Fire in the Desert: Initial Gullying Associated with the Cave Creek Complex Fire, Sonoran Desert, Arizona

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ABSTRACT

The June 2005 Cave Creek Complex Fire is one of the largest historic wildfires to affect Arizona's Sonoran Desert. Post-fire gullying was measured using 1:1900-scale aerial photographs. Detailed comparisons of pre-fire and post-fire imagery, selected using a stratified randomly sampling approach, reveal far more gullies formed in contact with dirt roads than adjacent wildlands, approximately four times more frequently. Post-fire gullies that did not form in contact with roads covered approximately 0.18 percent of the analyzed imagery after the 2005 Arizona monsoon and approximately 0.24 percent after the 2006 Arizona monsoon. Extrapolating this percentage to the total area burned, we estimate gullying to have impacted 456 acres after the 2005 Arizona monsoon and 592 acres after the 2006 Arizona monsoon. A corresponding field-based investigation reveals both deepening and widening of gullying over time.

Introduction

Wildfires dramatically increase soil erosion rates, increase gully formation, and alter the behavior of streams (Moody and Kinner 2006; Shakesby and Doerr 2006; Germanoski and Miller 1995; Doerr et al. 2000; Blake et al. 2005). This is true even in arid regions (Germanoski and Miller 1995; Shakesby and Doerr 2006). Despite a substantial history of over 200 wildfire fires in central Arizona over the past half-century (Arrowsmith 2004), only a handful of studies have analyzed erosional impact of fires in the Sonoran Desert (Desilets et al. 2007; Pearthree 2004; O'Dea and Guertin 2003; Misner et al. 2002; Arrowsmith 2004). Understanding the erosional impact of fires will become increasingly important as populations continue to expand in the arid southwestern United States.

Our paper presents initial results of monitoring gullying associated with a major fire in the Sonoran Desert, the 2005 Cave Creek Complex fire (Figure 1).

Figure 1. The Cave Creek Complex burned the northern edges of metropolitan Phoenix (Kekesi 2005). A small drainage basin informally termed the "bombpit basin," at an area of ~12,000 m^2, was the subject of field-monitoring erosional processes. The basin is centered at approximately N33.8567 W111.6677. Eleven randomly selected locations were established and measured after the fire (July 2005) and then resurveyed three times after the Arizona monsoons of 2005, 2006, and 2007.

The Cave Creek Complex Fire, started by lightning on June 21, 2005, resulted from the combination of the Bronco and Humboldt fires and burned 248,310 acres (USFS 2005). The fire was so spectacular that it was seen from space (Kekesi 2005), and thermal satellite imagery of the fire was used by the National Weather Service to illustrate how fire impacts the surrounding atmosphere (Flagstaff NWS 2005). The wildfire burned over a geological mix of intrusive granitic, extrusive basalt, and metamorphic rock types that host colluvial, alluvial, and pediment landforms.

Dr. Cecil Schwalbe of the U.S. Geological Survey explained that vegetation change played a substantial role in providing fuel including red brome, cheat grass, and buffelgrass. Thirty years ago, if a patch of desert caught fire, areas would burn here and there in a mosaic-type pattern, said Schwalbe, adding that today the dried grasses continuously carry the fire, causing it to spread out of control (Balazs 2005). These invasive grasses generated mats of dried remains that turned normally small, mosaic-producing fires into much larger burn areas (Lambrakis 2006; Wentz et al. 2001). In addition to burning invading grasses, the fire fed on drought-impacted desert scrub of creosote bush (*Larrea tridentata*), jojoba (*Simmondsia chinensis*), crucifixion-thorn (*Canotia holacantha*), bur sage (*Ambrosia dumosa*), brittlebush (*Encelia farinosa*), and ocotillo (*Fouquieria sp*). Small trees, including species of palo verde (*Cercidium*), some catclaw (*Acacia*), and mesquite (*Prosopis*), burned in the swales and washes.

The initial post-fire gullying studied here resulted from a very limited number of precipitation events (Figure 2).

