′24″N, 139°42′28″E) on a horizontal 50 × 100-m concrete slab. There were no high-rise buildings or obstacles around the site (Figure 1(a)). We organized 203 potted camellia plants into three groups with different horizontal biomass densities. Camellias were chosen because they are commonly used as landscape trees in Japan. The group with the lowest horizontal biomass density, hereafter 'low,' had a plant−plant separation of 6 m (Figure 1(d)); the group considered 'medium' had a plant separation of 1 m (Figure 1(c)); and the group with the highest horizontal biomass density, 'high,' had a plant separation of 0·5 m (Figure 1(a)). Given that the average height of plants from the surface of the concrete slab was about 2 m, the ratios of plant separation to plant height were 0·25 (high), 0·5 (medium), and 3 (low). Because the average diameter of the plant crowns was about 73 cm, the plants in the high group were tightly packed. The three groups were spaced >15 m apart to prevent mutual interference (Figures 1 and 2). Daily transpiration rate measurements were performed on 55 of the 203 plants (Figure 2(a−c), shaded circles). The main experiment ran
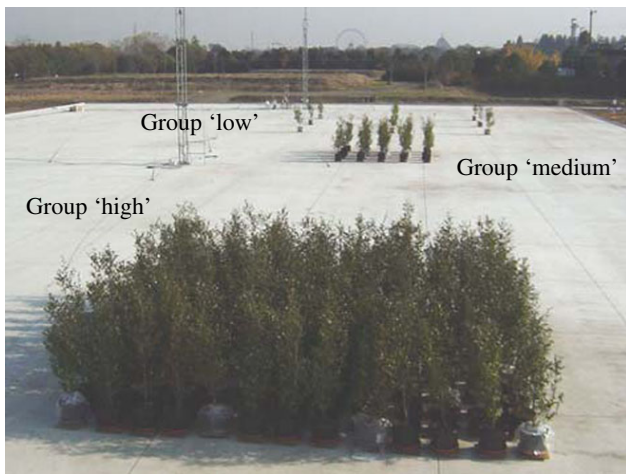
(a) Overview of the experimental site with the group 'high' plants in the foreground.

(b) A single potted plant.

(c) The 'medium' group.

(d) The 'low' group.

Figure 1. The experimental site and plants

(a) The 'high' density group.

(b) The 'medium' group.

(c) The 'low' group.

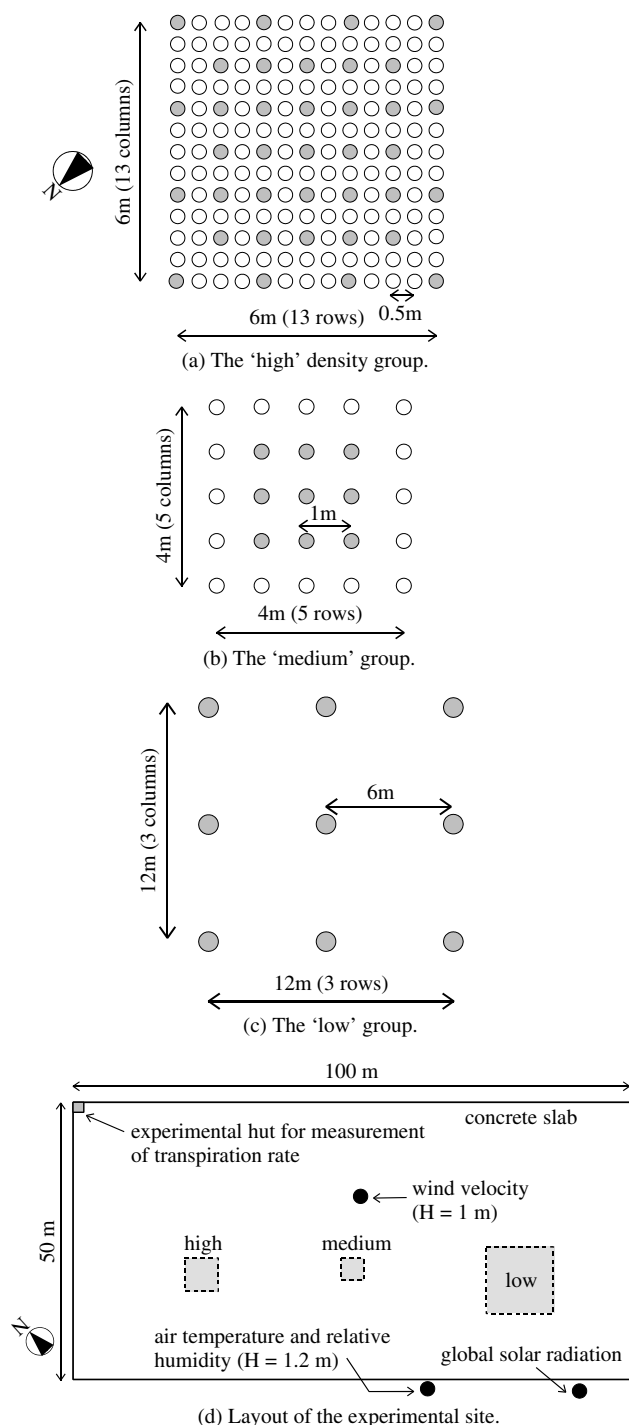(d) Layout of the experimental site.

