Postprint: Study on Changes in Ecological Security Pattern in the Kalamaili Region Based on the MCR Model

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Abstract

With the development of productivity, ecological and environmental issues such as vegetation destruction, water pollution, and soil pollution caused by human development activities have become increasingly prominent, and the contradiction between human activities and the natural environment, as well as ensuring the sustainable development of human society, have become urgent problems to be solved. Using the Minimum Cumulative Resistance (MCR) model, the changing patterns of ecological security patterns in the Kalamaili region from 1990 to 2019 were analyzed, and combined with the Cellular Automaton-Markov (CA-Markov) model to predict the ecological security pattern of this region in 2025. The results show that: (1) The ecological security pattern of the Kalamaili region is divided into secure areas, low-security areas, and insecure areas. The area of secure areas shrank to 3237.31 km^2 during 2010–2015, mainly converting into low-security and insecure areas. Human activities during this period severely impacted the ecological environment of this region. (2) In 2019, the area of secure areas was 6265.91 km^2, and the low-security and insecure areas basically returned to their natural state, indicating that ecological restoration efforts have achieved good results. (3) Predictions indicate that in 2025, the landscape pattern of the Kalamaili region will change little, still dominated by grassland and unused land. The area of ecological secure zones will be 6421.88 km^2, and the areas of low-security and insecure zones will continue to decline. (4) A belt-shaped low-security zone has formed near the transportation routes in the central part of the Kasan Protected Area, which will become a key area for ecological monitoring and conservation in the protected area in the future.

Full Text

Title and Authorship

Changes of Ecological Security Pattern in Kalamaili Region Based on MCR Models

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Abstract

With the development of productivity, ecological and environmental problems such as vegetation destruction, water pollution, and soil contamination caused by human development activities have become increasingly prominent. The contradiction between human activities and the natural environment, along with ensuring the sustainable development of human society, has become an urgent issue to be addressed. Using the Minimum Cumulative Resistance (MCR) model, this study analyzes the changing patterns of ecological security patterns in the Kalamaili region from 1990 to 2019, and combines the Cellular Automata-Markov (CA-Markov) model to predict the ecological security pattern of the region in 2025. The results show that: (1) The ecological security pattern of Kalamaili region can be divided into safe zones, low-safety zones, and unsafe zones. In 2010, the safe zone area was 3237.31 km^2, mainly transforming into low-safety and unsafe zones. Human activities during this period severely impacted the region' s ecological environment. (2) By 2019, the safe zone area had recovered to 6265.91 km^2, with low-safety and unsafe zones basically returning to their natural state, indicating that ecological restoration efforts have achieved good results. (3) Predictions indicate that by 2025, the landscape pattern will not change significantly, still dominated by grassland and unused land. The ecological safe zone area will reach 6421.88 km^2, with low-safety and unsafe zones continuing to decline. (4) A belt-shaped low-safety zone has formed near the traffic routes in the central part of the Kalamaili Reserve, which will become a key area for ecological monitoring and protection in the reserve.

Keywords: CA-Markov model; ecological security pattern; minimum cumulative resistance (MCR) model; Kalamaili region

Introduction

Since the turn of the 21st century, ecological and environmental problems have become increasingly prominent, and the contradiction between human activities and the natural environment has grown more acute. How to mitigate this conflict and ensure the sustainable development of human society has become an urgent issue requiring resolution. The report of the 19th National Congress of the Communist Party of China explicitly proposed a series of ecological and environmental protection policies, including the principle that "lucid waters and lush mountains are invaluable assets," implementing the strictest ecological and environmental protection systems, forming green development methods and lifestyles, and contributing to global ecological security. Against this backdrop, research on ecological security patterns in ecologically fragile areas under human influence holds important practical significance.

Ecologically fragile areas refer to regions where ecosystems are relatively fragile, easily damaged by external interference (both natural and anthropogenic), have poor recovery capabilities, and incur high restoration costs. Regional ecological security patterns refer to the potential spatial patterns composed of local elements, their positions, and spatial connections within a specific geographical unit. Constructing ecological security patterns in ecologically fragile areas helps identify core ecological areas and sensitive zones, which is of great significance for protected area land-use planning and the implementation of conservation policies.

