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VEGETATION MANAGEMENT TO STIMULATE DENITRIFICATION INCREASES MOSQUITO ABUNDANCE IN MULTIPURPOSE CONSTRUCTED TREATMENT WETLANDS

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ABSTRACT. Inundation of dried emergent vegetation that has been knocked down using heavy equipment is a vegetation management strategy that provides an inexpensive source of supplemental organic carbon to stimulate denitrification, a process important for nitrate removal in constructed treatment wetlands. The abundance of larval mosquitoes (*Culex* sp. and *Culiseta* sp.) in multipurpose constructed wetlands that had undergone autumnal vegetation management intended primarily to enhance denitrifying bacteria was significantly higher than in wetlands that remained in continuous operation. Mosquito abundance in wetlands that had undergone vegetation management during autumn was much lower than that observed during spring in a previous study; nevertheless, vegetation management practices that inundate dried, felled macrophytes are contraindicated for mosquito control.

KEY WORDS Constructed wetlands, vegetation management, *Culex*, denitrification, nitrogen removal

INTRODUCTION

Constructed wetlands can offer significant benefits to human populations in both developed and developing countries (Kadlec and Knight 1996, Kavisi 2001). Benefits include water-quality improvement, water reclamation, habitat for species conservation, flood control, and recreational and educational activities; however, management practices that attempt simultaneously to fulfill the diverse goals for multipurpose constructed treatment wetlands can create problems for agencies charged with protecting public health and reducing nuisance biting by mosquitoes. Routine mosquito abatement activities such as vegetation management may be restricted to particular periods of the year in order to fulfill the needs of endangered species, recreational activities, and water-quality improvement. For example, vegetation management in some multipurpose constructed wetlands in southern California is carried out in the late summer and autumn to avoid disturbance and to maintain critical habitat of bird species nesting in wetlands, to prepare open water zones for loafing by waterfowl, and to enhance visibility of birds during hunting. Restrictions imposed on vector control activities may hamper mosquito abatement during the spring when mosquito populations are increasing and during the early summer when host-seeking populations are at their annual maximum abundance (Walton et al. 1998).

Inundation of dried emergent macrophyte biomass that has been knocked down by heavy equipment (i.e., bulldozers or backhoes) is a vegetation management practice utilized by some wetlands operators to enhance the bacterial populations responsible for water-quality improvement. Supplemental organic carbon is often required to enhance denitrification in constructed wetlands that remove nitrate nitrogen from water containing low levels of organic carbon (Narkis et al. 1979) such as secondary-treated wastewaters, agricultural drainage waters, or contaminated groundwater (Gersberg et al. 1984). Methanol has been used to supplement organic carbon in treatment wetlands; mulched plant biomass is a low-cost alternative to methanol (Gersberg et al. 1984). Ideally, mulched material should be kept completely submerged to minimize conversion of plant biomass carbon to carbon dioxide and to maximize the conversion of nitrate nitrogen to gaseous forms of nitrogen via denitrification (Gersberg et al. 1984).

When emergent vegetation is dried, knocked down, and then inundated without mulching, dried plant biomass often floats on the water surface or water depth of constructed wetlands may be too shallow to permit complete inundation of the large amount of plant biomass produced by constructed wetlands treating municipal wastewater. Inundated decaying macrophytes provide harborage for immature mosquitoes (Berkelhamer and Bradley 1989, Wright et al. 1995, Keiper et al. 2003) and fermentation of organic matter releases volatile chemicals attractive to gravid mosquitoes (Gerhardt 1959, Beehler and Mulla 1993). The goal of this study was to compare mosquito abundance in wetlands that had undergone vegetation management during autumn to stimulate denitrifying bacteria versus wetlands that remained in continuous operation.

