REMOTE SENSING FOR RECONSTRUCTION OF OMBRONE RIVER DELTA BEACH RIDGES

Irene Maria Mammì, Lorenzo Rossi

Abstract: The study area focuses on the Ombrone River delta (located in southern Tuscany, Italy), a wave-dominated delta formed over the last 2,500 years. Beach ridges, a characteristic depositional landform of wave-dominated deltas, extend across the entire coastal plain. These ridges are associated with ancient shorelines and reflect variations in river input and longshore transport. The objective of this study is to combine different remote sensing data to create a detailed map of the beach ridges in the area. Satellite images and aerial photos were utilized to differentiate beach ridges, while Unmanned Aerial Vehicle (UAV) photogrammetry and LiDAR (Light Detection and Ranging) data were also employed. A topographic survey was conducted to calibrate the UAV imagery and verify the accuracy of LiDAR data. The research demonstrates how high-resolution digital terrain models (DTMs), generated from LiDAR and UAV data, combined with other remote sensing sources, can be useful tools for reconstructing ancient morphologies, even over large areas like delta plains. A very detailed map of the beach ridges was produced, allowing for a better understanding of the delta's evolution through the analysis of the geometries of these landforms most of which have never been identified before.

Keywords: Beach ridges, river delta evolution, remote sensing data, satellite images, LiDAR.

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Introduction

Coastal landforms are constantly shaped by the interaction of various natural processes, including sediment transport by rivers, wave action, and changes in sea levels. Accurate mapping and monitoring of these landforms are crucial for understanding coastal dynamics and for supporting effective coastal management strategies.

This study focuses on mapping the morphologies of the Ombrone River delta (Grosseto), located in southern Tuscany (Fig. 1). According to the delta classification of Wright and Coleman [27] and Galloway [10], it is categorized as a wave-dominated delta.

The Ombrone catchment area covers approximately 3,495 km² and extends for 65 km, making it the largest river in southern Tuscany and the one with the highest discharge in the area [5]. The coastal plain of the delta covers about 350 km², with the main wave directions coming from the southwest, while longshore sediment transport moves in a south-to-north direction [1]. Land subsidence in the region has been measured at around 3 mm per year from 1891 to 1951 [20].

Variations in sediment input over time have caused both erosional and progradation phases. The erosion phase during the Middle Ages might be linked to population decline caused by the Black Death. The dating of the main beach ridges has been done by several authors using old historical maps and archaeological information [12]. The delta's river mouth reached its maximum progradation during the 18th and 19th centuries [6]. However, over the past 50 years, the Ombrone River delta has experienced severe erosion, with rates of up to 10 meters per year near the delta apex [18].

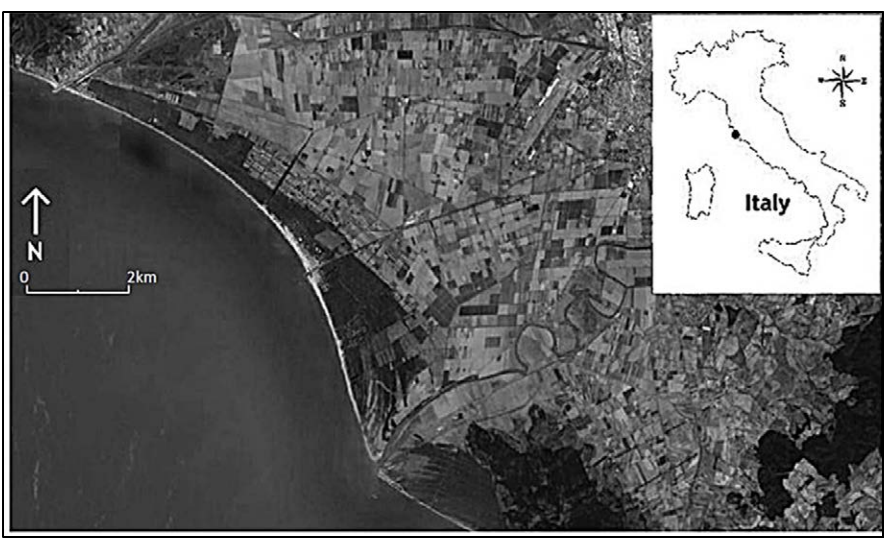

Figure 1 – Location map of the study area.