In recent years, major approaches to constructing regional ecological security patterns have included ecological security evaluation indicator systems, landscape index methods, and the Minimum Cumulative Resistance (MCR) model. The MCR model, first proposed by foreign scholar Knaapen and later refined by Chinese scholars such as Yu Kongjian, has been widely applied in ecological security pattern construction. Based on the source-sink theory in landscape ecology, this model studies the minimum cost for species to overcome heterogeneous landscape resistance from source to destination. It comprehensively considers the horizontal spatial connections of regional landscape units and effectively reflects the spatial variation patterns of ecological security, making it widely applicable in regional ecological security pattern construction.

With the increasing maturity of computer technology, numerous methods have emerged for simulating landscape pattern dynamics, such as the Cellular Automata-Markov (CA-Markov) model, small-scale land-use change and its spatial effects, and system dynamics models. Among these, the CA-Markov model, which combines Markov long-term prediction with cellular automata simulation of complex spatial patterns, is the most widely applied landscape pattern dynamic prediction model. It can effectively simulate regional land cover type changes and can also establish different transition rules to simulate and analyze landscape pattern evolution under various scenarios.

The Kalamaili region in Xinjiang is rich in mineral resources. The Zhundong Coalfield in the south is China' s largest intact coalfield, with proven reserves of 3900×10^{8} tons and predicted reserves of 2136×10^{8} tons. By the end of 2005, the Xinjiang Uygur Autonomous Region government began developing the Zhundong area and officially established the Zhundong Coal-Electricity and Coal-Chemical Industrial Park in 2006, demarcating the Kalamaili Mountain Ungulate Wildlife Nature Reserve (hereinafter referred to as the Kalamaili Reserve). In 2012, with State Council approval, the Zhundong Coal-Electricity and Coal-Chemical Industrial Park became a national-level economic and technological development zone. According to the official Zhundong website (http://zd.cj.cn/), by 2019, the total coal production capacity of the Zhundong Economic and Technological Development Zone reached 1.022×10^{8} tons per year, making it Xinjiang' s largest coal production area. In addition to coal resources, the Kalamaili region is also an important copper, gold, and tin metallogenic belt in the East Junggar area, featuring various deposit types including epithermal gold deposits, porphyry copper-gold deposits, structurally controlled vein-type copper deposits, and greisen-quartz vein-type tin deposits.

Between 2005 and 2015, companies such as Juefa Mining and Ouluo Stone established mining sites in parts of the Kalamaili Reserve to exploit these resources, causing several adjustments to the reserve' s spatial boundaries and severely impacting wildlife habitats. Previous studies have shown that mineral resource development in the Kalamaili region since 2005 caused severe damage to the fragile ecological environment, making ecological protection extremely urgent. After 2015, due to strengthened implementation of ecological civilization policies, mining sites within the Kalamaili Reserve were revoked and rectified, and the reserve' s ecological environmental quality gradually recovered, though the impact of roads on wildlife increased. In this context, studying the changing patterns and influencing factors of the ecological security pattern in the Kalamaili Reserve holds important practical significance for ecological conservation and construction in the region.

This study takes the Kalamaili region as the research area, utilizing land-use and water source data provided by the Kalamaili Reserve management, combined with Landsat images from 1990, 2000, 2005, 2010, 2015, and 2019, to investigate the changing patterns of the reserve' s ecological security pattern from 1990 to 2019, with the aim of providing preliminary scientific basis and recommendations for monitoring and protecting wildlife habitats, maintaining ecological security, preserving regional biodiversity, and rationally planning human activities in the region.

Study Area Overview

The Kalamaili region is located between 44°36 -46°00 N and 88°30 -90°03 E, encompassing the Kalamaili Reserve and the Zhundong Economic and Technological Development Zone, covering a total area of 18,000 km^2 (of which the reserve area is 14,856.2 km^2). The region has a typical temperate continental climate with an average annual temperature of 2.4°C and average annual precipitation of 186.8 mm. The average potential evaporation reaches 2090 mm, far exceeding precipitation and resulting in an extremely arid state with scarce permanent surface water systems. The Kalamaili Reserve has an average elevation of 1000 m with relatively gentle terrain. Vegetation is dominated by typical desert and semi-desert flora. Wildlife species are abundant, with records indicating 58 species, including nationally protected animals such as Przewalski' s horse, Mongolian wild ass (khulan), and goitered gazelle.