Figure 2. Positions and alignments of the potted plant groups. In a–c, circles indicate plant locations; shaded circles are plants used for the evaporation measurements

from 2 September to 7 November 2003. In total, 28 days of transpiration rate data were obtained.

Air temperature was measured using a platinum resistance thermometer, and relative humidity was measured using an electrical capacitance hygrometer. The sensors were positioned in instrument shelters with a forced draught at a height of 1·2 m near the experimental site (Figure 2(d)). The amount of global solar radiation was measured using a solar meter. Air temperature, relative humidity, and solar radiation data were recorded at 1-min

intervals. Wind velocity was measured near the centre of the experimental site at 10 Hz using a 3-D ultrasonic anemometer at a height of 1 m.

Measurement of plant transpiration rate

The daily transpiration rates of nine potted plants from 'low,' nine from 'medium,' and 37 from 'high' were measured, a total of 55 plants. To ensure that the plants had nearly optimal transpiration rates, only plants without leaf blight were selected for measurement. To prevent weight loss caused by soil evaporation, the soil surfaces of the experimental plants were covered with plastic.

Transpiration rates were measured as follows. At the start of all measurements, the 55 plants were moved after sunset to an experimental hut located in a corner of the site. In the calm air of the experimental hut, the plants, including pots and saucers (hereafter to be known as samples), were individually placed on a balance and weighed. We then slowly supplied water to the soil surface of the pot plant to increase the water content to a pre-determined level which was considered nearly saturated (hereafter referred to as 'target weight' (see Section 3·2 for details). All the plants were then returned to their respective vegetation groups; however, the positions of individuals in the groups changed daily and were randomly determined. The three vegetation groups were exposed to the natural atmosphere for about 23 h, after which the 55 samples were re-weighed in the experimental hut after sunset. Thus, the measurements provide 23-h transpiration rates. The procedure was then repeated.

To minimize transpiration during the measurement period, the measurements were taken at night. To reduce measurement time, the unmeasured plants were not watered, and to reduce time for redistribution, each pot (measured and non-measured) was placed on its own small movable cart (6-cm high). The total time to move, weigh, and water all 55 samples was less than 60 min; thus, because all the activities occurred after sunset, the mass losses during the measurement period were most likely to be negligible. The lack of watering of unweighed plants may have affected plant transpiration rates; however, we did not observe withering foliage on these plants. Hence, we assume that the lack of watering of unweighed plants had a negligible effect on our results.

Measurements were not made on rainy days and we waited several days after a spell of rain before resuming measurements. To recreate the conditions of urban trees surrounded by dry pavement, all measurements were made on a dry concrete slab.

