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Satellite Imagery Reveals Landscape and Land-Cover Change on Alberta's Eastern Slopes

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Abstract

Alberta's Eastern Slopes of the Canadian Rocky Mountains (ESCR) are a climatically sensitive headwaters region where steep elevation gradients and complex terrain can produce spatially heterogeneous land-cover responses to warming and disturbance. Applying a consistent workflow in Google Earth Engine (GEE), we mapped Alpine Treeline Ecotone (ATE) dynamics from 1984–2023 using Landsat-based vegetation metrics and quantified changes by watershed, aspect, and geological substrate. The study demonstrated a tendency for upslope ATE shift across the region (mean watershed-scale increase 23.41 m) with strong basin-to-basin variability. Warming of summer climate was significant (mean July-September (JAS) temperature ~+2.1 °C; Mann–Kendall $p = 0.0045$), marked by increasing rates of vegetation productivity. NDVI increased significantly ($p = 0.0003$) and was positively correlated with JAS temperature (Spearman $\rho = 0.71$, $p = 0.0003$). Geological overlays suggested heritage-dependent pattern, but large-scale testing revealed no significant differences between mapped units ($p > 0.05$), pointing to ATE changes being mediated by terrain and microsite controls at a finer scale.

Keywords

Alpine treeline ecotone (ATE), Upslope ATE Shift, Alberta's Eastern Slopes of the Canadian Rocky Mountains (ESCR); Google Earth Engine (GEE); climate warming; geological substrate.

Introduction

The Eastern Slopes of the Canadian Rocky Mountains (ESCR) represent an important ecological and hydrological zone where climate change, deglaciation, and forest disturbances reshape alpine treeline ecotone (ATE) dynamics. The ESCR covers approximately 61,158 km² (≈10% of Alberta) and spans a strong elevational gradient from about 985 m to 3,710 m a.s.l., with boundaries defined by the Rocky Mountain ridge, the Continental Divide, and encompass large, steep elevation gradients and multiple major watersheds (Government of Alberta 2022). These characteristics make the Eastern Slopes an ideal landscape for satellite-based detection of land-cover and vegetation change because steep elevation gradients and complex terrain can produce spatially heterogeneous responses to climate and disturbance across watersheds and aspects.

From a geological perspective, the Canadian Rockies are part of a classic fold-and-thrust belt, and the structural relief and resistant–less resistant rock contrasts contribute to rugged topography and strong aspect/slope gradients that influence landscape patterning and environmental gradients; this context is consistent with regional syntheses of Cordilleran tectonics and fold-and-thrust belt architecture (Price 2023). Such topographic complexity is important for land-cover change studies because it organizes microclimate, snow redistribution, soil development, and disturbance pathways, factors that can influence vegetation dynamics and the position/structure of ecotones over time.

The effects of ATE change on the ESCR have ecological implications but have a hydrological context as well in terms of how these changes will affect hydrological processes, e.g., retention of snowpack, rates of evapotranspiration and soil storage and downstream water availability where ATE "will influence the sustainability of water resources and the stability of ecosystems". This aligns with Alberta's long-standing policy framing that the Eastern Slopes require careful resource management (Sparrow 2023).

Globally, the distribution of trees reaches a natural limit along gradients of temperature, drought, or disturbance, referred to as treeline (Körner 2012). In this study, ATE is defined as a transition zone between closed-canopy montane forests and alpine tundra at higher elevations, where trees cannot grow due to harsh environmental conditions and may alter growth habits (Kim and Lee 2015). Within this zone, trees are commonly stunted and may grow horizontally rather than vertically (Holtmeier 2009). ATE is significant in this paper because it serves as an indicator of disturbance, reflected in changes in vegetation density, ecotone elevation, and spatial heterogeneity across watersheds and slope aspects. Previous studies indicated that such shifts can be especially dynamic in particular basins (e.g., Bow and Athabasca), reinforcing the value of monitoring ATE patterns at regional scales rather than only at individual sites (Hooshyarkhah et al. 2025).