Mongolian wild ass and goitered gazelle are the key wildlife species studied in this region. According to 2015 field surveys, the populations of Mongolian wild ass and goitered gazelle in the Kalamaili Reserve were approximately 2632–4200 individuals and 609–2107 individuals, respectively, primarily distributed in the central-eastern part of the reserve where water sources are more abundant. Both species exhibit strong seasonal migration patterns, generally moving collectively to the southwestern and southern parts of the reserve during autumn and winter, and returning to the central and northern parts in spring. In addition to seasonal migration, these animals also move east-west during summer due to changes in water source conditions. Currently, three north-south transportation routes traverse the central Kalamaili Reserve: National Highway 216, a newly built fully enclosed expressway, and a railway running parallel and close to each other. These parallel transportation routes split the wildlife habitat of the Kalamaili Reserve into two parts, affecting habitat connectivity. Although 36 wildlife passages have been established in the form of bridges and overpasses along the expressway and railway, their usage efficiency is still under investigation, and the impact of roads on wildlife migration and life remains significant.

[Figure 1: see original paper]

Methods

Data Sources

To improve data accuracy, this study utilized high-precision land-use data for the Kalamaili region provided by the reserve management, derived from visual interpretation of Landsat images for the years 1990, 2000, 2005, 2010, 2015, and 2019, with a spatial resolution of 30 m. To study landscape pattern evolution trends and construct ecological security patterns, the study adopted the first-level classification standard from the land-use data, dividing the study area into five land types: artificial surfaces, forestland, grassland, wetland, and unused land. Digital Elevation Model (DEM) data for the study area were obtained from the Geospatial Data Cloud (http://www.gscloud.cn/) with a spatial resolution of 30 m, from which slope data were extracted. Soil, water source point, vegetation type, mining site, road, and reserve zoning data were provided by the Kalamaili Reserve management.

Minimum Cumulative Resistance (MCR) Model

The MCR model studies the minimum cost sum required for species to overcome heterogeneous landscape spatial resistance from source to destination. The calculation formula is:

$$MCR = f \min \sum_{j=1}^{n} (D_{ij} \times R_j)$$

where D_{ij} represents the distance from the "source" to spatial unit i (km), R_j represents the resistance coefficient of spatial unit j, and f represents a positive correlation function.

Cellular Automata-Markov (CA-Markov) Prediction Model

Cellular automata are network dynamics models that simulate the spatiotemporal evolution processes of complex systems through interactions between cells and their neighborhoods depending on different temporal and spatial characteristics. The Markov model describes the changing characteristics of events during a certain period based on Markov stochastic processes and uses this as a basis to predict future development trends. The CA-Markov model leverages these advantages by introducing continuous spatial elements into Markov time series analysis to predict and simulate future regional landscape pattern spatiotemporal evolution.

Using the IDRISI 17.0 software, this study simulated the landscape pattern of the study area in 2025. The specific process was as follows: (1) The Markov module in IDRISI software was used to calculate the Markov transition matrix and probability transition images of land-use types in the study area. Artificial surfaces and wetlands were set as restricted land uses to create corresponding suitability map sets; (2) The CA-Markov module was used with a 5$×$5 filter, setting the number of iterations to 300. Using 2019 data as the base period, the suitability map set was used to predict the land-use conditions in 2025. Simultaneously, using 2015 data as the base period, the same method was applied to obtain the 2015 land-use map, and the data were exported and saved; (3) The Crosstab module in IDRISI was used to verify the prediction accuracy between the 2015 land-use prediction results and the actual 2015 image. The calculated kappa coefficient was 0.81. A kappa coefficient $ $0.75 indicates high prediction accuracy, confirming that the prediction results can be used for research and analysis.