PROPERTIES OF THE SAMPLES

Size and weight

The average and standard deviation (SD) of plant height from the soil surface were 1·6 and 0·11 m respectively, based on measurements made on 10 October, the

middle of the measurement period. By examining photographs of some of the plants at the beginning and end of the experiments, we estimate that the growth did not exceed 10 cm, or about 5% of plant height. The pots contained an average of 1.66×10^{-2} m^3 of andisol. The pots and saucers were made of solid plastic, and therefore, did not absorb water. Each pot and saucer weighed 349 and 251 g, respectively. Following the experiments, the weights of five plants, cut off at the base of their trunks, were 720 ± 96 g (average $\pm$ SD). The minimum amount of daily transpiration measured per potted plant was about 150 g; therefore if 2% of the plant mass was lost by the wind blowing off foliage or branches, the resulting transpiration overestimate would be <10%. As we did not find broken branches or foliage from the plants on the concrete slab, we opted not to include wind-driven mass loss.

Saturated weights and target weights of the samples

To obtain transpiration rates without stress from dry soil, the initial weights of the samples were always set to a target weight that approximated the weight of a pot containing water-saturated soil. The target weights of the 55 samples were determined as follows. We slowly supplied water to the soil surfaces of the 55 samples using a watering can until water leaked out from the soakaways at the bottom of the pots. After stopping the runoff, we measured the weights of the potted plants. This weight included the weight of the plant, soil, water, pot, and saucer. If water was supplied too quickly, runoff would occur before the soil was well-saturated because of non-uniformities in soil water content. These non-uniformities resulted in variations in the measurements of the same pot, with the largest value closest to the saturated value. In addition, we measured the weight of the samples (without the plastic over the soil) immediately after runoff caused by natural precipitation, as the relatively small raindrops of natural precipitation falling uniformly on the soil surfaces were likely to be more effective at fully saturating the soil. We assumed that the maximum measured weight (including both water spray and precipitation) was the saturated value. For all 55 samples, the average $\pm$ SD weight of the plant plus saturated soil was 25.99 ± 0.99 kg. The average saturated water weight content of soil was 1.075 kg-water/kg-dry soil.

To eliminate the effect of the soil water deficit on transpiration, the initial soil water content should be as close as practical to saturation point without incurring runoff. Therefore, we defined the target weight of each plant to be 97% of its saturated value, equivalent to a soil water weight ratio of 1.060. This target weight was fixed for each plant throughout the measurements.

The process for increasing the water content of the samples to saturation point was completed by hand, using a watering can, but sometimes following watering, the initial weight could not be equal to the target weight. To reduce possible errors from such variation in initial water content, all data in which the initial weight of a sample exceeded the target weight by more than 300 g were rejected.

Individual variation in transpiration rate among the 55 samples

In addition to the main experiment, we conducted a reference experiment in which the transpiration rates of 55 pot plants that were arranged regularly at 3.6-m intervals on the same concrete slab were measured. Because the inter-plant distance was nearly twice the plant height, the meteorological conditions such as wind speed and incident solar radiation were assumed to be the same for each plant. Thus, the reference experiment showed how transpiration rates varied among the plants.

The reference experiment ran from 9 October to 16 October 2003, during which time we obtained 3 days of data, hereafter referenced as runs R1, R2, and R3. The average transpiration rate increased with the amount of daily solar radiation (Table I). In contrast, the standard deviation of the transpiration rate was greatest when solar radiation was at a minimum, indicating that individual transpiration rates varied greatly under cloudy conditions. Previous research has shown that transpiration characteristics are affected simultaneously by various meteorological conditions, such as solar radiation, air temperature and humidity, and wind speed (e.g. Jarvis, 1979). However, we cannot estimate the effects of air temperature and humidity because these quantities were approximately equal in all three runs.

Figure 3 is a histogram of the transpiration rate per plant for each run. Although the shapes of the curves vary, all are single-peaked. The peak becomes gentler in the order R3, R1, R2, as the daily level of solar radiation increased. The normalized transpiration rates of 70% of the samples ranged from 0.5 to 1.5 in all three runs, but the values for a few samples exceeded 2.0. To

Table I. Transpiration rates and meteorological conditions of the reference experiment

Run	R1	R2	R3
Date	October 10	October 11	October 20
Average transpiration rate of all samples (g day^{-1} pot^{-1})	200.3	173.3	239.9
Number of samples	54	54	52
Standard deviation of transpiration rate (g day^{-1} pot^{-1})	68.3	77.8	70.0
Daily solar radiation (MJ m^{-2} day^{-1})	11.793	7.646	13.365
Mean daily air temperature (°C)	13.7	15.4	14.6
Mean daily deficit of absolute humidity (g kg^{-1})[a]	3.153	3.078	4.085
Mean daily wind speed (m s^{-1})	0.97	0.581	0.97

[a] The difference between absolute humidity and saturated absolute humidity of air.