Previous research demonstrated that regional warming can promote upward movement of ATE, while the realized upslope advance is often constrained by local non-climatic controls, especially substrate/soil development, geomorphic activity (e.g., unstable slopes), and fine-scale topo climate, so that trees may remain absent from areas that are climatically suitable for establishment (Holtmeier and Broll 2005; Körner 2021; Macias-Fauria and Johnson 2013). Building on this framework, we tested the hypothesis that geological setting influences ATE dynamics on Alberta's

Eastern Slopes by first quantifying and mapping the magnitude of ATE upslope shift from 1984–2023, and then overlaying the resulting shift patterns with mapped geological units to evaluate whether certain units are associated with amplified or constrained ATE migration.

Methods:

We assessed spatiotemporal change in ATE dynamics across the ESCR, using Google Earth Engine (GEE) ArcGIS Pro 3.6, and Python (v3.9), as well as employing long-term satellite imagery in a consistent geospatial workflow. The analysis relied mainly on Landsat 5 and 8 surface-reflectance imagery processed in GEE, with supporting GIS/Python steps for summaries and figures. To make the time series comparable and reduce noise (e.g., clouds and short-term variability), imagery was summarized into consistent growing-season composites and paired with terrain information (DEM) at the same working resolution.

Next, we produced ATE maps for each time period using the Alpine Treeline Ecotone Index (ATEI), which represents the ATE as a transition zone (probability distribution) rather than a single sharp ATE line. In simple terms, the model combines vegetation greenness patterns (from NDVI) with topographic context to highlight where forest transitions to alpine tundra, then applies a calibrated threshold to convert this surface into a mapped ATE zone. We then compared ATE patterns among periods to calculate how the ATE changed over time and summarized those changes across major spatial groupings such as geology and aspect to describe where change was strongest

Finally, to interpret what might be driving the observed patterns, we summarized regional growing-season temperature conditions using ERA5-Land and assessed the overall direction of change through time using standard trend approaches reported in the manuscript. To ensure the mapping results were credible, we also validated the ATE classification using a stratified set of reference points interpreted from high-resolution imagery and reported the overall accuracy of the final mapping approach.

Results and discussions:

Across the ESCR, our results indicated that the ATE has shifted upslope from 1984 to 2023, with a modest mean watershed-scale increase of 23.41 m but strong spatial variability among basins (e.g., Bow +65.79 m, Athabasca +24.32 m, Oldman +15.02 m, North Saskatchewan +13.20 m, and Red Deer ~0 to slightly negative values). This increase in elevation coincided with a quantifiable increase in the area of ATE (Figure 1), which differed by watershed as evidenced by the total area of ATE within each watershed (i.e., size range of approximately 54.88 km2 in Red Deer to approximately 264.00 km² in Athabasca; approximately equal size increases in Bow and North Saskatchewan). That is, while widespread ATE change is apparent, the spatial expression of this change varies across the entire ESCR.