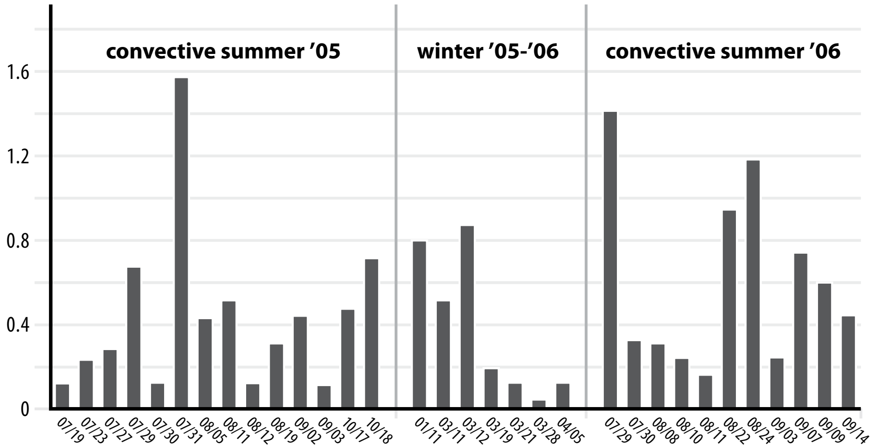


Figure 2. Precipitation (in inches) in the study area, as measured by the "Cave Creek Fire" automated rain gauge (Maricopa County Flood Control District 2007). This graph portrays all rain events greater than 0.10 inches of precipitation per day.

Between the June 2005 fire and the November 2006 observations reported in this paper, there were only two precipitation events greater than an inch per day and only 10 days with precipitation greater than a half-inch. All but two of these larger rain events occurred during the summer "Arizona monsoon" months where convective rainfall events could have occurred in short bursts of only tens of minutes. It is also important to note that all of the erosion discussed here took place during drought years, in which annual rainfall amounts were far below the long-term historic average.

Methods

We employed a twofold strategy to understand the gullying effects of post-fire precipitation events. Comparative aerial photography yielded a two-dimensional overview of the spatial extent of gullying. Ground-based surveys of one small basin then provided insight into the geomorphic processes.

Analysis of Aerial Photography

We obtained pre-fire and post-fire images at a scale of 1:1900 from the Maricopa County Tax Assessor. Thus, the aerial photography part of the study is limited to the Maricopa County portion of the burned area. Individual frames of 224 m by 224 m with 24 cm/pixel resolution permitted identification of gullies with enough detail to measure gully area. A stratified random sampling scheme selected 40 such frames adjacent to Forest Road 24, with 20 west-side frames and 20 east-side frames. We used pre-fire imagery to avoid measuring pre-existing gullies, December 2005 imagery to measure gullying after 2005 summer precipitation, and November 2006 imagery to measure gullying after another year of precipitation.

The process of measuring gully area used a combination of Adobe Photoshop, Adobe Illustrator, and a CADTools add-on for Adobe Illustrator to measure the traced polygons. The area of an entire contiguous gully with all tributary arms was treated as a single gully for measurement purposes. We also kept track of whether a gully developed in contact with roads, to better understand the role of dirt roads in erosional expansion. Gully area was compiled for 40 frames, in which a total of 121 identifiable gully systems formed in contact with no road by December 2005.

The largest complication in the identification of post-fire gullying involved shadows made by burned and standing trees. The narrow nature of the shadow could be interpreted as a small gully. Our solution to this problem required a careful examination of imagery at different times. For example, if the pre-fire image showed a tree-produced shadow, then the dark lineament in the post-fire imagery was interpreted as a snag-shadow and not a gully. Confidence in this decision sometimes came when the tree had fallen down by November of 2006, removing the shadow entirely.

Simple descriptive statistics were used to analyze gully changes over time between pre-fire conditions, after the 2005 monsoon precipitation, and after the 2006 monsoon precipitation. In addition, to compare the effect of roads on gullying area, we randomly sampled the first 30 "non-contact" gullies and the first 30 "road-contact" gullies, and then ran a log transform of the area of road-contact and non-road contact gullies to obtain a normal distribution for a 2-tail Student's t-test.

Field Monitoring

In order to obtain a field-based understanding of post-fire erosion processes, we selected a small, oval-shaped drainage basin of approximately 12,000 m^2 for field study. Immediately after the fire on July 15, 2005, prior to the onset of the Summer 2005 summer convective precipitation, we established a variety of survey sites. We measured: pre-existing gullies (e.g., Figure 3); cross-sections along pre-existing swales that we anticipated might develop gullies (e.g., Figures 4 and 5); the scale rainsplash erosion on slope convexities (e.g., Figure 6); and depressions made by the burning of desert-scrub root systems that we termed "bomb pits" (e.g., Figure 7) that served to collect sediment.