Table II. Leaf areas and transpiration rates of three selected plants

Plant	Average transpiration rate of three runs (g day^{-1})	Transpiration rate rank among all test subjects	Number of leaves	Leaf area (m^2 pot^{-1})	Crown volume[a] (m^3 pot^{-1})
#1	456·25	1st	2454	1·47	0·380
#2	227·25	23rd	1641	0·98	0·349
#3	149·5	50th	2015	0·99	0·264

[a] Crown volume was estimated from the measured diameter of the crown at every 10 cm along the height.
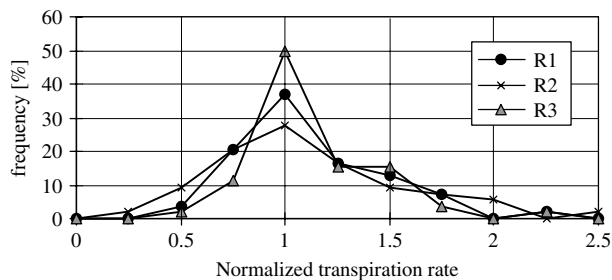

Figure 3. Histogram of transpiration rate normalized by the average of 55 potted plants

determine the reason for the variation in transpiration rates, we estimated both leaf area and the number of leaves for three plants by direct measurement of leaf sizes after the leaves were removed at the end of the experiment (Table II). The three samples consisted of a plant with an exceptionally high transpiration rate (#1), a plant with a medium rate of transpiration, and a plant with an exceptionally low rate. The leaf area of pot plant #1 was 1·3 times that of the others. The leaf areas of #2 and #3 were similar, despite their significantly different transpiration rates.

RESULTS AND DISCUSSION

The plants in the 'high' group were further classified into three sub-groups, hereafter referred to as 'centre,' 'off-centre,' and 'edge,' for analysis (Figure 4). In addition, the edge and off-centre sub-groups were further divided into 'north' and 'south.' The ratio of the average transpiration rate per pot plant of each group to that of the centre–high plants was then generated for all 28 runs, and the average was then calculated as the average ratio of

transpiration rate per pot hereafter referred to as (ARTP). The ARTP indicated the ratio of transpiration rate per pot plant from each group to that from a vegetation canopy more enclosed by the surrounding plants (Table III). We evaluated the statistical significance of the differences in ARTP caused by vegetation density and position using a one-way analysis of variance and confirmed that the result was statistically significant at 0·1% level. The projected area of the 'high' plant crown was smaller than that of 'medium' and 'low' because the 'high' plant crowns overlapped each other. Thus, we were also able to calculate the average ratio of transpiration rate per unit projected area (ARTA) from above.

Although the transpiration rates of the 55 samples varied (Figure 3), the effect caused by the identity of the samples on ARTP can be ignored because each of the 55 samples had a different position in the vegetation canopy on each run.

ARTP increased with decreasing vegetation density (Figure 5); in other words, transpiration per unit biomass increased with decreasing horizontal biomass density. In particular, the ARTP of an isolated 'low' was about 59% higher than that of a centrally located 'high.'

