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A standard procedure for dune mapping along the Bulgarian Black Sea coast: an integrated approach combining UAS photogrammetry, geomorphological and phytocoenological surveys

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Coastal dunes (CD) are dynamic environments shaped by sediment accumulation, sea breeze and vegetation cover, which are also highly sensitive to human intervention. The urbanization of coastal areas, global warming and rising sea levels pose significant threats to CD systems, leading to erosion and habitat loss. In the past decade, the total CD area in Bulgaria has decreased by over 12 hectares, resulting in the complete loss of five dune systems. Over 5% of the CDs along the Bulgarian Black Sea Coast (BBSC) face similar challenges, primarily due to human-induced pressure and alterations in dune landforms. This study introduces a Standard Dune Mapping Procedure (SDMP) for the BBSC based on geospatial data of dune habitats, facilitating the cadastral maps and registers and effective conservation and management activities. The proposed methodology, developed through the collaboration of the Ministry of Environment and Water of the Republic of Bulgaria, the Institute of Oceanology and the Institute of Biodiversity and Ecosystem Research at the Bulgarian Academy of Sciences, is a multidisciplinary approach that integrates remote sensing, geomorphological, geological and phytocoenological surveys and habitat analysis in GIS environment. The procedure involves seven stages: initial inventory and data collection to processing, classification, and high-resolution mapping of coastal dune habitats. The SDMP aims to support sustainable management and conservation of CD ecosystems by emphasizing low-cost, non-intrusive remote sensing techniques. A pilot application on the "Kavatsi" CD system (Sozopol Municipality, Burgas District) validates the SDMP's effectiveness in addressing the challenges of dune maintenance and anthropogenic impact. This comprehensive approach ensures accurate data collection and supports the development of sustainable management practices

for CD ecosystems. The proposed procedure offers a significant step forward to the systematic mapping of CD habitats, responding to the urgent need for effective conservation strategies in the face of significant degradation due to human activities. The SDMP thus plays a crucial role in the sustainable management and conservation of the Bulgarian Black Sea CDs.

KEYWORDS

coastal dunes, dune habitat, habitat mapping, unmanned aerial system (UAS), UAS photogrammetry, dune vegetation, coastal geomorphology, Bulgarian Black Sea coast

1 Introduction

The coastal zones hold significant importance due to the presence of various elements, including recreational/residential settlements and other infrastructure, opportunities for economic activities, sites for thematic/specialized tourism – for example, dunes as geomorphosites for geotourism, archaeological sites, different ecological/natural systems and their biodiversity, and etc., but notably, the beach-dune systems for sun/marine-bath tourism (Marrero-Rodríguez and Dóniz-Páez, 2022; Martínez et al., 2013; Johnston et al., 2023). The coastal dune landforms are situated at the interface between land and sea and are frequently shaped by anthropogenic activities and exposed to wave action (Arens et al., 2001; D’Alessandro et al., 2022; Fontán-Bouzas et al., 2022; Foti et al., 2021; Huggett, 2011; Milne et al., 2012; Prodanov et al., 2023; Rangel-Buitrago et al., 2023; Woodroffe et al., 2023).

The beach and coastal sand dune landforms are among the most dynamic environmental elements. The formation and development of CD systems are primarily influenced by three essential factors: the availability of sediment, wind patterns and the presence of vegetation (Aagaard et al., 2007; Costas et al., 2012; Delgado-Fernandez and Davidson-Arnott, 2011; Hesp, 2011, 2024; Masselink et al., 2014; Nordstrom, 2015; Psuty and Silveira, 2010; Pye, 1983). These systems are composed of sediments derived from both alluvial and marine sources, and they remain constantly influenced by a confluence of physical, chemical and biological agents, which play pivotal roles in their genesis and structural evolution. Additionally, dune mobility is also affected by other elements, such as storms and fluctuations in sea level, which can lead to alterations in sediment supply and vegetation (Feagin et al., 2005; Miller et al., 2009). The CD systems are characterized by their high dynamism, exhibit spatial and temporal variability, and are shaped by both natural forces and human activities (Anthony, 2013; Feagin et al., 2019; Pye, 1990; Sancho et al., 2011).

Beaches and dunes are essential natural features that act as buffers, reducing wave energy and protecting against storms and coastal flooding, as dune systems are typically found in flat coastal regions. They also support biodiversity, maintain ecological balance

and offer significant recreational and economic benefits, so thus, they are especially important for sustainable coastal management (Bridges et al., 2022). Dune systems (DS), in particular for the overall coastal region, are crucial due to their environmental and scenic values and also as they function as natural coastal defenses by storing sand and acting as a physical barrier to protect landward areas (Hanley et al., 2014; Sabatier et al., 2009). On the other hand, coastal urbanization and the challenges posed by global warming with the resulting rise in sea levels make coastal areas and, especially the CD, increasingly susceptible to both main threats - overdevelopment of the region and erosion (Gao et al., 2020).