Results and Analysis

Prediction of 2025 Landscape Pattern Based on CA-Markov

According to model predictions (Figure 2 [Figure 2: see original paper]), the landscape pattern of the Kalamaili region will not change significantly by 2025, with unused land remaining the dominant landscape type, covering 9891 km^2 (54.98% of the total area). Grassland and forestland are the second and third largest landscape types after unused land. Forestland is concentrated at the edge of desert hills in the northwest, with small amounts distributed in the central Kalamaili mountainous area and northeastern hilly Gobi region, covering 1661 km^2 (approximately 9.23%). Grassland is mainly distributed in patches and strips in the northeastern hilly Gobi, central Kalamaili mountainous area, and southern Jiangjun Gobi region, covering 6279 km^2 (34.91%). Artificial surfaces are dominated by mineral extraction and processing industries, covering 154 km^2 (0.86%), primarily distributed in the Zhundong Economic Zone in the southern part of the region, with small amounts of transportation land distributed within the Kalamaili Reserve. Due to climatic conditions, wetlands in the Kalamaili region consist mainly of reservoirs and water supply facilities established by humans, attached to cultural landscapes, with an area of only 4 km^2 (0.02%).

Source Site Identification

The Kalamaili Reserve was established to protect large ungulate wildlife in the region. Studying the ecological security pattern of this area essentially means studying the ecological security pattern of wildlife within the reserve. Therefore, the habitats of representative species should be considered as the "source" in ecological security pattern research. Currently, the key species studied in the Kalamaili region are Mongolian wild ass and goitered gazelle, so this study treats the habitats of these two species as the "source"for the regional ecological security pattern.

Due to the relatively simple landscape types in the Kalamaili region, habitats cannot be simply defined as a single landscape type. Instead, multiple factors including natural elements, human elements, and comprehensive elements must be considered.

Natural Elements: According to research on Mongolian wild ass and goitered gazelle in the Kalamaili region, these animals typically do not engage in large-scale activities beyond 15 km from water sources, making water the primary limiting factor for large wildlife. In addition to water sources, Mongolian wild ass and goitered gazelle select suitable activity locations based on plant species preferences. Mongolian wild ass preferentially consumes *Seriphidium terrae-albae*, *Haloxylon ammodendron*, *Anabasis salsa*, *Stipa glareosa*, etc., while goitered gazelle preferentially consumes *Stipa glareosa*, *Haloxylon ammodendron*, and *Artemisia desertorum*. Therefore, the vegetation type map of the Kalamaili region was classified into high, medium, and low suitability types based on the foraging preferences of these two species, making vegetation type the second most important factor affecting wildlife distribution. In addition to water and foraging preferences, terrain and soil are also important influencing factors. Mongolian wild ass and goitered gazelle typically inhabit areas with gentle slopes and flat terrain, while soft soil is not conducive to the movement of large wildlife such as Mongolian wild ass. Since soft soil in the Kalamaili region is mainly distributed in the northwest, its impact on wildlife is smaller than that of slope. Based on the above research, water source points, slope, soil type, and vegetation type were selected as natural elements for habitat evaluation.

Human Elements: Wildlife exhibits avoidance effects toward human activities. Human interference in the Kalamaili Reserve mainly consists of two types: one is the impact of transportation routes such as National Highway 216, and the other is large-scale regional mineral development and the construction of the Zhundong Economic Zone in the southeast during 2005–2015. The former divided the reserve into three relatively independent areas, which is detrimental to wildlife population exchange in the long term, while the latter squeezed wildlife living space. Based on this research, distance to roads, distance to mining sites, and distance to economic zones were selected as human elements for habitat evaluation.

Comprehensive Elements: Land cover is a comprehensive element under the dual influence of humans and nature that directly reflects spatial changes in land and serves as an important carrier for wildlife activity.

After establishing the influencing factor system, reference was made to research results from other scholars on source site identification to classify the spatial suitability levels of each influencing factor and assign values (Table 1): suitable (9), moderately suitable (7), marginally suitable (5), and unsuitable (1). Each habitat indicator layer was created through reclassification and ArcGIS tools. The Analytic Hierarchy Process (AHP) was used to assign weights to each influencing factor (Table 2), and the layers were overlaid in ArcGIS to obtain the final source site identification map (Figure 3 [Figure 3: see original paper]). The habitat areas for 1990, 2000, 2005, 2010, 2015, and 2019 (predicted) were 4736.31 km^2, 4524.91 km^2, 4525.08 km^2, 5900.03 km^2, 660.47 km^2, and 6200.10 km^2, respectively, accounting for 24.04%, 23.12%, 23.12%, 30.12%, 3.37%, and 31.45% of the total Kalamaili Reserve area. Overall, wildlife habitat area in the Kalamaili Reserve showed an increasing trend. Before 2010, wildlife habitats were continuously expanding, and field surveys during this period showed that the population and distribution density of Mongolian wild ass were also continuously increasing. After 2010, as human mineral resource development intensified, animal habitats continued to shrink, and by 2015, habitat area had decreased to 660.47 km^2, severely impacting wildlife living environments, with the most severely affected areas mainly distributed in the central-eastern parts of the habitats. By 2019, after ecological restoration efforts, animal source sites had recovered substantially, with a total increase of 1163.72 km^2. Under current protection conditions, predictions indicate that habitat area will increase by 300.07 km^2 by 2025. According to field surveys, the distribution density of Mongolian wild ass and other animals increased significantly after 2015, indicating improved ecological environmental quality in animal habitats.