Figure 3. Example of a pre-existing gully surveyed July 15, 2005, immediately after the fire and before the start of the summer Arizona monsoon (left image), and again in October of 2005, after the end of the Arizona monsoon (right image).

The pre-monsoon volume of each bomb pit was calculated using a pegboard and a measurement rod, and then the changes were remeasured after the monsoon in October of 2005. Sediment traps in nearby unburned sites served as "controls" to compare erosion rates for the same time period. We also surveyed a stream cross-section immediately downstream of the small basin to understand channel changes in response to sediment transport. Also, prior to the summer of 2006 precipitation season, 50 green-painted cobbles were placed in one gully, 50 green-painted cobbles were placed in another gully, and three radiotransmitters were placed in each of these gullies in order to determine the distance of bedload particle transport.

Results and Discussion

Analysis of Aerial Photography

Analyzing only those gullies that did not develop in contact with a road, 121 gully systems formed between the June 2005 fire and January of 2006. These gullies covered a total of 3,680 m^2, with an average gully area of 30 m^2. If the 0.18 percent total area randomly selected from 40 frames randomly

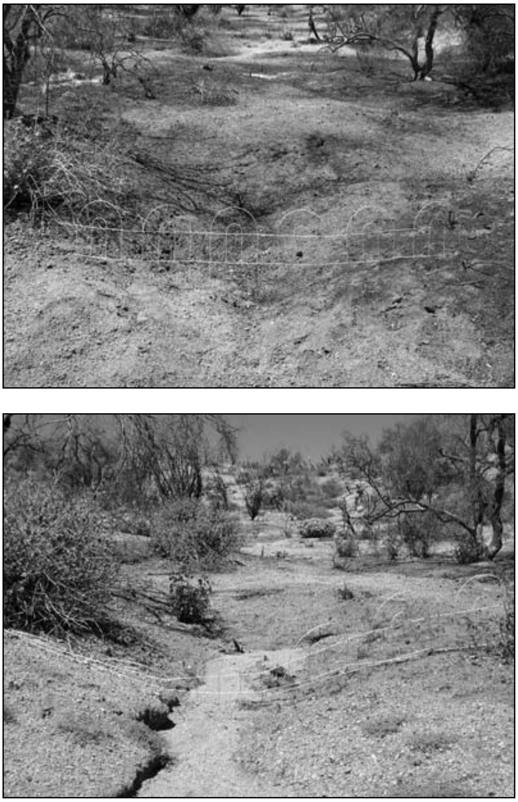


Figure 4. Example of a swale surveyed and identified with a gated system to assist in relocation. The top photo was taken July 2005, prior to the monsoon, and the bottom photo is from October 2005, after the end of the Arizona monsoon, showing the development of a small gully in the swale.

covered by gullies is extrapolated to the entire burn area, an estimate of approximately 456 acres of the burned area may have been gullied after the first season of summer convective precipitation.

The area was reflown in November of 2006, and those 121 gully systems were remeasured (Figure 8).

Although a few gullies shrank in apparent area, the vast majority enlarged, with over 10 gully systems doubling in size. An additional 23 gullies were identified in the November 2006 imagery not seen in the January 2006 frames. These 144 gully systems had a total area of 4,777 m^2, with an average gully area of 33 m^2, amounting to coverage of 0.24 percent of the area of the 40 randomly selected frames. When extrapolated to the entire burn area, approximately 592 acres were gullied in the Cave Creek Complex burn by November of 2006.