1.1 Human impact and coastal dunes

The process of human intervention (anthropogenization), which began in the latter half of the previous century, and which had been primarily driven by urban expansion, industrial activities and tourism, has brought significant alterations to the natural and environmental characteristics of numerous coastal ecosystems (Aguilera et al., 2020; Calderisi et al., 2021; Catto, 2002; Ciccarelli, 2014; Martínez et al., 2008; Pinna et al., 2015; Prodanov et al., 2023; Syvitski et al., 2005; Wang et al., 2019; Yi et al., 2018; Zhai et al., 2020; Sytnik and Stecchi, 2014). This transformation has led to the exacerbation of erosive phenomena and the degradation of multiple DS (Barbaro et al., 2021; El Mrini et al., 2012; Martínez et al., 2013). According to the latest estimations, approximately 30% of the world’s coastlines are presently influenced by erosion (Luijendijk et al., 2018; Mentaschi et al., 2018; Vousdoukas et al., 2020). On a European level, the DS area decrease has been especially pronounced, with an imposing 70% (EEA, 2020). Additionally, it is essential to emphasize that the climate change impacts could exacerbate these coastal challenges, primarily through rising sea level (FitzGerald et al., 2008; De Figueiredo et al. 2018; Piazza Forgiarini et al., 2019; Reguero et al., 2019).

Due to the ecological importance of dune landforms, modern conservation biology focuses on their protection. So far, the conservation importance of dunes is recognized and exposed in conservation legislation at global, European and national levels, bound by the UN Global Convention on Biological Diversity (CBD, 1992, 2022) and formulated in the 2050 vision and 2030 mission in

Abbreviations: BBSC, Bulgarian Black Sea Coast; SDMP, Standard Dune Mapping Procedure; CD, coastal dunes; DS, dune systems.

the Kunming-Montreal Global Biodiversity Framework. In the European Union (EU), dune habitats are protected as they have been included in Annex I of the Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora, also known as the Habitats Directive (HD). The HD is the main EU legal framework that aims to protect a wide range of rare, threatened, and vulnerable habitats (those listed in Annex I of HD) by requiring each Member State to monitor the habitat range, area and status of its territory and regularly reporting on a six year-period to the European Commission (art. 17, [Council Directive 92/43/EEC, 1992](#)). In Bulgaria's last two HD Article 17 reports, coastal dune habitats have been assessed in "unfavorable poor" conditions because of the cumulative effect of various threats ([EEA, 2015, 2020](#); [European Commission, 2008](#)). In Bulgaria's national legislation, CDs are subjected to the Biological Diversity Act ([BDA, 2002](#)) and the Black Sea Coast Spatial Development Act of the Republic of Bulgaria ([BSCSDA, 2007](#)).

1.2 Dune mapping using remote sensing

Mapping and monitoring of CD are crucial for their evolution understanding and for assessment of their relation with the surrounding areas. Remote sensing methods have emerged as useful tools for dune mapping due to their non-destructive characteristic and ability to cover large areas efficiently. Among all the remote sensing techniques, drones have gained prominence for their cost-effectiveness, flexibility and high-resolution imaging capabilities.

Satellite imageries provide wide spatial coverage and temporal resolution suitable for monitoring of dune dynamics and over-time changes ([Al-Dabi et al., 1997](#); [Flores-de-Santiago et al., 2023](#); [Hugenholtz et al., 2012](#); [Mohamed and Verstraeten, 2012](#); [Mohammadpoor and Eshghizadeh, 2021](#)). Some recent studies have utilized multispectral and hyperspectral data to classify dune types and assess their spatial distribution within landscapes ([Fisher and Hesse, 2019](#); [Frati et al., 2020](#); [Zheng et al., 2022](#)). The integration of satellite-derived data with geographic information systems (GIS) facilitates the analysis of dune morphology and its relationship with environmental factors such as vegetation cover ([Andrews et al., 2002](#); [De Giglio et al., 2017](#); [Kozhoridze et al., 2022](#); [Marzialetti et al., 2019](#); [Medina Machín et al., 2018](#); [Sanjeevi, 1996](#); [van Kuik et al., 2022](#)).

Airborne LiDAR (Light Detection and Ranging) offers high-resolution elevation data, enabling detailed mapping of dune morphology and volume estimation. LiDAR-derived digital elevation models (DEMs) provide insights into dune topography and surface characteristics with high accuracy ([Doyle and Woodroffe, 2018](#); [Grohmann et al., 2020](#); [Pinton et al., 2022](#); [Sofonia et al., 2019](#); [Solazzo et al., 2018](#); [Woolard and Colby, 2002](#)). Furthermore, LiDAR data could be integrated with other remote sensing datasets for creation of comprehensive maps of CD habitats and for assessing their vulnerability to environmental changes ([Bazzichetto et al., 2016](#); [Doyle and Woodroffe, 2018](#); [Frati et al., 2020](#); [Hantson et al., 2012](#); [Lin et al., 2019](#); [Mahmoud](#)

[et al., 2021](#); [Sellars and Jolls, 2007](#); [Suo et al., 2019](#); [Valentini et al., 2020](#)).