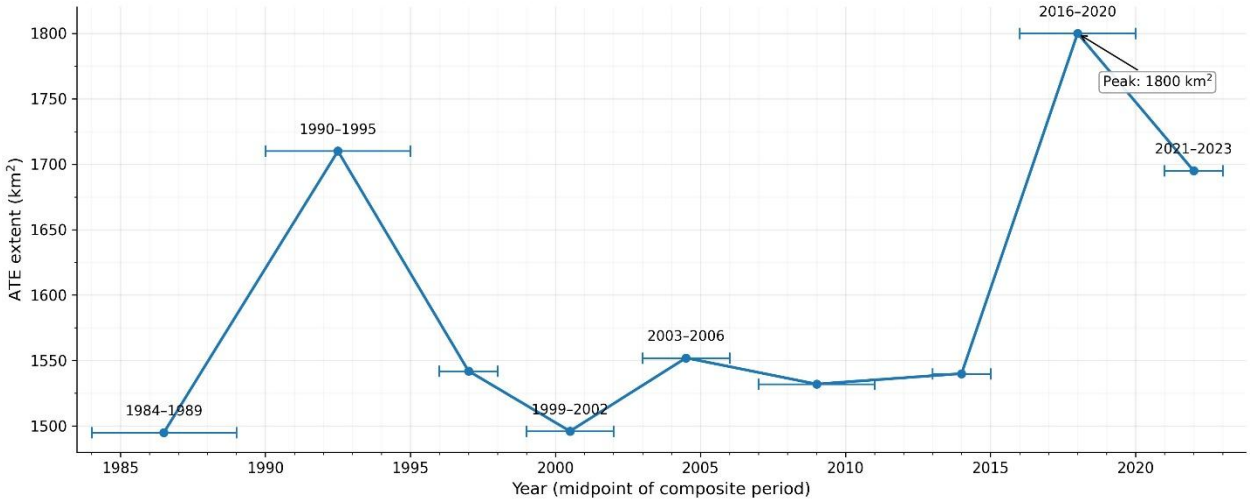


Figure 1: Changes in ATE extent over time in ESCR.

The ESCR-wide expansion is aligned with an ongoing warming signal for the region from July to September during the time frame of this research. Average temperatures in the region during these months have increased by approximately 2.1 °C on average since this research began (as calculated using LOESS). A statistically significant upward trend has also been identified for the average temperature over this same period through the Mann-Kendall method (where $p \approx 0.0045$) confirming that climate changes (including shifts to the growing season) continue to be among several factors impacting the dynamics of ATE at the regional scale. Simultaneously, prominent watershed-to-watershed and aspect-level differences indicate that the ESCR-wide extent is also tempered by the interplay of local controls (e.g. moisture redistribution, sunlight exposure, soil properties) and episodic disturbances such as wildfire which can facilitate local declines within a general upslope/expansion trend.

To evaluate whether ATE dynamics vary by substrate, ATE change (increase, decrease, unchanged) from 1984–2023 was overlaid with Alberta surface and bedrock geology maps, and change areas were calculated per geological unit using zonal statistics in ArcGIS Pro, because geological units differ in areal extent, change totals were normalized by unit area to enable fair comparison among units. The results show clear geology-dependent patterns: bedrock and colluvial deposits exhibit the highest normalized increases and decreases, suggesting these units are particularly responsive and may represent active transition zones, with bedrock showing the strongest increase consistent with relatively stable substrates and favorable microsite conditions for upslope establishment. In contrast, moraine units show a comparatively high normalized decline, plausibly linked to weaker soil development and post-glacial instability, while eolian and glaciofluvial deposits display minimal relative change, indicating a limited role in ATE dynamics under less suitable or more unstable conditions (Figure 2 and 3). Overall, the analysis indicates that geological substrates meaningfully mediate the spatial variability of ATE responses across the Eastern Slopes.