These findings, in which wildfires promote erosion through gullying, are consistent with results on wildfire-increased erosion in other physical geography settings (Wilson et al. 2001; Shakesby and Doerr 2006; Benda et al. 2003; Pearthree 2004; Keller et al. 1997). The biggest difference between our findings and the other studies lay in the percent of slope area occupied by gullying. Most other studies occur in forested settings, where the gully area is less than in this desert setting (i.e., non-road contact gully density is about double that of forested areas). The general qualitative appearance of the

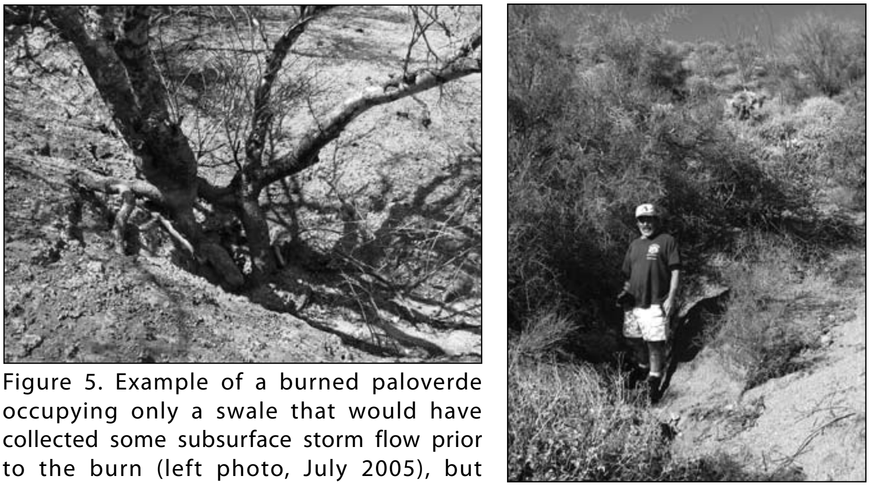


Figure 5. Example of a burned paloverde occupying only a swale that would have collected some subsurface storm flow prior to the burn (left photo, July 2005), but that swale was the site of rill development during the 2005 summer convective season. Over the next two years (right photo, December 2007), the rill developed into a gully with depths reaching 3 m and a length of over 200 m. The location of the root collar served as a basis for measuring rill and gully.

Figure 6. Examples of a two-dimensional understanding of rainsplash transport was measured by placement of a gate system on randomly selected inter-rill slope convexities. Our assumption was that such a slope position would be the location of rainsplash detachment (Parsons et al. 1994).

fire-related desert gullying drainage pattern, however, appears to be similar to wildfire gullies in other settings (Moody and Kinner 2006).

Approximately four times as many post-fire gullies developed in contact with roads than in more natural settings, as analyzed from adjacent imagery. For every post-fire gully in a more "natural" setting, approximately four gullies developed in contact with roads or other human infrastructures. The road-contact gullies were, however, two-thirds smaller in area, on average, than non-road contact, with a statistically significant difference at the

Figure 7. Depressions created by burning of desert scrub roots provided opportunities to measure sediment transport through surveying the dimensions of the depressions. The arrow indicates true north, and the meter-fence provides scale. The top photo pre-dates the summer monsoon (July 15, 2005, just after the fire); the bottom photo represents the same location after the end of the first post-fire Arizona monsoon (October 2005).

$p < 0.01$ level in a 2-tail Student's t-test. The reason for more aerially extensive gullies in settings not in contact with dirt roads has to do with a confounding factor inherent in the methodology related to slope length, an important factor in fire-developed drainage networks (Moody and Kinner 2006). Because dirt roads bisect slopes, gullies formed downhill of the road had shorter slope lengths for development, as did those gullies formed between roads and hillcrests. In other words, those gullies that developed away from roads could grow longer.

Field Monitoring

Our field study of a small basin (as seen in Figure 1) reflects the larger pattern seen in the aerial photography: gullying growth over time. However, our strategy of surveying different parts of the geomorphic system in the drainage basin yielded insights into processes of post-fire erosion in the Sonora Desert.

The miniature fences we installed to understand the scale of rainsplash erosion (see Figure 6) did not yield any dramatic results. Sand-sized sediment did erode from placement on microtopographic convexities where slope angles were greater than about 12˚. However, the maximum amount of slope erosion was limited to depths of less than one centimeter after two

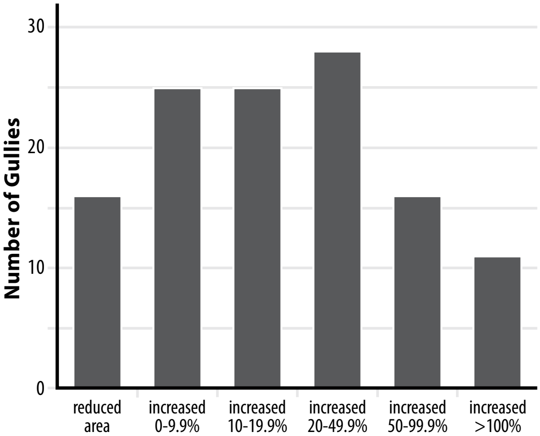


Figure 8. Percent change to the sizes of 121 gully systems between January 2006 and November 2006.

summer convective precipitation seasons.