However, among the various remote sensing methods, drones have emerged as particularly cost-effective and productive tools for dune mapping. The UAVs (Unmanned Aerial Vehicles) – drones equipped with high-resolution cameras, could capture detailed imagery of dune surfaces at varying spatial scales ([Pagán et al., 2019](#); [Turner et al., 2016](#)). The flexibility and affordability of drone-based surveys make them suitable for frequent monitoring of CD dynamics and rapid response to environmental events ([Caroti et al., 2018](#); [Casagrande et al., 2023](#); [Contreras-de-Villar et al., 2023](#); [Duffy et al., 2018](#); [Fabbri et al., 2021](#); [Flores-de-Santiago et al., 2023](#); [Gonçalves and Henriques, 2015](#); [Laporte-Fauret et al., 2019](#); [Mancini et al., 2013](#); [Papakonstantinou et al., 2016](#); [Rotnicka et al., 2020](#); [Scarelli et al., 2017](#); [Sofonia et al., 2019](#); [Solazzo et al., 2018](#); [Suo et al., 2017](#)). Moreover, drones offer a non-intrusive means of coastal dune habitat data acquisition, minimizing disturbances to fragile dune ecosystems and preserving their natural state ([Agrillo et al., 2023](#); [Bañón et al., 2019](#); [Carr, 2021](#); [Cruz et al., 2023](#); [De Giglio et al., 2019](#); [Fabbri et al., 2021](#); [Green et al., 2019](#); [Innangi et al., 2023](#); [Kotsev et al., 2020](#); [Laporte-Fauret et al., 2020](#); [Madurapperuma et al., 2018](#); [Marzialetti et al., 2021](#); [Prodanov et al., 2023](#); [Suo et al., 2019](#)).

Drones have emerged as the primary tool for mapping Bulgaria's coastline and dunes due to their cost-effectiveness and efficiency ([Prodanov et al., 2023](#)). For the accurate mapping of dunes along the BBSC, very high-resolution orthophoto mosaics with resolutions between 2 cm and 5 cm GSD and digital surface models (under 25 cm/pix) are essential ([Bekova and Prodanov, 2023](#); [Kotsev et al., 2020](#); [Prodanov et al., 2019a, 2019b, 2020a, 2021a, 2021b, 2023, 2024](#); [Prodanov, 2023](#); [Prodanov and Bekova, 2023, 2024](#)). Drones equipped with an advanced imaging sensor can fulfill this requirement, providing detailed imagery necessary for precise mapping and analysis. [Prodanov et al. \(2023\)](#) state that drone-based mapping has become the most economical and effective method for CD mapping in Bulgaria, offering some advantages compared to traditional ground-based surveys or satellite imagery methods. Finally, drones have revolutionized dune mapping by offering cost-effective, high-resolution solutions that minimize disturbance to sensitive environments. In Bulgaria, where CDs are under significant anthropogenic pressure, drone-based mapping has become the preferred method for accurately assessing dune dynamics and guiding the respective conservation efforts ([Prodanov et al., 2023](#); [Prodanov and Bekova, 2023, 2024](#)).

This paper presents a Standard Dune Mapping Procedure (SDMP) for the BBSC, the main purpose of which is the preparation and the maintaining of the so called "Specialized cadastral maps and registers", e.g., the CD maps according to the Bulgarian legislation for the Cadastral-Administrative Information System (CAIS). This methodology involves the integration of a wide range of methods, including geomorphological and geological surveys, precise geodetic measurements, a non-intrusive UAS-photogrammetric survey method and field phytocoenological studies on the spatial characteristics and species composition of the different phytocoenoses and habitats, related to CD.

1.3 Aim of the standard dune mapping procedure

The primary aim of the Standard Dune Mapping Procedure (SDMP) is to develop and apply a consistent, high-precision workflow for mapping CD habitats along the BBSC. The methodology was developed in response to the urgent need for accurate and up-to-date geospatial data on these habitats, which are increasingly threatened by intensifying human-induced pressures, especially from tourism.

The SDMP is specifically designed to support the needs of national environmental authorities, such as the Ministry of Environment and Water (MOEW), enabling the preparation and long-term maintenance of DS maps and dune registers. The delineation of the actual field DS and dune habitat types is essential for lawful and sustainable spatial planning in coastal zones, particularly with regard to the placement of tourist infrastructure and other construction activities on beaches. In the coming years, the SDMP will be used to actualize more than 250 cadastral maps. The proposed Methodology includes geomorphological and geological surveys, precise geodetic measurements, non-intrusive UAS photogrammetry, UAV LiDAR, and phytocoenological assessments integrated into a robust and efficient mapping workflow.

While the structure of the SDMP has been tailored to meet the specific legal and institutional requirements of the Bulgarian context, including the sequencing and types of surveys it mandates, it also offers a replicable model. The procedure that we propose could be transposed and adapted to other countries, e.g., the ones with similar-sized beach-dune systems, similar high-accuracy obligations of coastal mapping, and sustainable development and conservation efforts. By balancing globally accepted scientific practices with cost-effective remote sensing, the SDMP supports not only accurate mapping but also the enforcement of current environmental regulations and the development of new policies aimed at sustainable coastal management under increasing tourism and climate-related pressures.

2 Bulgarian Black Sea coastal dunes

2.1 Regulatory and definition

The legal basis for SD management and protection in Bulgaria stems from several key national documents. Article 18 of the [Constitution of the Republic of Bulgaria \(1991\)](#) postulates the coastal beach strip as exclusive state property, setting the foundation for regulatory frameworks that follow.

The [Black Sea Coast Spatial Development Act \(BSCSDA, 2007\)](#) provides the first legal definition of “sand dunes,” later refined in 2014, to reflect their formation through sea, land, and wind interaction. Although that is more comprehensive, the current definition remains limited from a geomorphological point of view, as it omits some CD sandy areas. Additionally, this Act

highlights the importance of psammophytic vegetation for identifying CD habitats, but it still excludes some vegetation types, such as humid dune slacks, from its latest amendments.