MATERIALS AND METHODS

The 186-ha Prado Constructed Wetlands are located 7 km northwest of Corona (Riverside County), CA (33.9°N, 117.9°W), and consist of 47 marshes and ponds (Fig. 1). The wetlands receive approximately one-half of the flow (1.7–2.3 m^3/sec) of the Santa Ana River and are operated by the Orange County Water District for multiple uses. A

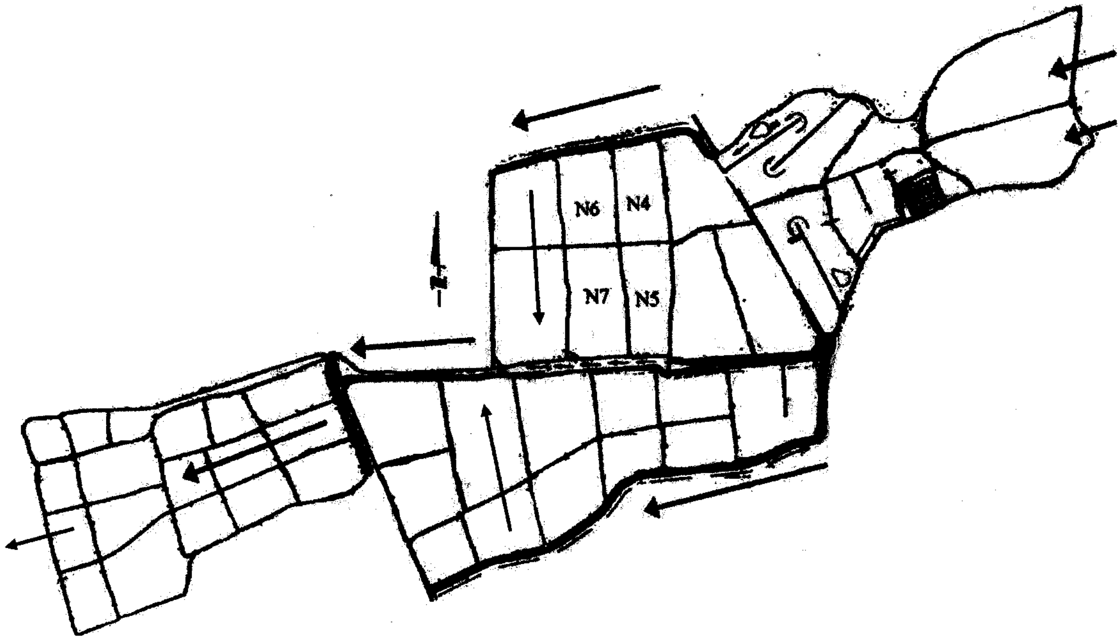

Fig. 1. Location of marshes that had either undergone vegetation management (N4 and N5) or remained in continuous operation (N6 and N7) at the Prado Wetland, Norco, CA, during autumn 2001. Arrows indicate water flow.

primary function of the wetlands is to remove nitrate nitrogen from the river water before groundwater recharge (Mills et al. 1998). In addition to water-quality improvement, the wetlands are managed to provide habitat for endangered riparian species (e.g., least Bell's vireo [*Vireo bellii pusillus* Coues]), for recreational duck hunting and birding, and for flood control.

The abundance of mosquitoes in 4 large (3- to 5-ha) marshes that either had undergone vegetation management to stimulate denitrification or were maintained in continuous operation without vegetation management were compared for 9 wk during autumn 2001. Two wetlands (N4 and N5; Fig. 1) were drained, allowed to dry for several weeks, and the vegetation (primarily cattail [*Typha* sp.]) was knocked down with a backhoe and bulldozer. Inundation of knocked-down vegetation began on October 1. Before vegetation management, emergent vegetation covered approximately 90% of the water surface. The vegetation had been growing for nearly 4 years after being reduced by flooding during winter 1997–98 (Keiper et al. 1999).

Two marshes (N6 and N7; Fig. 1) that were not dried served as controls. Vegetation management in the control wetlands was carried out in April 2000; the vegetation had been growing in control wetlands for approximately 17 months before the start of this study.

Twelve composite samples were taken weekly from the margin of each wetland from October 5 until November 27. Each composite sample consisted of five 350-ml dips that were combined in a concentrator cup (148-μm-mesh screen) and preserved at a final concentration of ~50% ethanol. All mosquito larvae and pupae were identified to genera. Third- and 4th-stage larvae were keyed to species by using the keys of Meyer and Durso (1998).

Mosquito abundance was compared among the 4 wetlands by using a nonparametric repeated measures analysis of variance on ranks (SigmaStat version 2.03; Fox et al. 1995). Pairwise comparisons among the wetlands were made by using Tukey's test.