A different picture emerged from analyses of depressions created by the burning of desert scrub species. For 13 "bomb-pits," or depressions made by the burning of root systems (e.g., Figure 7) that had tiny upslope drainages of only a few dozen square feet, the erosional story reveals tremendous place-to-place variability. Each of the 13 monitored depressions completely filled up and overflowed after just the 2005 summer convective precipitation season. Thus, the pre-monsoon volume of each depression could only provide a minimum estimate of sediment eroded from the small drainages upslope, as well as sediment eroded from the rims of the bomb pits. After subtraction of the rim erosion, the sediment filling in each depression was mathematically "redistributed" over the upslope area to calculate a minimum rate of erosion.

The average historic erosion rate for central Arizona is about 0.13 acre-feet per m^2 per year (Henze 2000). The unburned control sediment collection sites and three of the burned sites were within a factor of two of this long-term average. However, six burned areas experienced rates of erosion over 10 times greater. Four slope areas had erosion rates more 30 times the long-term historic average. Thus, the fire zone displays tremendous site-to-site variability in erosion. This is seen on the plot scale of a few square centimeters (Figure 6) and square meters (Figure 7), and along gully systems (Figure 5).

The few gullies that existed in the small drainage prior to the fire all grew in depth (e.g., Figure 9).

These pre-existing gullies did change in their dimensions, but most did not change dramatically. Rather, they appeared to serve as important conduits for sediment transfer. For example, after the second summer precipitation season in October 2006, many of these initial gullies developed an extensive updrainage network of rills (e.g., Figure 10). The initial gully seg-

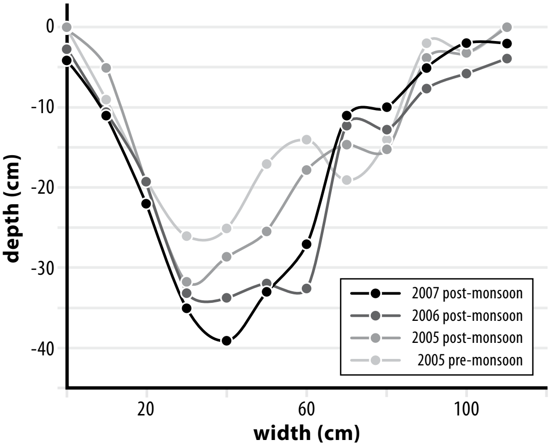


Figure 9. Example of the slight deepening of pre-existing gullies.

ment then simply routed the eroded sediment.

In other cases, a new gully that developed during the 2005 precipitation season (e.g., Figure 4) then developed an extensive gully system upstream the following year. A few intrabasin alluvial fans, with areal extents of a few tens of square meters each, deposited downstream of the gully segments that formed in the summer of 2005. Again, the location of previous-year gullying was a conduit for sediment excavated through headward extension.

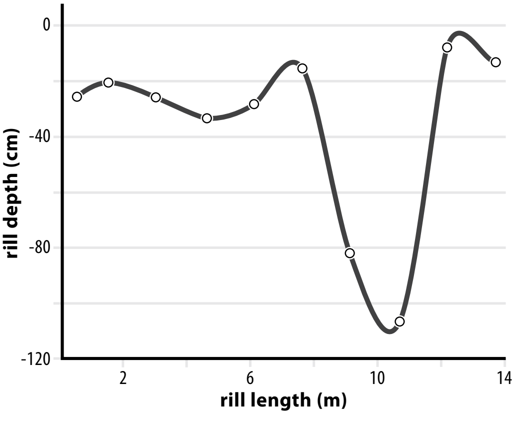
Observations of the ephemeral wash fed by this and other small basins suggests that waves of sediment seem to move through larger washes. Some of this aggradation was recorded in a stream cross-section revealing up to a meter of aggradation after the summer 2005 monsoon (Figure 11).