The [Biological Diversity Act \(BDA, 2002\)](#) offers a framework for the classification of CD habitats as natural habitats of conservation value for the European Union, listed in [Supplementary Appendix 1](#). This is supported by national and EU guidance documents, such as the [Interpretation Manual of EU Habitats \(2013\)](#) and the [Red Data Book of Bulgaria \(2015\)](#), [Kavrakova et al., 2009](#).

[Ordinance \(2008\)](#) under the BSCSDA mandates the creation and maintenance of “Specialized maps and registers” for coastal features that should be included in the Bulgarian Cadastral-Administrative Information System (CAIS). It provides a list of nationally presented CDs (e.g., embryonic, white, grey, humid slacks, wooded dunes) and formalizes a procedure for field-based identification, obligated the involving both coastal geomorphologists and vegetation experts appointed by the Ministry of Environment and Water.

In practice, the demarcation and classification of coastal sand dunes and dune habitats are conducted *in situ*. This process involves the collaboration of coastal geomorphologists and botanists-phytocoenologists, whom the Ministry of Environment and Water (MoEW) appoints. Their expertise is critical for the accurate identification and classification of the various dune types based on both their physical and ecological characteristics. This collaborative approach ensures a comprehensive understanding of the DS along the BBSC, facilitating their effective management and conservation.

The [Cadastral-Administrative Information System \(CAIS\)](#), managed by the Geodesy, Cartography and Cadastre Agency at the Ministry of Regional Development and Public Works, includes a thematic module for coastal features such as beaches and dunes based on Article 6 of the [BSCSDA \(2007\)](#). Although publicly accessible and comprehensive in scope, this module suffers from severe limitations.

Most notably, the mapping of CD is outdated and often inaccurate due to the absence of a standard procedure and the infrequent update cycle (once every ten years). Other difficulties also arise from using a parcel-based approach and inconsistent classification systems of the CAIS. These deficiencies complicate both conservation efforts and property rights enforcement. Thus, all these accumulated shortcomings of CAIS, specifically concerning its thematic module for beaches and dunes. Recent years of mapping activities highlight the need for a standardized dune mapping procedure (SDMP) to ensure accurate, consistent, and legally reliable data for coastal management.

2.2 Overview of coastal dunes along the Bulgarian Black Sea coast

In 2023, the Institute of Oceanology at the Bulgarian Academy of Sciences (IO-BAS) conducted an inventory and mapping of coastal DS along the BBSC, identifying 46 DS with a total area of 988 ha, extending a length of 73 km, or 14% of the total of 518 km coastline of Bulgaria ([Prodanov et al., 2023](#)) - [Figures 1A, B](#).

The depositional sandy area of the BBSC formed both primary and secondary DS, with varied geological, geomorphological and respective vegetation characteristics. Primary DS, incl. mainly embryonic dunes and foredunes, cover about 312 ha (32%) and are formed predominantly by aeolian processes, including wind-driven sand transport and deposition within pioneer vegetation communities. Secondary DS represent more mature and stabilized dune formations with approximately 676 ha area, formed initially by aeolian processes but later transformed into relict or fixed dunes due to vegetation development and the loss of direct sediment supply from the beach (Prodanov et al., 2023).

Dune systems in Bulgaria have been studied during the last decades (Passports of the Bulgarian Beaches, 1994; Kenderova et al.,

1999; Petrov, 2013; Valchev, 2014, 2015; Sinnyovsky and Sinnyovska, 2016, 2017; Prodanov et al., 2019a, 2019b, 2020b, 2021a, 2023, 2024; Baltakova, 2023; Prodanov and Bekova, 2024; Prodanov, 2023). These studies reveal the five dune habitat types along the BBSC, all of them protected under Supplementary Appendix 1 of the Biodiversity Act, including 2110 Embryonic shifting dunes, 2120 Shifting dunes along the shoreline with *Ammophila arenaria* (white dunes), 2130 Fixed coastal dunes with herbaceous vegetation (grey dunes), 2180 Wooded dunes and 2190 Humid dune slacks (for more information see Supplementary Appendix 1). The typical/characteristic plant species associated with each habitat type are summarized in Table 1. These dune habitats share the respective areas on the



FIGURE 1 (A, B) Location of the Bulgarian Black Sea coastal dune systems; (C–F) Aerial photographs of the Kavatsi case study area (an example of a heavily man-modified beach-dune system along the Bulgarian Coast).

TABLE 1 Typical plant species (short check list) for coastal dune habitats along the BBSC.