The complex of beach ridges extends across both wings of the delta in a northwest-southeast direction. The northern, longer, down-drift side has more widely spaced ridges, while the southern, shorter, up-drift lobe has closely spaced ridges running almost parallel to each other, terminating near the Collelungo rocky promontory, which marks the southern boundary of the delta plain.

Beach ridge plains hold valuable information on coastal evolutionary history, including long-term processes and significant events that occurred during the Holocene [21]. In this study, we approximate beach ridges to ancient shorelines [17]. Additionally, the spatial arrangement of beach ridges is related to changes in wave direction, sediment input, and available space for accommodation [23, 24, 25]. Reconstructing and mapping the geometries of beach ridges, sometimes through mathematical models [14], allows us to identify the erosional and accretional phases of the Ombrone River delta.

Remote sensing techniques have been widely used to study delta morphology changes.

This study has two main objectives: first, to deepen the understanding of the evolutionary history of the Ombrone River delta, located in southern Tuscany, by mapping beach ridges and analysing their geometries and distributions; second, to evaluate the advantages and limitations of various remote sensing techniques, including multispectral satellite imagery, LiDAR, UAV, and aerial photographs. This work specifically explores the effectiveness of these methodologies in reconstructing ancient morphologies and creating high-resolution digital models useful for studying deltaic dynamics.

This paper presents a study on the use of remote sensing data to map beach ridges on delta rivers [16, 22, 7], including the use of Synthetic Aperture Radar [9]. We will discuss the advantages and limitations of different remote sensing techniques and present our findings on their effectiveness for mapping beach ridges in deltaic environments. We will also discuss the potential applications of our findings for improving our understanding of delta morphology and their implications for sustainable planning and management.

Digital terrain models (DTMs), derived from LiDAR and UAV point clouds, provide high-resolution and accurate 3D metric information. These models allow for height analysis using cross-sectional profiles from the 3D data. The processing of satellite images and related transformation algorithms enables the enhancement of otherwise hidden or subtle morphologies, such as inter-ridge features.

The integrated use of various remote sensing techniques described here thus addresses both challenges of this study: providing a detailed map of beach ridges while also assessing the utility of each method in obtaining morphological data and identifying features that reflect the delta's evolutionary processes.

Material and methods

In this study, data acquired from both active and passive remote sensors were utilized. Various satellite images were processed, including Landsat TM and Landsat ETM+ (from 1986 to 2002), Quickbird (2004), Landsat 8 (2015), and

Sentinel 2a (2017). Additionally, some Google Earth images were used. The satellite images had varying spatial resolutions: Landsat with 30 m, Sentinel 2a with 15 m, and Quickbird with 2.44 m resolution.

The images were acquired based on weather and seasonal conditions to achieve better textural discrimination based on soil wetness. All images were georeferenced using the UTM ED50 coordinate system and processed using ENVI 4.5 to extract geomorphological information from the study area.

To process the multispectral satellite images, several steps were followed: contrast stretching, density slicing, and the creation of RGB color composites from the original bands. In addition, the Normalized Difference Vegetation Index (NDVI), Tasseled Cap Transformation (Brightness, Greenness, and Wetness) [8], and Principal Component Analysis (PCA) were applied. The use of satellite images with varying resolutions and from different time periods allowed for an extended search of beach ridges through processing with multiple algorithms. For example, lower resolution but older Landsat images enabled the identification of certain previously unobserved forms in areas later affected by human activity or converted to agricultural use. In addition, lower resolution, in some cases, proved beneficial for distinguishing large-scale morphologies such as beach ridges.

Some results of these processes are shown in Figure 2.

Aerial photographs were also used for beach ridge mapping, including images from 1947 and 1954 (from RAF and GAI flights). These images were georeferenced by comparing them with regional maps (CTR 1:10000) using about 15 Ground Control Points (GCPs). The 1947 aerial photos were particularly useful for mapping the final portion of beach ridges close to the river mouth, which are now eroded.