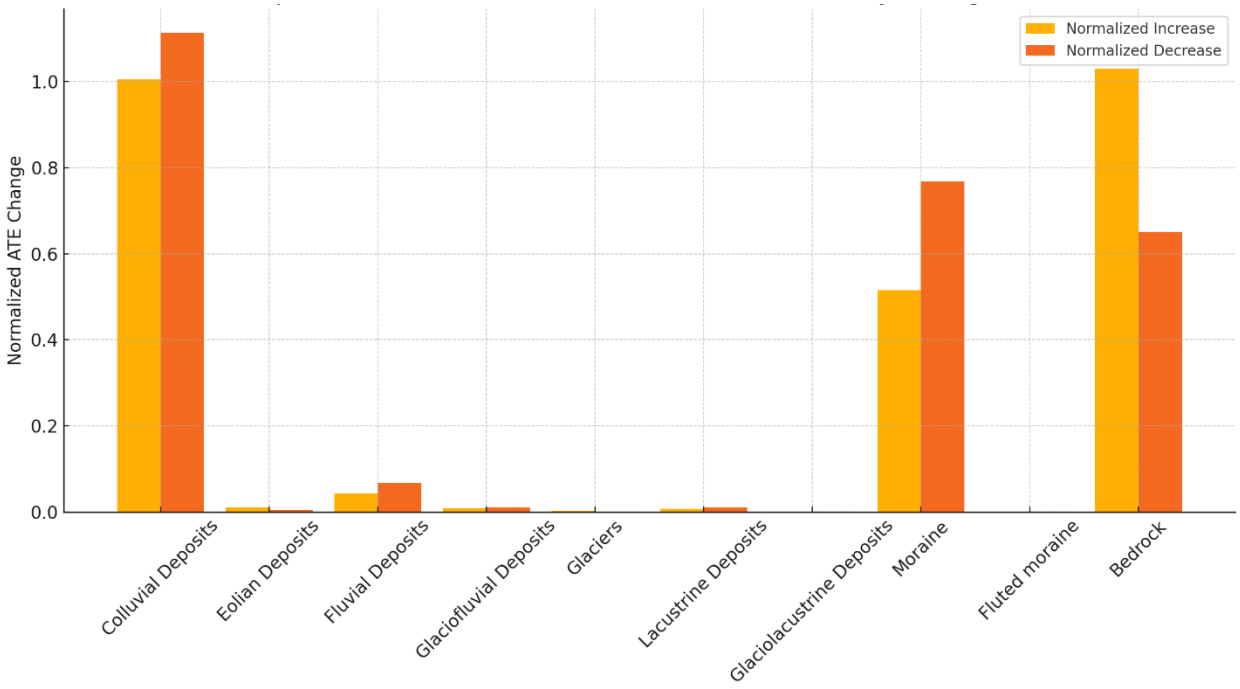


Figure 2: Comparison of normalized ATE increase and decrease by geological units

To test whether ATE responses differ significantly among geological units, we applied a nonparametric Mann–Whitney U test in Python, which is well suited to small samples and non-normal or skewed distributions. The analysis found no statistically significant differences in normalized ATE change among the ten geological units for any category (Increase, Decrease, or No Change), with all pairwise comparisons yielding $p > 0.05$ (e.g., Increase vs. Decrease $p = 0.73$; Increase vs. No Change $p = 0.47$; Decrease vs. No Change $p = 0.97$). These results suggest that although some units (e.g., bedrock, moraine, colluvial deposits) show visibly different patterns, the inter-unit variability at the regional scale is large enough that lithology alone does not explain ATE dynamics; instead, finer-scale controls such as aspect, elevation, soil properties, and drainage likely exert stronger influence.