BSCSDA (2007)	Natura 2000 Habitats	Typical plants
Embryonic dunes	2110 Embryonic shifting dunes (incipient dunes)	<i>Ammophila arenaria</i> , <i>Argusia sibirica</i> , <i>Cakile maritima</i> subsp. <i>euxina</i> , <i>Crambe maritima</i> subsp. <i>pontica</i> , <i>Centaurea arenaria</i> , <i>Corispermum nitidum</i> , <i>Eryngium maritimum</i> , <i>Euphorbia paralias</i> , <i>E. peplis</i> , <i>Glaucium flavum</i> , <i>Hypocoum ponticum</i> , <i>Leymus racemosus</i> subsp. <i>sabulosus</i> , <i>Maresia nana</i> , <i>Medicago marina</i> , <i>Otanthus maritimus</i> , <i>Polygonum maritimum</i> , <i>P. mesembricum</i> , <i>Silene thymifolia</i> , <i>Stachys maritima</i> , <i>Salsola ruthenica</i> , <i>Suaeda altissima</i> .
White (shifting) dunes	2120 Shifting dunes along the shoreline with <i>Ammophila arenaria</i> (white dunes)	<i>Ammophila arenaria</i> , <i>Astrodaucus littoralis</i> , <i>Calystegia soldanella</i> , <i>Centaurea arenaria</i> , <i>Convolvulus persicus</i> , <i>Corispermum nitidum</i> , <i>Eryngium maritimum</i> , <i>Euphorbia paralias</i> , <i>E. seguierana</i> , <i>Festuca vaginata</i> , <i>Hypocoum ponticum</i> , <i>Leymus racemosus</i> subsp. <i>sabulosus</i> , <i>Linaria genistifolia</i> subsp. <i>genistifolia</i> , <i>Maresia nana</i> , <i>Medicago falcata</i> subsp. <i>tenderiensis</i> , <i>M. marina</i> , <i>Otanthus maritimus</i> , <i>Papaver rumelicum</i> , <i>Peucedanum obtusifolium</i> , <i>Polygonum maritimum</i> , <i>Secale sylvestre</i> , <i>Silene conica</i> subsp. <i>conomaritima</i> , <i>S. thymifolia</i> , <i>Stachys maritima</i> .
Grey (fixed) dunes	2130 Fixed coastal dunes with herbaceous vegetation (grey dunes)	<i>Alyssum borzaeanum</i> , <i>A. hirsutum</i> , <i>Artemisia campestris</i> , <i>Astragalus onobrychis</i> subsp. <i>skorpilii</i> , <i>Carex ligerica</i> , <i>Centaurea arenaria</i> , <i>Cionura erecta</i> , <i>Corispermum nitidum</i> , <i>Cynanchum acutum</i> , <i>Ephedra distachya</i> , <i>Erysimum diffusum</i> , <i>Galilaea mucronata</i> , <i>Jasione heldreichii</i> , <i>Jurinea albicaulis</i> subsp. <i>kilaea</i> , <i>Lepidotrichum uechtritizianum</i> (= <i>Aurinia uechtritiziana</i>), <i>Linaria genistifolia</i> , <i>Linum tauricum</i> subsp. <i>bulgaricum</i> , <i>Pancratium maritimum</i> , <i>Rumex tenuifolius</i> , <i>Scabiosa argentea</i> , <i>Silene euxina</i> , <i>S. thymifolia</i> , <i>Syntrichia ruralis</i> , <i>Teucrium polium</i> subsp. <i>vincentinum</i> , <i>Verbascum purpureum</i> .
	2190 Humid dune slacks	<i>Ceratophyllum demersum</i> , <i>Cladium mariscus</i> , <i>Juncus littoralis</i> (<i>Juncus acutus</i> subsp. <i>tommasinii</i>), <i>Lemma minor</i> , <i>L. trisulca</i> , <i>Myriophyllum spicatum</i> , <i>Phragmites australis</i> , <i>Potamogeton crispus</i> , <i>P. pectinatus</i> , <i>Scirpus lacustris</i> , <i>Typha angustifolia</i> .
Wooded dunes	2180 Wooded dunes	<i>Carpinus orientalis</i> , <i>Dactylis glomerata</i> , <i>Fraxinus ornus</i> , <i>F. oxycarpa</i> , <i>Quercus cerris</i> , <i>Q. frainetto</i> , <i>Q. pubescens</i> , <i>Q. robur</i> , <i>Ruscus aculeatus</i> , <i>Hedera helix</i> , <i>Periploca graeca</i> .

Bold values indicate habitat codes under Annex I of the EU Habitats Directive.

BBSC: shifting (incipient) dunes (68.3 ha, 6.91%), shifting (white) dunes (150.3 ha, 15.21%), fixed (grey) dunes (546.27 ha, 55.28%), wooded dunes (222.61 ha, 22.53%) and humid dune slacks (0.94 ha, 0.09%) (Prodanov et al., 2023). About 70% of these habitats are within the Natura 2000 network (Gushev and Tzonev, 2015).

3 Standard dune mapping procedure along the Bulgarian Black Sea coast

Why is a Standardized Mapping Procedure needed? The coastal DS along the BBSC have experienced degradation, which is predominantly driven by human-induced pressures, such as urbanization, construction of hydraulic structures and intensified recreational use (European Environmental Agency, <https://cdr.eionet.europa.eu/>). These processes have disrupted the natural evolution of the DS, resulting in a considerable reduction in their area to 988 ha, representing 0.0089% of Bulgaria's land territory, and for a decade, the dune systems have diminished by over 12 ha, with five of them entirely lost. Over 5% of the CD is currently exposed to permanent anthropogenic impacts (Prodanov et al., 2023).

As a primary factor for this unfavorable trend, the initial inaccuracy and incompleteness in the mapping of DS procedure according to the Bulgarian legislative documents should be considered. Between 2012 and 2023, large portions of the coastal dunes were not mapped, and, respectively, they have not been included in the government Cadastral-Administrative Information System (CAIS), which contributed to their neglect and

subsequent degradation (Prodanov et al., 2023). The persistent decline in the condition of CD and the critical gaps in their documentation have been alarmed by Bulgarian scientists (Tzonev et al., 2005; Gushev, 2015; Tzonev, 2015a, 2015b, 2015c, 2015d, 2015e; Tzonev and Gushev, 2015; Valcheva et al., 2018, 2020, 2021; Prodanov and Bekova, 2024; Prodanov et al., 2023), highlighting the urgent need for a standardized approach.