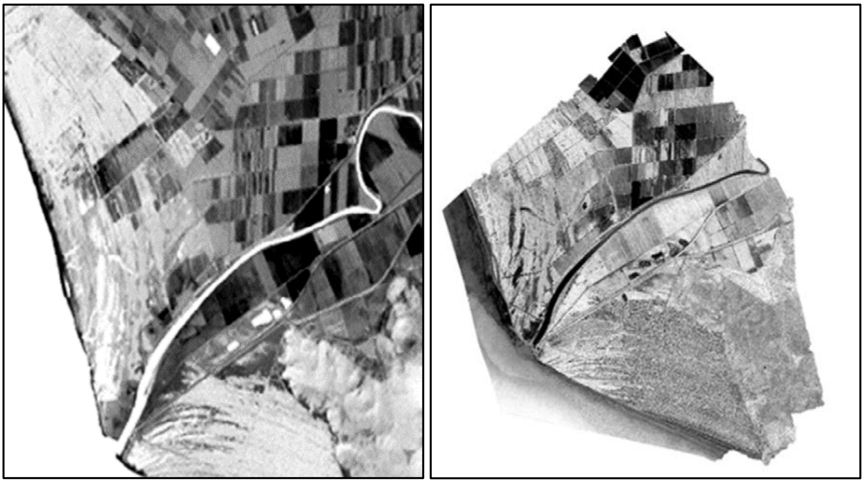

Figure 2 – Left: Wetness image from Landsat TM 5 acquired on February 1st, 1987, on the Ombrone river delta; Right: PCA image from Quickbird acquired on August 29th, 2004.

Additionally, three-dimensional data were acquired using LiDAR and UAV systems, which provided valuable information for generating cross-sectional profiles. LiDAR technology determines the distance between the ground and sensors by measuring the time it takes for a transmitted energy pulse to return to the LiDAR sensor [15]. The first LiDAR return typically corresponds to the top of tree canopies, while the last return corresponds to the ground, allowing the vegetation to be filtered. This method is especially helpful when morphologies are obscured by vegetation, as is often the case with beach ridge plains and dunes.

LiDAR data, provided as open data by the Ministry of the Environment and the Protection of the Territory and Sea in 2008, were processed into DTMs and DSMs with 1x1 meter and 2x2 meter resolution near the coast (Fig. 3).

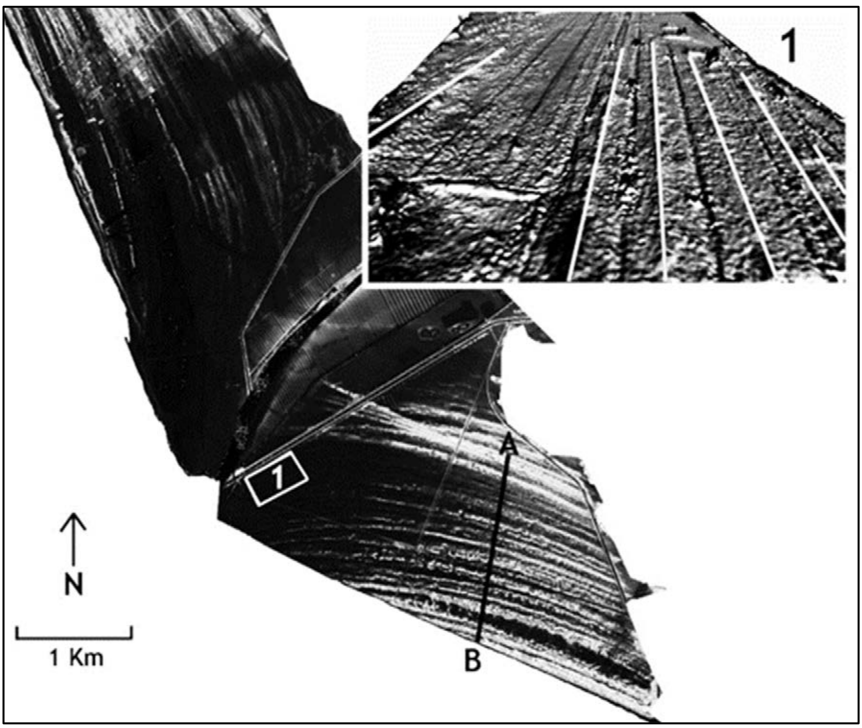

Figure 3 – LiDAR DTM and a detail of UAV survey performed in Area 1 with small beach ridges enhancement. AB LiDAR profile in black.