ARTA for 'low' and 'medium' was 2·7 and 2·37 times as high as that for 'centre–high.' Although ARTA should be dependent on crown shape, the evapotranspiration rate per unit of green area from real irrigated small vegetation in urban areas may be more than 2·7 times that of a vegetation canopy with sufficient fetch, and it should be considered that this result does not include evaporation from the ground surface and that the reference value should be affected by micro-scale advection (the distance of the 'centre–high' from the edge of the vegetation canopy was only about 3 m). This implies that the current method for estimating spatial averaged heat flux in urban
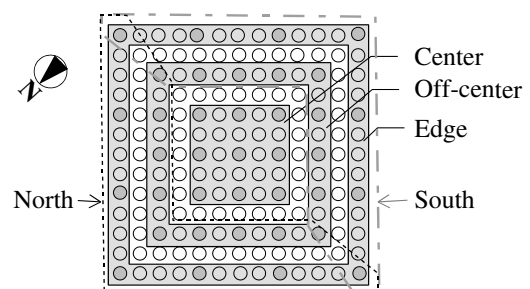

Figure 4. Classification of plants in the 'high' group

Table III. Average ratio of transpiration rate to that of the centre in the high-density group

| Vegetation group	Low	Medium	High				
			Centre	Off-centre South	Off-centre North	Edge South	Edge North
Plan area per pot (m^2 pot^{-1})	36·00	1·00	0·25	—	—	—	—
Projected area of vegetation from above per pot (m^2 pot^{-1})	0·424	0·424	0·250	—	—	—	—
ARTP (normalized transpiration per pot)	1·587	1·404	1	1·105	1·057	1·352	1·264
Standard deviation of ARTP	0·208	0·187	—	0·161	0·128	0·186	0·149
ARTA (normalized transpiration per unit projected area)	2·692	2·381	1	—	—	—	—
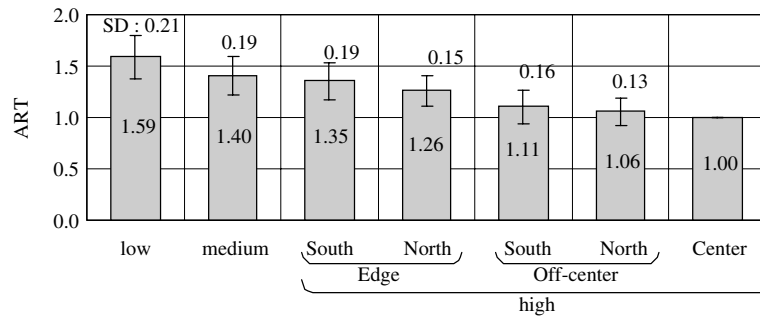
Figure 5. Average ratio of transpiration rate (ART) to that of the center in the crowded group

areas based on aerial photograph-derived GIS maps tends to underestimate the latent heat flux from vegetation. To improve estimates, an extra coefficient that describes the increase in evapotranspiration rate caused by the small size or low density of vegetation may be effective for current models of surface water availability, such as the Bowen ratio model or the surface resistance concept.

The distance from the edge of a vegetation group also had a significant effect on transpiration. The ARTP of 'edge–high' was about 1·3 times that of 'centre–high.' The transpiration rate of the south edge was greater than that of the north edge, presumably because the sunshine was from a southern direction. Similarly, the transpiration rate of 'south–offcentre' was also greater than that of 'north–off-centre.'

CONCLUSIONS

Field experiments were conducted to better understand transpiration from isolated and sparse urban plants. Three types of vegetation canopy were created by positioning 203 camellia pot plants at various horizontal densities of biomass, i.e. 'low,' 'medium,' and 'high,' on a large concrete slab. Daily transpiration rate was measured for 28 days in 55 of the 203 potted plants. The average transpiration rate per plant in the 'low' group was 1·6 times that of plants located in the centre of the 'high' group. This result indicates that the transpiration rate per unit of land-covering area of scattered small vegetation is about 1·6 times that of large vegetation. Also, the transpiration rate per unit of projected area of plants from above for isolated 'low' plants was 2·7 times that of the centre 'high' plants. The transpiration rate of plants in the 'high' group decreased with increasing distance from the canopy edge, and the transpiration rate of the centre plants was about 75% that of the edge plants.

Although we analyzed vegetation transpiration rates under the idealized condition of saturated soil, our results indicate the need for improved modelling of latent heat flux from small urban vegetation. Given that the evapotranspiration rate increased about 2–3 times with the small size or low density of vegetation, the parameters of surface water availability used in present procedures such as the Bowen ratio model or the surface resistance concept should be modified.

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