In response, the Ministry of Environment and Water (MoEW) has involved the Institute of Biodiversity and Ecosystem Research (IBER-BAS) and the Institute of Oceanology (IO-BAS) to collaboratively design a comprehensive, high-resolution mapping methodology for coastal dune habitats to ensure consistent and scientifically grounded representation and management of these sensitive ecosystems. By adopting a unified methodology, the SDMP will provide a reliable foundation for documenting the current state of dune systems and support informed decision-making for their conservation and sustainable use.

The SDMP represents a foundational framework established by the Ministry of Environment and Water (MoEW) of the Republic of Bulgaria with the support of IBER-BAS and IO-BAS, and Sofia University "St. Kliment Ohridski" from the scientific team of MapBGBeachDune project. This workflow proposes a minimum required surveys, yet a comprehensive set of research surveys, including remote sensing, geomorphological, geological, phytocoenological analyses, and Geographic Information System (GIS) analysis, based on best practice of successful dune surveys in the anthropogenic environment (Meshinev et al., 1994; Tzonev et al., 2005, 2015; Gushev and Tzonev, 2014; Janssen et al., 2016; Tashev et al., 2017; Vladimirov and Petrova, 2018; Marcenò et al.,

2018; Valcheva et al., 2018, 2020, 2021; Prodanov et al., 2019a, 2019b, 2021a, 2021b, 2023; 2024; Prodanov, 2023; Prodanov and Bekova, 2023; Bekova and Prodanov, 2023; Kotsev et al., 2020), visualized in Figure 2. The aim is to ensure a sustainable, fast, accurate, and detailed approach to mapping protected dune habitats.

3.1 Stage 1: inventory and archive data

Before embarking on field research, an initial inventory and previous (archival) review of existing data are conducted (Figure 2). This foundational step is critical for the following:

Establishing baselines: Gathering and reviewing historical data (e.g., old topographic maps, aerial photographs), previous geomorphological and environmental studies, satellite imagery from various sources, and time series available through platforms such as Google Earth. The satellite data include high-resolution images from the Google Earth Engine archive, providing visual records from the early 2000s to the present. Historical and thematic maps were sourced from Bulgarian national repositories and institutions, such as the Military Topographic Service, the Geocardfund of BAS and the Cadastre Agency. These materials help to establish a baseline spatial distribution of dune landforms over time;

Identifying gaps and GIS database organization: Through the inventory, gaps in the existing data are identified, which helps in planning the subsequent field research more effectively. Organizing and archiving these data in a systematic manner ensures easy access and reference throughout the project.

3.2 Stage 2: field research and data collection

The initial stage involves comprehensive field research and data collection (Figures 2, 3). This preparatory phase includes the summation of currently available data to establish a baseline for new findings. The field research encompasses:

3.2.1 UAS photogrammetry and LiDAR technology

High-resolution unmanned aerial system (UAS) surveys are conducted using RTK-equipped drones, ensuring geospatial precision compliant with national standards and photogrammetric best practices (Prodanov et al., 2023). Flights are planned with the overlapping nadir and oblique images ($\geq 80/70\%$) to generate accurate orthophotomosaics and digital surface models (DSMs).

Recommended flight heights typically range between 60 and 120 meters above ground level (AGL), depending on the terrain complexity, desired spatial resolution, and vegetation density. A flight altitude of 60–100 m AGL is optimal for beach-dune systems, allowing for a balance between wide-area coverage and high spatial resolution. The spatial resolution (ground sampling distance – GSD) must meet or exceed 3–5 cm for orthophotos and 20–25 cm for DSMs in order to ensure a sufficient level of detail suitable for subsequent manual object-based image analysis (OBIA) workflows in later stages of the SDMP. The UAVs should be equipped with cameras capable of at least 20 MP resolution and high optical quality. Global or mechanical shutters are encouraged