Construction of Minimum Cumulative Resistance Surface and Ecological Security Pattern

Based on source site identification, this study simulated the spatial diffusion process of Mongolian wild ass and goitered gazelle, using landscape type, reserve zoning, and distance to roads as resistance factors affecting animal movement. The Analytic Hierarchy Process was used to assign weights to resistance factors. Referencing the assignment methods of numerous scholars for resistance factors in different regional types including ecologically fragile areas, ecological land, single ecosystems, and urban areas, relative resistance values were set within the range of 0-100. Smaller resistance values indicate less resistance overcome during animal spatial diffusion. The specific classification was: minimal spatial resistance (0–25), moderate spatial resistance (26–50), relatively high spatial resistance (51–75), and high spatial resistance (76–100). After determining resistance values (Table 3), each single spatial resistance factor map was reclassified according to resistance values in ArcGIS and overlaid based on weights calculated through AHP (Table 4) to obtain the final comprehensive resistance factor surface. Using source site identification data as spatial sources and the comprehensive resistance factor surface as cost data, the Cost Distance model in ArcGIS was used to construct the minimum cumulative resistance surface for the study area, which represents the ecological security pattern of the region. It should be noted that water source point data were provided by the Kalamaili Reserve management and are limited to within the reserve boundaries, lacking water source data for the Zhundong Economic Zone. Additionally, since the Zhundong Economic Zone was delineated outside the reserve boundary after 2015, it was not considered when constructing the 2019 ecological security pattern.

Comprehensive Ecological Security Pattern Analysis

Based on research by relevant scholars on suitable habitats for Mongolian wild ass and goitered gazelle in the Kalamaili Reserve, the ecological security level of the study area was divided into three grades: safe, low-safe, and unsafe (corresponding to suitable, moderately suitable, and unsuitable habitats in suitability studies). After establishing the three-grade classification, the Natural Breaks method in ArcGIS was used to classify the minimum cumulative resistance surface, and the Raster Calculator in ArcGIS was used to calculate the area of each security grade zone, ultimately obtaining ecological security pattern maps and area statistics for each period (Figure 4 [Figure 4: see original paper], Table 5).

Safe zones are mainly located in the central-eastern part of the Kalamaili Reserve. In 1990, 2000, and 2005, safe zone areas did not change significantly, while in 2010 and 2015, safe zone areas decreased by 3607.37 km^2 and 704.08 km^2 respectively, showing obvious fragmentation, with reduced areas mainly located in the central-eastern region. By 2019, with ecological restoration and management implementation, the safe zone area recovered to 6265.91 km^2, accounting for 42.49% of the total Kalamaili Reserve area. During the same period, the Mongolian wild ass population increased significantly compared to the 2015 field survey results (2632–4200 individuals), indicating improved regional ecological environmental quality. According to predictions, the safe zone area will increase to 6421.88 km^2 by 2025. However, the three parallel transportation routes have divided the safe zone into two relatively independent parts, which will affect wildlife habitat connectivity in the long term.

Low-safe zones serve as buffer areas between safe and unsafe zones, distributed in ring-shaped belts around the periphery of safe zones. The area of low-safe zones showed no significant change between 1990 and 2005. In 2010, low-safe zones increased to 3075.36 km^2, accounting for 21.45% of the total Kalamaili Reserve area, with most of the increase converted from safe zones. By 2015, low-safe zone area decreased to 115.01 km^2, with some areas transforming into unsafe zones. By 2019, after ecological restoration, low-safe zone area decreased to 3863.57 km^2, with most central low-safe zones restored to safe zones and only small amounts distributed in the western region. Landscape types are dominated by grassland and unused land. Notably, a belt-shaped low-safe zone has formed near the transportation routes in the central part of the Kalamaili Reserve, indicating that this area, as the most directly affected sensitive zone, should become the focus of future ecological conservation and monitoring efforts.