Daily maximum, minimum, and mean air temperatures and precipitation were recorded by 2 computerized weather stations at Pomona (station 78) and the University of California (UC)–Riverside (station 44; California Irrigation Management Information System, California Department of Water Resources, Sacramento, CA). Hourly means for each weather variable were calculated by using data collected at 1-min intervals. The Pomona and UC–Riverside weather stations were approximately 23 km northwest and 27 km northeast of the Prado Wetlands, respectively. A daily mean of each weather variable was calculated by using the data from the 2 stations.

RESULTS

The abundances of 1st and 2nd instars (χ^2 = 24.07, df 3, $P < 0.001$) and 3rd and 4th instars (χ^2 = 25.21, df 3, $P < 0.001$) differed significantly among the wetlands. The abundance of larval mos-

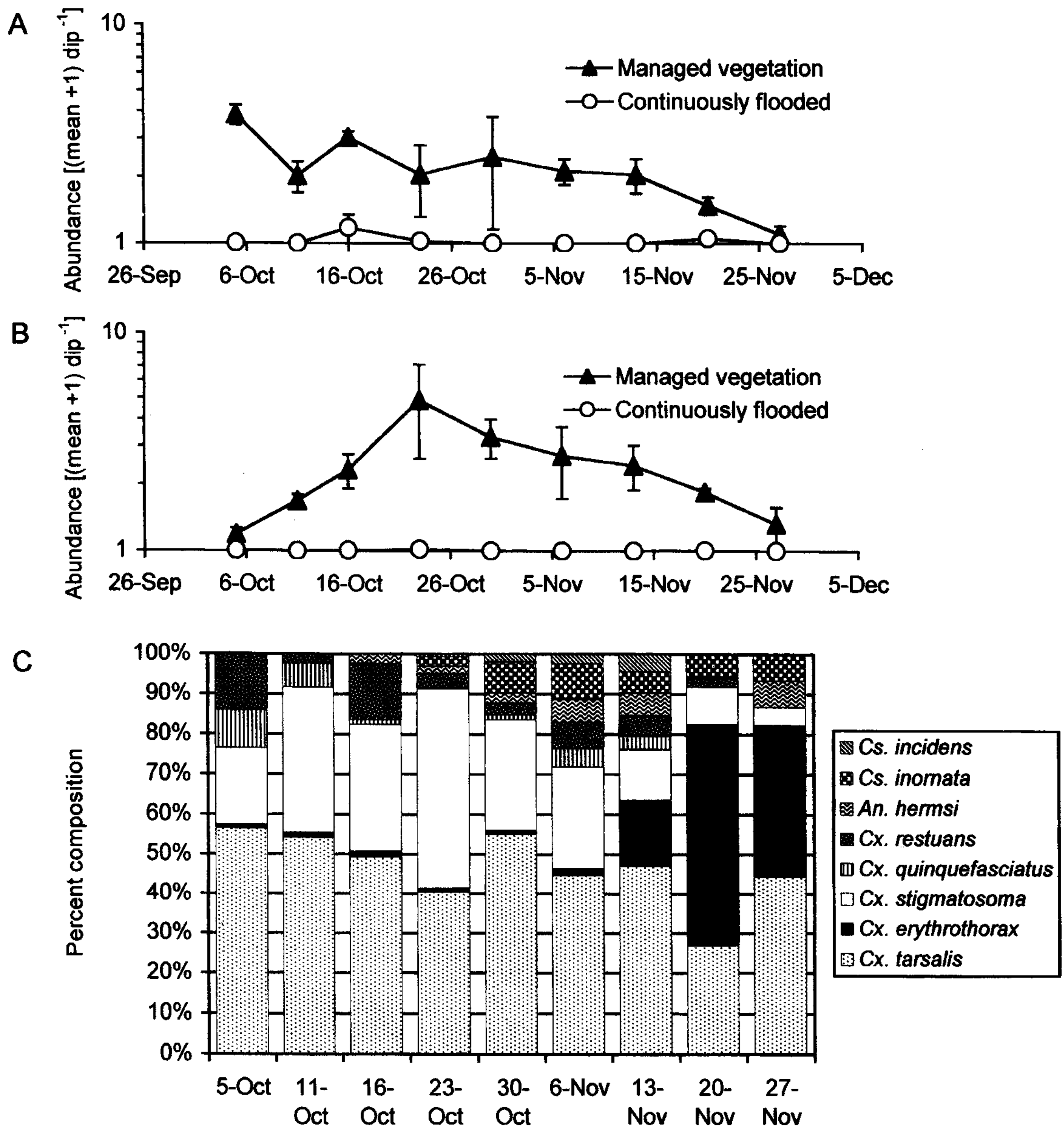

Fig. 2. (A, B) Abundance (mean ± SE) of larval *Culex* (A, 1st and 2nd instars; B, 3rd and 4th instars) in marshes that had undergone vegetation management and remained in continuous operation, and (C) species composition of mosquito larvae in managed marshes at the Prado Constructed Wetlands during autumn 2001.

quitoes in wetlands that had undergone vegetation management was significantly greater than in wetlands that were flooded continuously (Tukey's test, $P < 0.05$). Abundance of immature mosquitoes did not differ significantly between the 2 wetlands within each of the management regimes (Tukey's test, $P > 0.05$). The mean abundance of early instars of *Culex* sp. in wetlands that had undergone vegetation management was between 1 and 3 larvae/dip from October 5 until November 15 and thereafter declined to levels similar to that observed in the control wetlands on November 27 (Fig. 2A). Mosquito larvae (total no. *Culex* sp. and *Anopheles hermsi* Barr and Guptavanij collected = 77) and pupae (total no. collected = 4) were rare in the control wetlands.

Third- and 4th-stage larvae of *Culex* sp. in the managed wetlands also were more abundant than in the wetlands where water levels were maintained throughout the study (Fig. 2B). The number of 3rd and 4th instars in dipper samples from managed wetlands increased to 3 larvae/dip through week 4