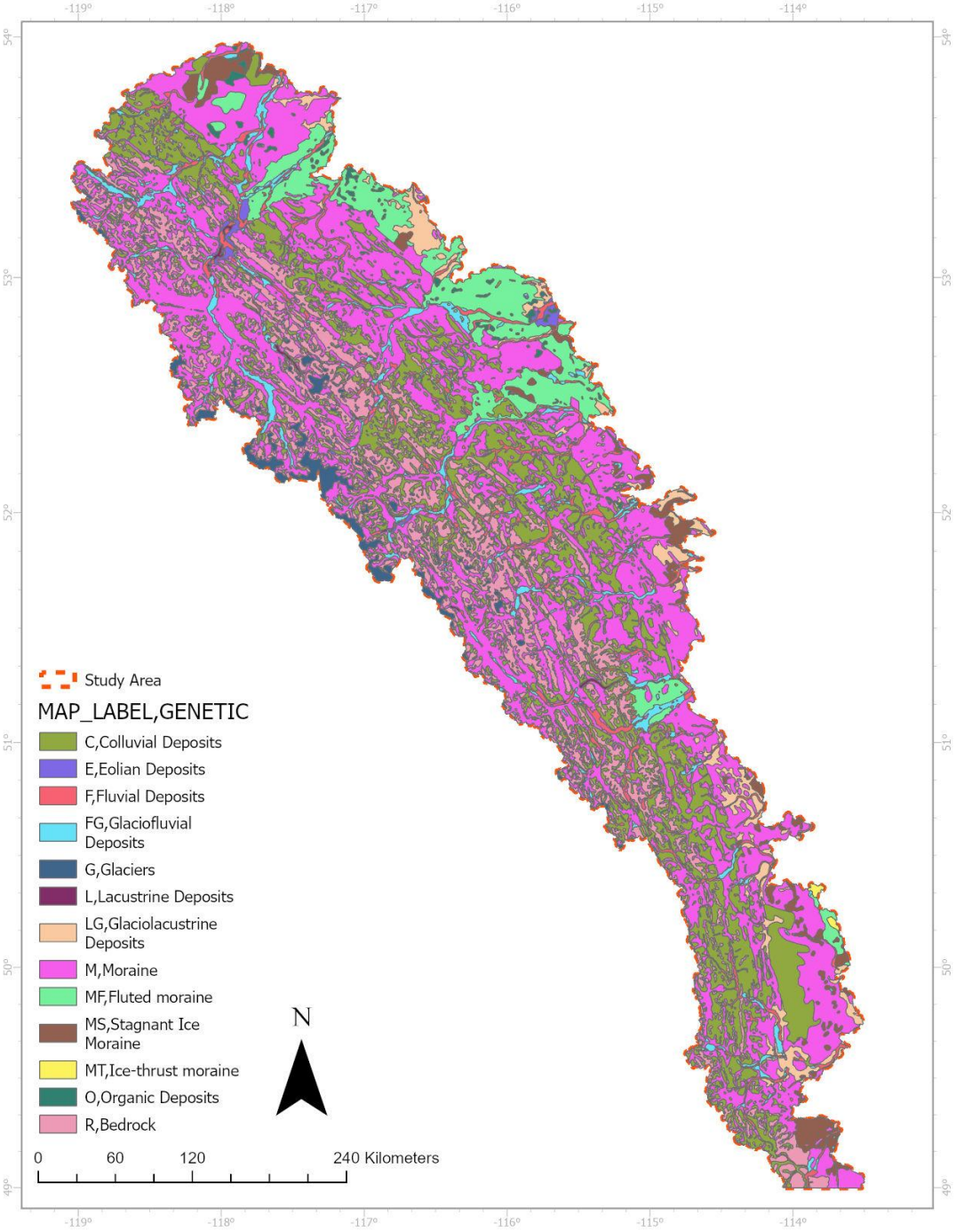


Figure 3: Displays the surface geology map of the study area.

Do carbonate lithologies constrain ATE expansion on Alberta's Eastern Slopes?

Geological units containing carbonate appear to be an important factor in areas where ATE has decreased or remained stable across the ESCR, with declines most frequently linked to moraine, colluvial deposits, and fluted moraine (glacial till) containing limestone and dolomite fragments, where limited drainage and shallow, nutrient-poor soils can restrict tree establishment and upslope migration (Davis, Hager, and Gedalof 2018; Friedrich-Karl and Gabriele 2018; Liptzin, Sanford, and Seastedt 2013; Schmid et al. 2009). Similarly, glaciofluvial and glaciolacustrine deposits that may include reworked carbonate sediments from limestone-dominated terrains can create stratified and unstable rooting conditions (e.g., ice-melt slumping), which are also unfavorable for tree growth. Although carbonate-rich bedrock (e.g., limestone and dolomite) shows high normalized increases in some locations, it can also exhibit notable decreases, indicating strong mediation by local controls such as slope aspect, elevation, and microclimate; mechanistically, carbonate substrates can elevate soil pH and reduce phosphorus bioavailability and other nutrients (Schmid et al. 2009), while thin, organic-poor soils reduce moisture retention and high surface reflectivity may lower soil temperatures or delay snowmelt, together likely contributing to the observed ATE decline or stagnation in carbonate-influenced units.

NDVI vs mean JAS temperature change

Between 1984 and 2023, we evaluated how vegetation productivity (NDVI) relates to climatic warming in the ESCR by jointly analyzing NDVI and mean July–September (JAS) temperature time series (Figure 4). To reduce interannual noise and better capture medium-term dynamics, both variables were modeled using a 2-year moving average, and their association was assessed using Spearman rank correlation to accommodate non-linear and monotonic relationships. The smoothed NDVI trend showed a statistically significant increase over time ($p = 0.0003$), while the moving-average curves indicated rising temperatures and increasing NDVI variability, particularly after 2015; the moving-average fits demonstrated strong goodness-of-fit for NDVI and temperature ($R^2 = 0.69$ and 0.60, respectively). Consistent with these trends, NDVI and temperature were strongly and positively correlated (Spearman $\rho = 0.71$, $p = 0.0003$), indicating that warmer summers are associated with increased greenness across the ESCR and supporting the interpretation that recent warming has contributed to increased vegetation activity over the past four decades.