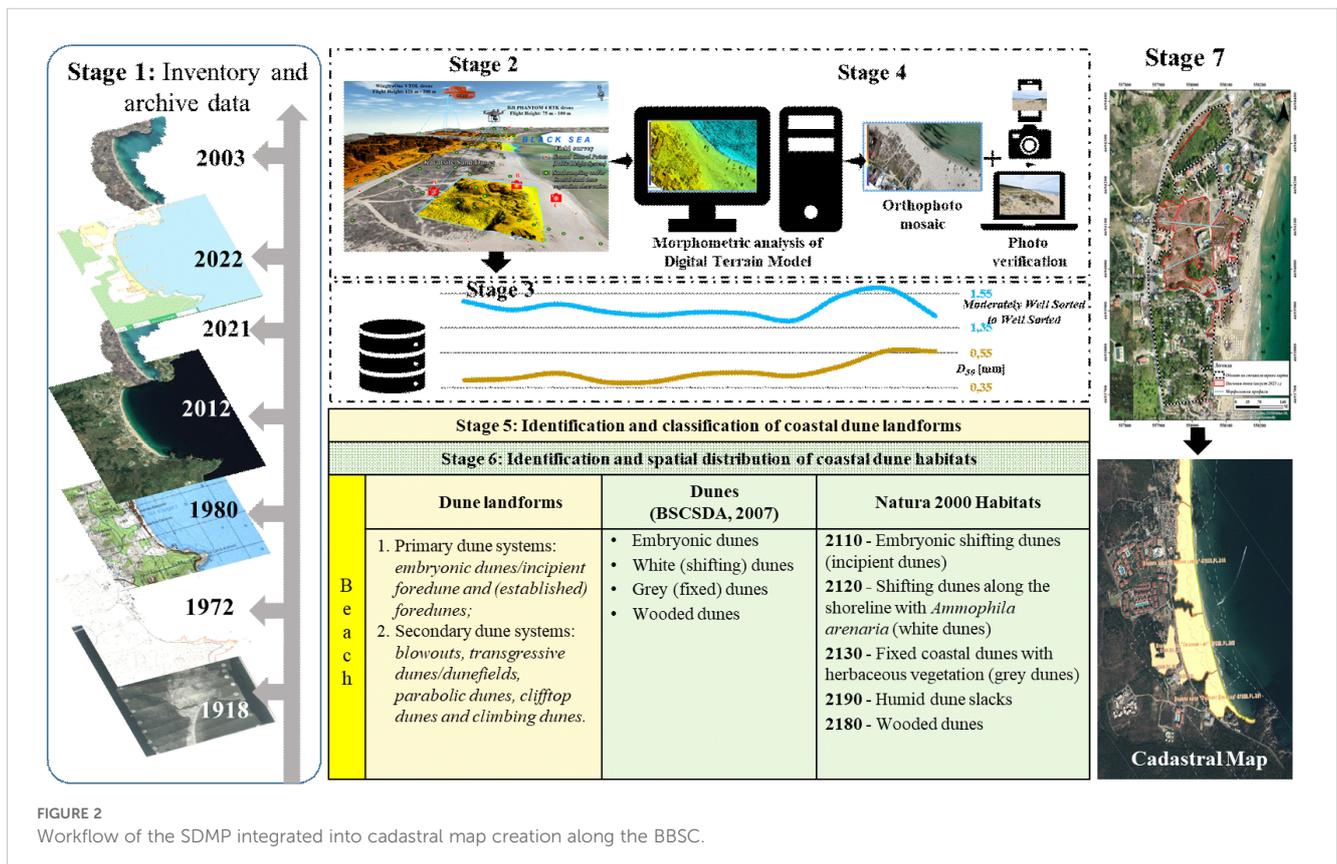


FIGURE 2 Workflow of the SDMP integrated into cadastral map creation along the BBSC.