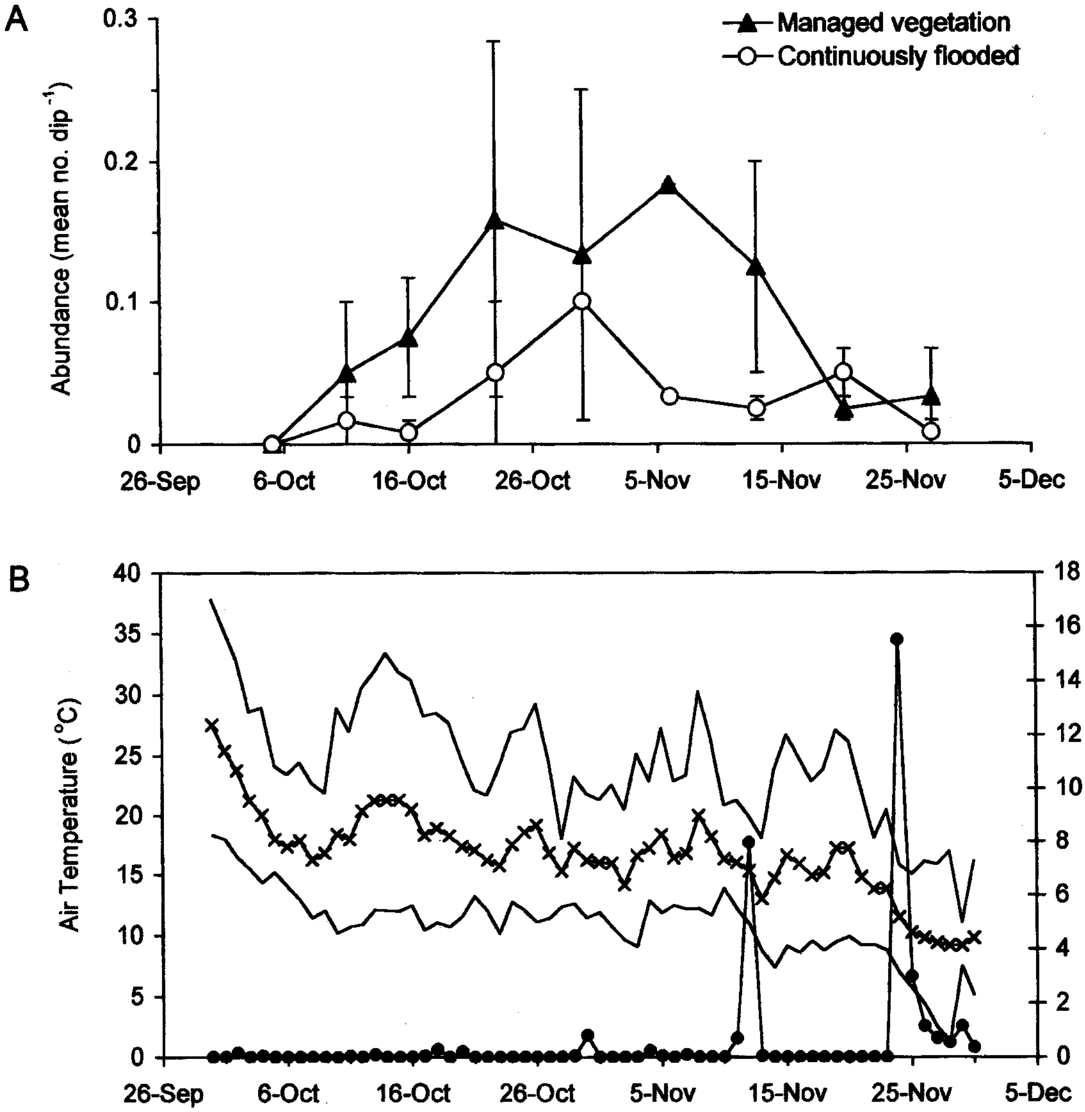

Fig. 3. (A) Abundance (mean ± SE) of larval *Anopheles hermsi* in 2 vegetation management regimes, and (B) weather (air temperature and precipitation) at the Prado Constructed Wetlands during autumn 2001. The daily mean of each weather variable was calculated by using data collected by continuous recording weather stations at Pomona and Riverside, CA.

and then declined (0.014/day). The abundance of 3rd and 4th instars in managed wetlands was greater than that in the control wetlands for 7 wk.

The assemblage of mosquito species in the managed wetlands consisted of 9 species (Fig. 2C), whereas only 4 species were collected from the control wetlands. *Culex tarsalis* Coquillett was the most common species (mean across sampling dates ± SE: 46 ± 3%) collected from managed wetlands. The relative abundance of *Culex stigmatosoma* Dyar (24 ± 5%), *Cx. quinquefasciatus* Say (3 ± 3%), and *Cx. restuans* Theobald (3 ± 2%) declined across the study, whereas the relative abundance of *Cx. erythrothorax* Dyar (13 ± 6%) and *An. hermsi* (3 ± 1%) increased toward the end of the study (Fig. 2C). Larvae of *Culex thriambus* Dyar were collected on only 1 date (23 October in pond N5; not shown in Fig. 2C). *Culiseta inornata* (Williston) was the more common of the 2 species in this genus collected from the managed wetlands.

Larval *An. hermsi* in managed wetlands were 2 times or more abundant than in the control wetlands on most dates between mid-October and mid-November (Fig. 3A), but abundance did not differ significantly (χ^2 = 3.69, df 3, P > 0.29) among the wetlands during the study. *Anopheles hermsi* was the most commonly collected species (64 ± 13%) in the control wetlands. *Culex quinquefasciatus, Cx. tarsalis,* and *Cx. erythrothorax* were rarely collected from marshes that were continuously inundated.

The abundance of mosquito larvae in the managed wetlands declined after November 13. The declines in numbers of 1st and 2nd instars during the late season were associated with minimum air temperatures falling to <10°C and rainfall (Fig. 3B), suggesting that oviposition activity by mosquitoes declined. After November 23, air temperature declined conspicuously.