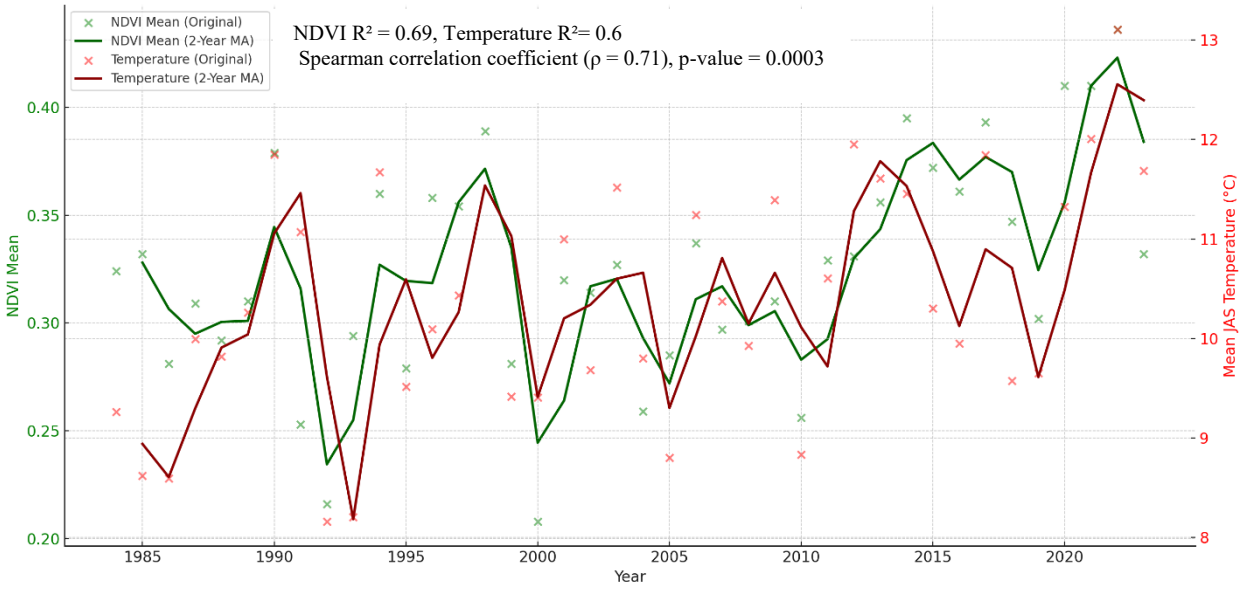


Figure 4: Relationship between NDVI and mean July–September (JAS) temperature in the ESCR (1984–2023).

Conclusion

In summary, our satellite-based work suggests that the ATE across Alberta's Eastern Slopes has overall moved upslope and increased in area from 1984–2023 but exhibits strong spatial heterogeneity among watersheds and terrain settings, such that regional change is broad, but the local expression is very variable. The ESCR-wide patterns fit a clear warming signal during the growing season and increasing greenness, but the variability among watersheds/aspects and mixed substrate response suggest ATE dynamics are being conditioned by the joint influence of interacting controls (climate forcing and local constraints: moisture/snow redistribution, disturbance, site conditions) versus temperature alone.

Moreover, although geological overlays showed readily observed differences in normalized ATE change among units, regional-scale tests indicated that lithology alone cannot explain ATE behaviour, reinforcing the role of finer-scale controls (e.g. aspect, elevation, drainage, and microsite).

Further research should incorporate snowpack and disturbance records, as well as indicators of climate extremes, when attempting to reduce uncertainty in short-term variations and to provide better projections for continued warming. In addition, the addition of NDVI-based greening to measurements of vegetation height, species composition, and recruitment would enhance understanding of how functional changes result in long-term structural/ecotonal migration.

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