Unsafe zones are located in the western and southern parts of the reserve, characterized by scarce water resources, mainly aeolian sandy soil, poor natural environmental conditions, and intensive human activities in the southern region, making them unsuitable as animal habitats. In 1990, unsafe zones were mainly distributed in the western and southern parts of the Kalamaili Reserve, with an area of 4616.66 km^2. In 2010, some unsafe zones appeared in the central-eastern part of the reserve, with a larger range than in 2015, mainly converted from safe and low-safe zones. By 2015, unsafe zone area reached 704.08 km^2, and the Mongolian wild ass population during this period decreased to 609–2107 individuals, indicating that the ecological environment of the Kalamaili Reserve had reached a relatively poor state. By 2019, after governance, unsafe zones basically shrank to their natural state range and showed a continuing downward trend, indicating good results from ecological governance.

Driving Factors Analysis

Natural Factors: The Kalamaili region suffers from scarce surface water systems, with only a few mineralized bitter springs such as Kamusite and Laoyaquan, and multiple rain-snow water storage points such as Kezilerishi and Qiaomuxibai. The severe water shortage is the main factor limiting animal distribution in the reserve. Additionally, excessively dry summers and winter snowstorms also threaten wildlife survival.

Mineral Resource Development: The Kalamaili region contains abundant coal and other mineral resources. The establishment of the Zhundong Economic

Zone, Kamusite Economic Zone, and some mining areas for mineral resource development not only encroached upon wildlife water sources but also caused habitat fragmentation to some extent. These impacts were reflected in field survey results of wildlife population numbers and distribution densities. After mineral development was rectified in 2015, the impact of roads has gradually become the most direct manifestation of human influence.

Road Construction: Currently, three north-south transportation routes traverse the Kalamaili Reserve. These roads divide the safe zone into two parts, destroying its integrity and adversely affecting normal wildlife migration and life. After mineral resource development was rectified, road impact has become the main form of human interference. Although ecological passages for animals were reserved during road construction, threats from road traffic and noise pollution continue to adversely affect wildlife. Future efforts should intensify monitoring and research around roads and ecological passages in the Kalamaili Reserve, installing infrared cameras and other monitoring equipment to gather historical data on animal activities and provide support for wildlife conservation.

Conclusions

This study examined the Kalamaili region from a species protection perspective, using the MCR model to construct ecological security patterns for the Kalamaili Reserve from 1990 to 2019 and analyzing the evolution patterns of these patterns. The main conclusions are:

1) According to CA-Markov model predictions, the landscape pattern of the Kalamaili region will not change significantly by 2025, remaining dominated by grassland and unused land, with artificial surfaces concentrated in the southern Zhundong Economic Zone, accounting for only 0.86%. It should be noted that the influencing factor system used in this prediction is based on existing literature summaries, which may cause some deviation in prediction results. Future work should improve the influencing factor system to make predictions more accurate.

2) The ecological security pattern of the Kalamaili Reserve can be divided into three levels based on MCR model calculations. Safe zones are mainly located in the central-eastern part of the reserve, accounting for approximately 42.49% of the total reserve area in 2019. Low-safe zones are distributed in ring-shaped belts around safe zone peripheries, with a total area of 3863.57 km^2 (26.20%). During the most intensive human interference period (2010–2015), 3607.37 km^2 of safe zones transformed into low-safe zones, and the Mongolian wild ass population decreased to 609–2107 individuals, indicating declining regional ecological environmental quality. Unsafe zones are basically located in the western and southern parts of the reserve, with an area of 4616.66 km^2 in 2019. In 2010, unsafe zones were also distributed in the central-eastern region, mainly converted from safe and low-safe zones.

3) According to calculations, a belt-shaped low-safe zone will form in the central part of the Kalamaili Reserve by 2025 due to road impacts. This area will become an ecologically sensitive zone and a focus of future ecological security research in the region.

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