In 2016, a topographic survey was conducted to establish Ground Control Points (GCPs) for the UAV survey and to verify the accuracy of LiDAR vegetation filtering. Eighty points were surveyed using a total station, and these were compared with the remote sensing data, yielding a vertical accuracy (Root Mean Square Error, RMSE) of 22 cm.

UAV-based photogrammetry is a method used to obtain DEMs and orthoimages of the area being studied. In this case, a DJI Phantom 3 drone equipped with a 12.4-megapixel non-metric camera with a 14 mm F/2.8 lens was used, offering a diagonal viewing angle of 94°. The camera was set to take one image per second automatically. The flight altitude was selected to achieve images with a ground resolution of less than 5 cm. UAV-derived orthophotos were captured in 2016, from a flight altitude of approximately 60 meters. For ortho-photo and DEM georeferencing, 29 ground control points were measured using differential GPS.

The UAV survey area covered about 1 km², located in the southern lobe of the delta near the river mouth, where smaller beach ridges are present, and vegetation is sparse (Fig. 3). The survey aimed to highlight these small landforms, which were difficult to distinguish using other sensors such as LiDAR. Image processing was performed primarily with Metashape and Pix4D software, which allowed for image correction, orientation, point cloud extraction, and the production of an ortho-photo mosaic. A DSM with a 10 cm grid spacing and vertical accuracy (RMSE) ranging from 3 to 5 cm was processed using ArcGIS 9.3. The assessment of accuracy depends on camera resolution, flight altitude and speed, and the number of GCPs. All DTMs were later processed using ArcGIS 9.3 algorithms, such as Slope, Aspect, and Topographic Position Index [26, 13], to highlight coastal morphologies and perform morphometric and statistical analyses.

Results

Satellite images were processed using Principal Components Analysis, Tasseled Cap Transformation (Brightness, Greenness, and Wetness), and corresponding color composites. These analyses showed that the near-infrared and red wavelength bands provided the most information about the natural environment. Based on image processing and data analysis, many previously unknown beach ridge morphologies were identified, alternating with wet inter-ridge swales. These techniques allowed for the recognition of beach ridges that were not visible through LiDAR, UAV data, or aerial photographs.

Additionally, the DTM created by the UAV, with its 0.1x0.1 m resolution cells, allowed the digitization of smaller morphologies, especially those near the river mouth. Finally, LiDAR-derived DTMs enabled 3D reconstruction of the beach ridges and analysis of height variation across profiles.

The integration of these remote sensing techniques, applied over large areas, enabled the collection of substantial information about the distribution of beach ridges and the creation of a comprehensive beach ridge map (Fig. 4).

Using high-resolution 3D models, we identified various morphological features that reveal delta evolution dynamics, such as blowouts, beach ridge truncations, and geometric relationships between ridges and their height variations. Changes in beach ridge configurations and heights may be linked to reductions in sediment availability. High sedimentation rates typically result in smaller ridge dimensions, while slower deposition leads to larger ridges with wider swales [24].

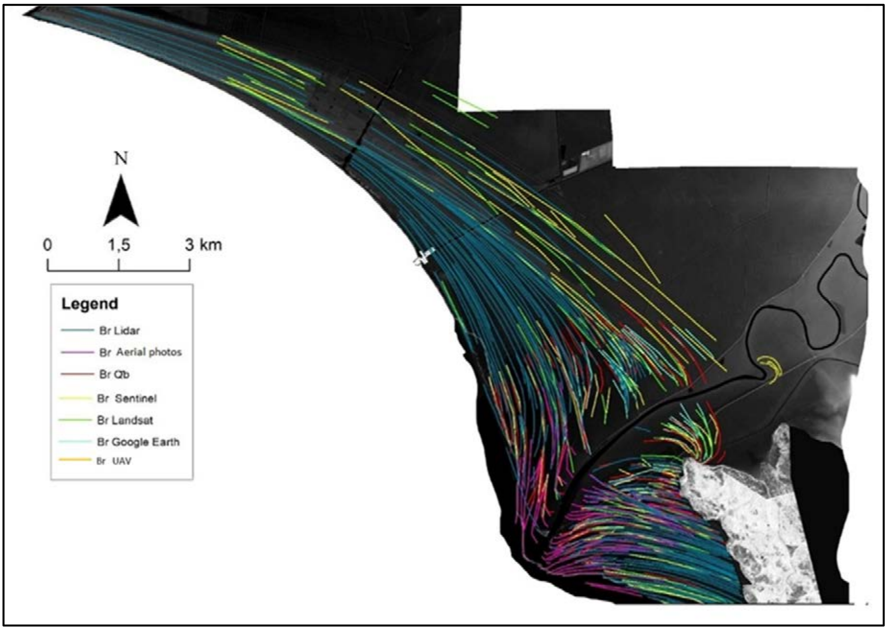

Figure 4 – Beach ridges mapped with different remote sensing technologies.