DISCUSSION

Vegetation management practices intended to supplement denitrification by inundating dried, felled emergent vegetation are contraindicated for the reduction of mosquito production from constructed treatment wetlands. Keiper et al. (2003) found that vegetation management practices intended to stimulate denitrifying bacteria carried out during April enhanced abundance of immature mosquitoes; mosquito abatement with bacterial larvicides was needed for 2 months after vegetation management. Between repeated applications of bacterial larvicides, abundance of larval mosquitoes increased to nearly 60 larval *Culex* sp. (all stages)/dip after dried emergent vegetation was inundated (Keiper et al. 2003). The abundance of larval mosquitoes also was enhanced by similar vegetation management practices during autumn; however, the maximum number of larvae collected in dip samples during the autumn study was 12 times lower than during the spring–summer study of Keiper et al. (2003).

Although under normal operating conditions the marshes in the Prado Wetlands produced comparatively few mosquitoes per unit area of inundated emergent vegetation, abundance of larval mosquitoes in continuously flooded marshes increased as the wetlands aged and emergent vegetation filled in the marshes (Keiper et al. 1999, 2003). Mosquito abundance increased from <0.1 larvae/dip to between 0.5 and 2 larvae/dip during the 1st and 2nd year, respectively, after emergent vegetation density was reduced by flooding (Keiper et al. 2003). In the present study, mosquito abundance in the continuously flooded marshes was low during autumn. Despite the comparatively low mosquito production from continuously flooded marshes, vegetation management is eventually needed for mosquito abatement and to fulfill other goals for the wetlands, such as enhancing the efficiency of water-quality improvement.

Alternative vegetation management practices to inundation of dried, felled vegetation include harvesting or mowing, burning, or incorporating features, such as raised planting beds, to limit coverage of the water surface by dense emergent vegetation. Harvesting large macrophytes such as bulrush and cattail is expensive (Walton 2003). Drying a wetland and using heavy equipment to raze and remove emergent vegetation potentially disrupts the wetland substrate and may compromise water-quality performance (Knight et al. 2003). Mosquito abundance was enhanced for 2 wk after inundation of wetlands that were dried and shallowly dredged to reduce the density of emergent macrophytes as compared to wetlands that were dried but not dredged (Jiannino and Walton 2004). Mowing of grasses (e.g., salt grass [*Distichlis* sp.]) or low emergent vegetation (e.g., pickleweed *Salicornia* sp.) may reduce mosquito abundance and enhance forage for waterfowl in seasonal wetlands (Batzer and Resh 1992, de Szalay and Resh 1997).

Burning is effective for wetlands where regrowth of vegetation is important for wildlife goals (de Szalay and Resh 1997, de Szalay et al. 1999) and is generally less expensive than are harvesting and disposing of large macrophytes, but controlled burns typically require extensive permitting and coordination with agencies responsible for air quality and fire suppression (Walton 2003) and may detrimentally affect postburn water quality (Knight et al. 2003). If rhizomes and roots remain in the substrate, vegetation rapidly recolonizes shallow basins where the emergent vegetation has been burned (Thullen et al. 2002) or harvested (Jiannino and Walton 2004). Both harvesting and burning of wetland vegetation often provide only a short-term reduction of emergent vegetation in treatment wetlands in mild Mediterranean climates.

Mosquito production may be reduced on a comparatively long-term basis by including features that limit the proliferation of emergent vegetation across the water surface (Russell 1999, Thullen et al. 2002), choosing species of emergent vegetation that are less favorable for mosquito production (Collins and Resh 1989) than are the macrophyte species most often used in constructed wetlands (Jiannino and Walton 2004), and utilizing multiple integrated approaches for pest management (Knight et al. 2003). The cost effectiveness and the impact on the achievement of multiple goals of such features, such as narrow (1- to 2-m-wide), raised planting beds, and operational procedures remain to be determined for large wetlands.

Vegetation management practices that enhance mosquito populations are problematic at any time of the year, but carrying out vegetation management in the autumn reduced mosquito abundance compared to that after vegetation management earlier in the year. During autumn, cool water temperatures slow development rates of immature mosquitoes to 2–3 times those of the early summer. Although abundance of immature mosquitoes and potential adult production in autumn is lower than in summer, vegetation management carried out during late summer–early autumn may be of particular concern if large populations of host-seeking mosquitoes occur during the period that arbovirus activity is detected in humans. In southern California, this period often occurs from the end of the summer through autumn (Reeves et al. 1990).

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