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Circular Bedforms Due to Pit Foraging of Greater Flamingo *Phoenicopterus roseus* in a Back-Barrier Intertidal Habitat

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Abstract: The Greater Flamingo *Phoenicopterus roseus* is known as an ecosystem engineer, rearranging sediment in peculiar bedforms as a consequence of its filter-feeding behaviour. In recent decades, the populations of the Greater Flamingo have notably increased, and now the species is one of the most abundant waterbirds in Mediterranean wetlands. Owing to its range expansion, it inhabits and exploits new and suitable foraging sites detectable by foraging structures left on the sediment. There are few images of the foraging morphologies in the literature, possibly due to their ephemeral nature and difficulty in detecting them. In this manuscript, we present a very detailed UAV (Unmanned Aerial Vehicle) image of an aggregate of pit foraging structures of Greater Flamingo discovered on a back-barrier washover fan in the Marano and Grado Lagoon (Northern Adriatic, Italy).

Keywords: Greater Flamingo; pit foraging; bedform; ecosystem-engineering; Marano and Grado Lagoon

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Organisms known as ecosystem engineers have the ability to alter environment abiotic conditions for their own benefit and modify biotic communities [1]. Ecosystem engineering regards several bird taxa, such as woodpeckers [2] and seabirds [3]. The Greater Flamingo has been deemed as an ecosystem engineer in modern wetlands because of its capability to alter benthic communities, sediment properties, and micro-topography [4–7]. It is mainly a bottom filter-feeder and exhibits several feeding behaviours on aquatic invertebrates, algae and plant material [8]. Pit foraging is a high-water foraging strategy [9] probably to grab deeper-dwelling prey [10,11], linked to benthic microalgal biomass concentrations [12]. Large pit or donut-shaped depressions have been described because of Greater Flamingo trampling and filtering activities on soft sediment [6]. Birds create them by standing still and moving in a circular motion while stirring up sediment with their feet [11]. Thus, they ensure their own food supply, improving productivity and nutrient flows [5] and enhancing biofilm production [6]. Despite being known, very few images of these foraging biological bedforms are depicted in the literature [4–6,12,13], as they are ephemeral underwater structures, that are difficult to capture in a photograph, or record in their organization.

The Greater Flamingo *Phoenicopterus roseus* is a colonial waterbird widespread across the Mediterranean Sea, much of Africa and West Asia, where it inhabits generally salt pans, brackish shallow saline and alkaline water bodies [14,15], frequently in coastal and estuarine zones [8]. The populations of Greater Flamingo have notably increased in size and occurrence range since the 1970s, and now it is one of the most abundant waterbirds in Mediterranean wetlands [11,16,17]. In Italy, it is a resident and migrant breeder of recent origin [18]. Its presence has gradually expanded along the Northern Adriatic Sea, from early breeding sites in Emilia-Romagna to the north, in the Venice Lagoon [19,20]. The growth of the population size has also been noted in the northernmost part of the Adriatic, the Friuli Venezia Giulia wetlands [20], with an increasing trend in frequency and individual numbers from 1554 in 2018 to 3134 in 2021 [21], particularly in the Marano and Grado Lagoon. The use of feeding habitats by the Greater Flamingo has been extensively studied at the Mediterranean scale [18,22-25], but data for Adriatic wetlands are limited [19]. The species mainly feeds or roosts in the large and open extensions of shallow tidal flats and in the basins of the several extensive fish farms, which characterize the Marano and Grado Lagoon ecosystem.

Here, we present a UAV (Unmanned Aerial Vehicle) image of a large field of donut-shaped depressions due to Greater Flamingo feeding activities (Figure 1). The UAV acquisition was carried out in May 2022, during a geomorphological monitoring activity on the Martignano barrier island in the Marano and Grado Lagoon.

The UAV survey was conducted with a DJI Phantom RTK connected to a reference stations network for real-time positioning correction. A total of 327 high resolution RGB images were taken at a flying altitude of 16 m. To increase further the precision in the georeferencing photogrammetric model, three Ground Control Points (GCPs) were strategically placed and measured with a NRTK-GNSS system. On GCPs, the accuracy was roughly sub-centimetric. This procedure allowed us to obtain a very detailed and accurate orthophoto and DTM (Digital Terrain Model) with a resolution of 4 mm/pix and 8 mm/pix respectively.

In the orthophoto, around 700 flamingo-feeding circles are visible, occupying an intertidal flat area with elevation between −0.2 and +0.5 m (mean tidal range 0.76 m; spring tidal range 1.05 m [26]) extending about 3500 m^2. The bedforms consist of an internal mound with a small dip in the centre and an exterior circular channel (Figures 1B and 2). The mean diameter of the circles is 1.07 ± 0.19 m ($n = 560$) with a difference in elevation between mound and channel of about 7.5 cm (Figure 1C). The surveyed habitat is part of a relict washover morphology on the Martignano Island's back-barrier (Figure 3). A storm in 2013 caused the barrier island to breach, resulting in the formation of a washover channel and a washover fan, i.e., a landfacing, sandy, deltalike landform (Figure 3B). The beach ultimately returned to its original configuration in 2021, after the washover channel had been fully filled and vegetated (Figure 3C). The sandy structure of the washover fan remains as a relict landform in the back-barrier area today, with a gentle topography that gradually joins the back-barrier tidal flats connected to a complex tidal channel network.

Greater Flamingos use several fish farms in the Marano and Grado Lagoon throughout the year as resting and foraging sites. It is reasonable to assume that individuals that normally inhabit nearby sites use this back-barrier intertidal habitat as a foraging area, similar to what occurs in the Venice Lagoon [19]. Although birds have not been spotted and the flock's size is unknown, we may presume that all of the structures were created at the same time. In fact, the morpho-structures were fresh, non-overlapping and well preserved at the time of the survey, possibly due to the very recent activity of pit foraging in an intertidal environment with a very high hydroperiod and scarce potential for conservation of ephemeral bedforms.

The presented case emphasizes the importance of coastal dynamics and episodic events (such as storm surges) in generating landforms and habitats (such as washover fans) that can support biodiversity in lagoon ecosystems. The use of UAVs in coastal surveys allows for the acquisition of high-quality, precise images that are easy to manipulate in order to obtain quantitative micro-topographic data. These methodologies can help us learn more about the Great Flamingo foraging behaviour and its role as an ecosystem engineer in environments with rapid morphological changes.

Figure 1. Pictures taken by an Unmanned Aerial Vehicle (UAV) of Greater Flamingo pit foraging bedforms in the back-barrier intertidal environment in the Marano-Grado Lagoon (Italy): (**A**) orthophoto of the sizeable pit aggregation field; (**B**) a close-up of the hi-res orthophoto; and (**C**) a close-up of the DTM (Digital Terrain Model) with a focus on an elevation profile.

Figure 2. Photos of the aggregation of Greater Flamingo's foraging structures.

Figure 3. A sequence of aerial photographs depicting the morphological changes involving the Martignano barrier island (Marano and Grado Lagoon, Italy). 2012 (**A**) shows that the beach is continuous. A washover channel and a washover fan are clearly visible in 2014 (**B**). The washover channel is totally filled and the beach has reverted to its usual linear configuration in 2021 (**C**) (UAV photogrammetric survey); the white box indicates the area surveyed by UAV in 2022 (centroid Coordinates: 45°42′17.80″ N; 13°10′04.62″ E).

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