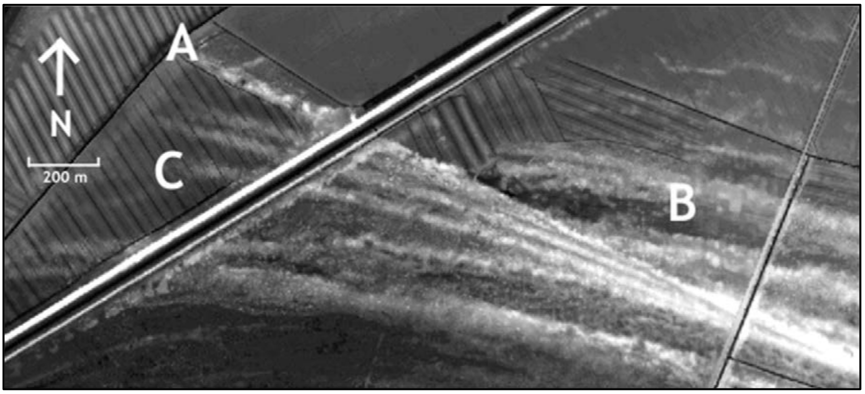

Figure 5 – LiDAR profile (AB) with Beach ridges evidence on the Southern wing of the delta.

Beach ridge profiles derived from the LiDAR 3D survey displayed variable elevations, reflecting different evolutionary phases. Taller beach ridges, such as those along the AB profile, correspond to major erosion phases, one occurring in recent times (after the 19th century) and another during the Middle Ages (Fig. 5, where the AB profile location is indicated in Fig. 3).

The geometric relationships between beach ridges also helped identify erosion and accretion phases (Fig. 6). Beach ridge truncations indicate periods of reduced river sediment input (Fig. 6B), while accretional phases at the delta apex are characterized by divergent ridge geometries (Fig. 6C). A straight coastline suggests a pronounced erosion period (Fig. 6A).

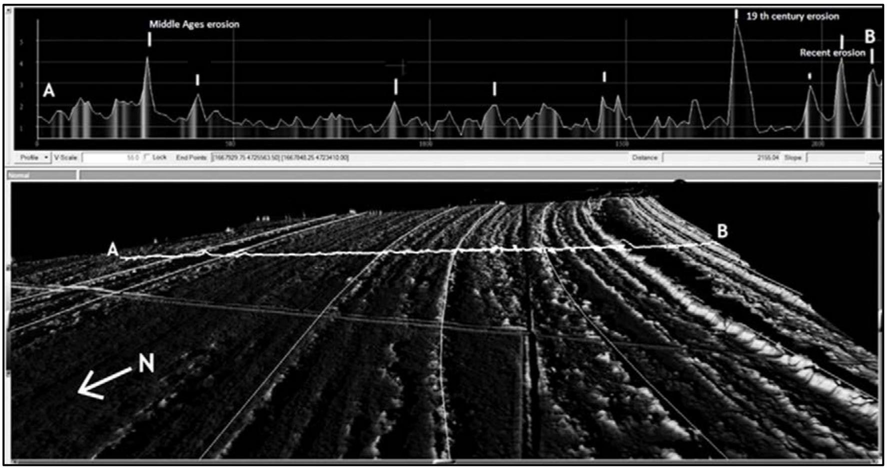

Figure 6 – Beach ridge geometries reflecting different evolution phases. Strong erosion with coastline straightening (A) and antecedent beach ridges truncation (B). Subsequent progradation (C).

Subsequently, the morphological differences between the ridges on the delta's two wings were explained through a morphometric analysis, which considered factors such as the number of beach ridges, their length, spacing, and orientation. These differences correspond to variations in local environmental conditions, such as river mouth migration or avulsion events.