However, just a few tens of meters downstream of this cross-section, much of the wash had degraded a half-meter from the pre-fire soil surface, while a few tens of meters upstream of the cross section, up to two meters of aggradation occurred on top of a pre-fire soil surface. As a result, the ephemeral washes fed by small basins appear to be extremely active corridors for transport of sediment waves. During one ground survey, a small flash flooding event was witnessed in this area, displaying both degradation upstream of the stopping point and aggradation where flow came to a stop. These anecdotal observations of the dynamic nature of sediment transport in washes were supported by the complete loss (inability to relocate) of painted cobbles and cobbles hosting radiotransmitters, despite walking the entire length of the wash to its terminus at Bartlett Lake, a local reservoir.

Conclusion

This study presents the initial results of an ongoing monitoring of geomorphic changes associated with the Cave Creek Complex Fire in central Arizona. Our study generated a mix of empirical insight about the aerial

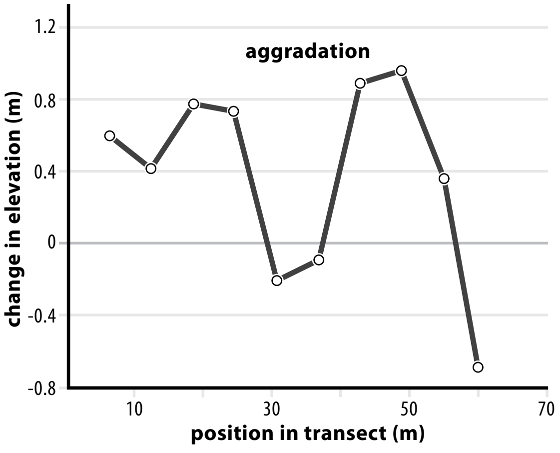
Figure 10 (photo and graph). Example of rill network development upstream of a pre-fire gully. The photo shows the upper end of a rill system formed between the end of the first 2005 monsoon and the second 2006 monsoon (photo from October 2006). The graph shows this rill system: almost 14 meters long above the enlarged gully, with typical depths under 40 cm and occasional, deep knickpoints exceeding 80 cm in height.



extent of gullying and anecdotal field observations about the processes of gullying in one small basin of the impacted area. The aerial extent of gullying after a very limited 2005 Arizona monsoon generated new gullies over approximately 0.18 percent of the fire, based on photogrammetric analyses of aerial photographs selected by a stratified random sampling scheme. After a drought year of limited rainfall, the number and aerial extent of gullies measured through aerial photographs grew to approximately 0.24 percent of the burn.

Our field study of one basin suggests several mechanisms leading to the initial phase of gullying and its subsequent expansion. Some initial gullying developed from the overflow of depressions made when the roots of desert scrub plants burned. Other gullies developed in swales after the first Arizona monsoon started. Still others, due to the concentration of overland flow, started as rills extending from ridgecrests. Then, these initial gullies extended upslope—sometimes as a dendritic complex of centimeter-scale rills and other times as a linear gully system with depths at the meter scale. Anecdotal observations of the wash downstream from the small basin suggest that sediment had been delivered in pulses, where a few meters of

Figure 11 (graph and photo). The graph displays the approximate elevation change in a wash cross-section. This wash is fed by several small basins, including the one studied here. The change occurred during the 2005 summer monsoon season, between July 15, 2005, and October 2005. The photo illustrates the aggradational surface between 10 and 25 m along the transect.



aggradation might temporarily stop, burying one part of the wash but leaving an adjacent wash to degrade.

Much research on the processes of fire-associated gullying (Moody and Kinner 2006; Pearthree 2004) tends to be focused on regions wetter than the Sonora Desert. The general lack of wildfire-related gullying studies in dry, hot desert settings elevates the importance of the Cave Creek area. The nonnative grasses that fueled the fire (Lambrakis 2006; Balazs 2005; Brookes and Pyke 2001; Geiger et al. 2003) will undoubtedly fuel future fires on the margins of metro Phoenix, metro Tucson, metro Las Vegas, and other expanding desert cities. As residential communities continue to expand from the urban fringe into desert regions in the southwestern U.S., studies on the Cave Creek Complex fire area have potential to be useful in understanding future fire impact.

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