Approximately 100 beach ridges were identified across the coastal plain. The angles between the ridges and the riverbank varied, with no constant values. Beach ridges associated with the Middle Ages erosion phase formed angles of about 90°, while others formed sharper angles. Ridges linked to the 19th-century erosion phase had smaller angles, ranging from 23° to 40°.

LiDAR and UAV-derived DTMs allowed for the measurement of ridge heights, with most ridges reaching up to 3 meters, while a few extended to about 8 meters. The distance between adjacent ridge crests varied from a few meters to hundreds of meters and differed between the delta's lobes, correlating with ridge height.

Mapping beach ridges using multi-temporal satellite images and high-resolution DTMs provided valuable insights into the evolution and morphological changes of the wave-dominated delta over time. The results demonstrate the successful identification and mapping of beach ridges within the Ombrone Delta region using satellite imagery. The classified images showed strong agreement with ground-truth data, validating the effectiveness of the methodology. The spatial distribution and morphological characteristics of the mapped ridges also offered important information on local coastal processes and landform evolution.

Conclusion

The high-resolution data obtained from active and passive remote sensing techniques significantly improved the reconstruction of beach ridge morphologies and provided valuable insights into the dynamics of the river delta lobes.

The integrated remote sensing study provided several new insights beyond what was previously known about the evolution of the Ombrone River delta:

1. Detailed beach ridge mapping: The combination of satellite images, LiDAR, and UAV data enabled a much more detailed mapping of beach ridges. New ridge morphologies were identified that were not visible in aerial photos or through LiDAR alone, especially near the river mouth.
2. Beach ridge height analysis: The DTMs from UAV and LiDAR allowed for a 3D reconstruction of the ridges, providing insight into height variations along profiles, which highlighted different evolutionary phases, such as periods of erosion and accretion.
3. Identification of new evolutionary phases: The study revealed previously undocumented phases of accretion and erosion. Ridge configurations and varying heights were linked to sediment availability and wave direction changes, offering a better understanding of sediment dynamics and the area's morphological shaping. Several accretion and erosion phases, which had not been fully identified before, were mapped. Different ridge heights were also observed and linked to variations in fluvial sediment input. Smaller ridges were associated with rapid progradation phases, where sediment quickly distributed along the shoreline, preventing the ridges from growing taller. In contrast, larger ridges formed when fluvial sediment input was lower, allowing more prolonged exposure to wind action, consistent with models in the literature.
4. Geometric relationships and coastal processes: The multidisciplinary approach visualized geometric relationships among beach ridges, revealing phenomena like ridge truncation (indicating reduced river sediment input) and morphological differences between the delta's two lobes, with one being more continuous and the other fragmented. The morphological differences between the two delta lobes can be attributed to the dynamics of a wave-dominated delta [4].
5. Wave angle impact on delta evolution: Morphometric analysis suggested that wave incidence angle contributed to an uneven coastline, especially visible in the northern lobe, where there are more wet areas and ridge discontinuities. One of the factors may be the angle of wave approach, which causes an uneven shoreline [3, 2]. On the northern, down-drift lobe, beach ridges are discontinuous, with more wet areas and ponds. In contrast, the southern lobe has more continuous and closely spaced ridges, with fewer wet areas. The reduced spacing between ridges in the southern lobe may be due to a greater

accumulation of sediment caused by the hydraulic "groyne" effect of the river flow [11, 19, 2].

We have therefore seen how various types of data were used, including high- and medium-resolution satellite images and three-dimensional models. DTMs proved extremely useful for obtaining profiles and elevation information, while aerial photos and satellite images were indispensable for landform mapping and for identifying beach ridge morphologies associated with wet areas. The combination of these different data types enabled the visualization of the geometric relationships between beach ridges. Some challenges arose from managing the diverse datasets and analysing information from various sensors to draw consistent conclusions about the identification of morphological elements

Finally, the use of GIS proved highly beneficial for data management and analysis. An integrated, multidisciplinary remote sensing approach was essential for producing a detailed map of the Ombrone River delta's morphology, which will serve as a valuable resource for future research on coastal evolution.

In summary, the study offered a much richer, more precise view of the delta's morphological structures and its accretion-erosion processes, leading to a more comprehensive understanding of the Ombrone delta's evolutionary dynamics and providing a valuable foundation for future studies.

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