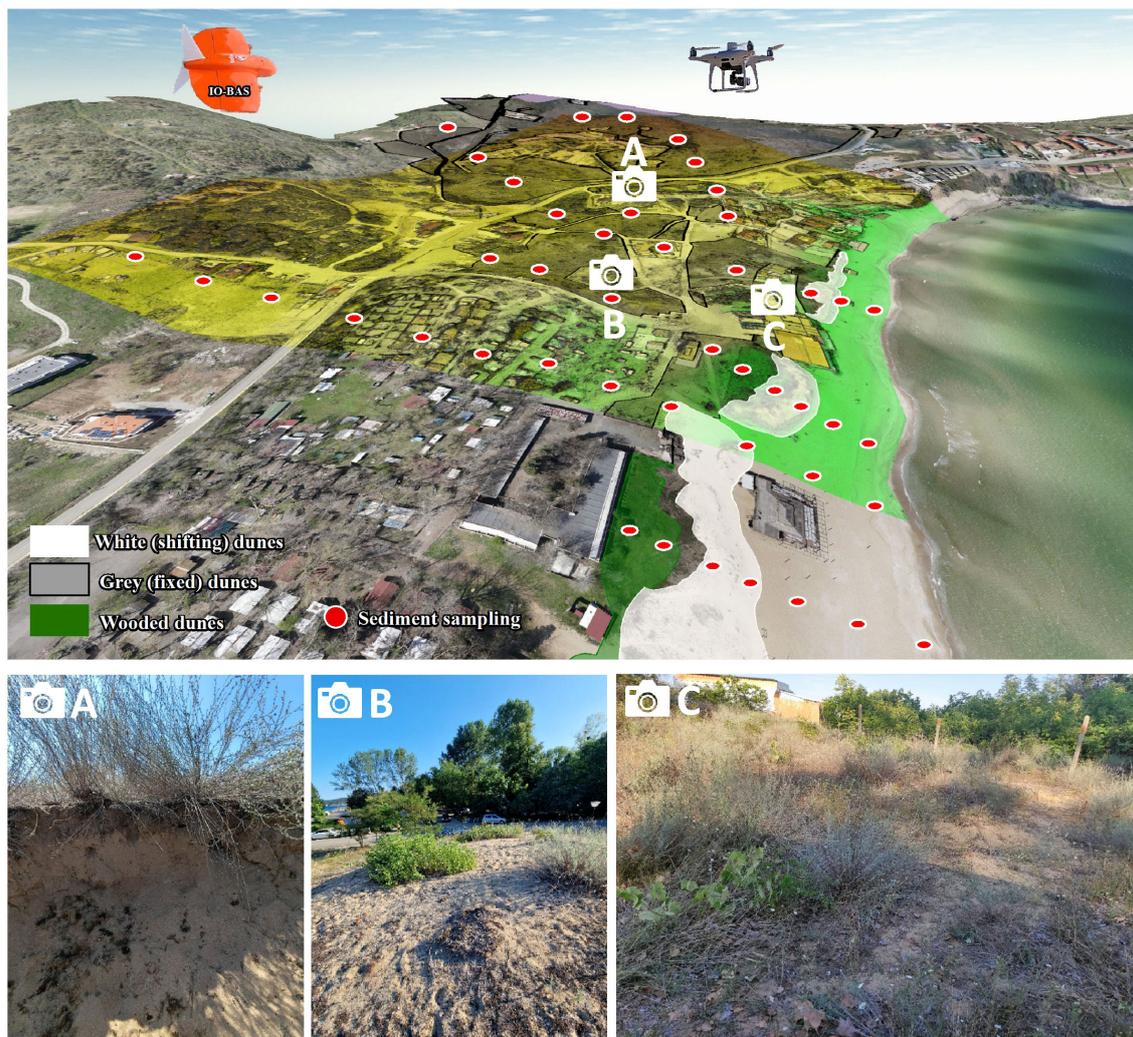


FIGURE 3

Three-dimensional visualization of different stages in the standard procedure of dune mapping along the BBSC (A – sand dune field profile with *Centaurea arenaria*, *Artemisia campestris*/grey dunes/; B – dune crest with *Cionura erecta*, *Scabiosa argentea*, *Artemisia campestris*/grey dunes/C – dune field with *Artemisia campestris*, *Scabiosa argentea*, *Paliurus spina-christi*, *Vitis sylvestris*/grey dunes/).

to reduce motion blur. The preferred flight mode is autonomous grid-based flight using pre-programmed waypoints with terrain-following capabilities. This ensures consistent altitude and overlaps across variable topography, which is particularly useful for dynamic and undulating dune landscapes.

When economically and technically feasible, UAS-LiDAR is integrated to enhance vertical accuracy and penetrate sparse vegetation cover, significantly improving topographic modeling of complex terrains, especially in vegetated grey and wooded dunes (Grohmann et al., 2020; Lin et al., 2019; Pinton et al., 2022). LiDAR data also supports volumetric analyses of dune migration and erosion/accretion trends (Frati et al., 2020). Despite its technical advantages and global recognition as a “gold standard” in terrain modeling, the application of LiDAR in Bulgaria remains limited. This is primarily due to the sensitive nature of high-resolution elevation data in the context of national security, particularly along the Bulgarian Black Sea

coast, where military and strategic considerations impose restrictions on aerial scanning technologies. As such, the integration of LiDAR-based approaches is still emerging and must be aligned with national geospatial policies and security frameworks.

3.2.2 GPS and ground control measurements

The accuracy of digital surface models and raster orthophotomosaics is a priority goal in the proposed UAS approach. This implies the use of reference and control geodetic points. The control measurements are made with RTK GPS, providing high enough coordinate accuracy through a certified RTK network in Bulgaria. The achieved horizontal accuracy of 2 cm and height accuracy of 3 cm guarantee high spatial reliability of the conducted surveys.

Measurements are supported by topographic profiles and photographic documentation. All dune elements are systematically analyzed along geomorphological cross-shore profiles, which also serve

dual purposes: they guide the selection of geological sampling locations and act as spatial control references during photogrammetric processing. Where feasible, drone-based 3D modeling is complemented with handheld GPS tracking and elevation benchmarks to further refine positional accuracy and feature delineation. In areas where drone imaging is not conducted due to technical, logistical, or regulatory limitations, GPS-based data acquisition is mandatory to ensure full spatial coverage and consistency of the recorded dune morphology.

3.2.3 Geomorphological survey

Identification and documentation of beach-dune system characteristics (beach face, beach face crest, summer berm, high beach winter berm, seaward dune slope, the crest and lee slope of the primary dune, a transition zone between primary and secondary dunes, middle sections of secondary dunes and the end of the secondary dunes).

3.2.4 Geological sampling

The collection is performed in transects perpendicular to the coastline. In addition to these standard cross-shore transects, sampling is also carried out in locations where a distinct transition from sandy substrates to sand-dominated soils (such as Arenosols) is observed, which is critical for substrate differentiation. Sediment is extracted from fixed geomorphic units (beach face, berms, dune slopes, crest, slacks) using standardized core samplers (Figure 3).

3.2.5 Phytocoenological survey

Detailed field observations to identify typical plants and plant communities in dune habitats and their potential spatial distribution. The process includes the collection of data and

photographs on the floristic composition and structure of plant communities, their spatial occurrence and projective cover, the presence of invasive species in plant communities consistent with the phenological characteristics of species and communities, as well as the presence of threats and impacts.

3.3 Stage 3: processing of acquired data

The processing stage involves:

UAS data processing with photogrammetric software: generation of digital surface models (DSM) with minimum 20 cm/pix resolution and very high-resolution raster orthophotomosaics (GSD: 3÷5 cm/pix) – Figure 4;

Phytocoenological data processing: Analysis of field data on plant communities, e.g., total vegetation cover, presence and cover of typical (characteristics) plant species, overall floristic composition and structure of plant communities and their spatial occurrence, presence and cover of invasive species, etc.;

Sedimentological analysis: Examining sediment profiles from various sections of the beach-dune system. The sediment stations are necessarily classified according to the Wentworth grain-size scale (Wentworth, 1922) or other classification if needed (Figure 5).

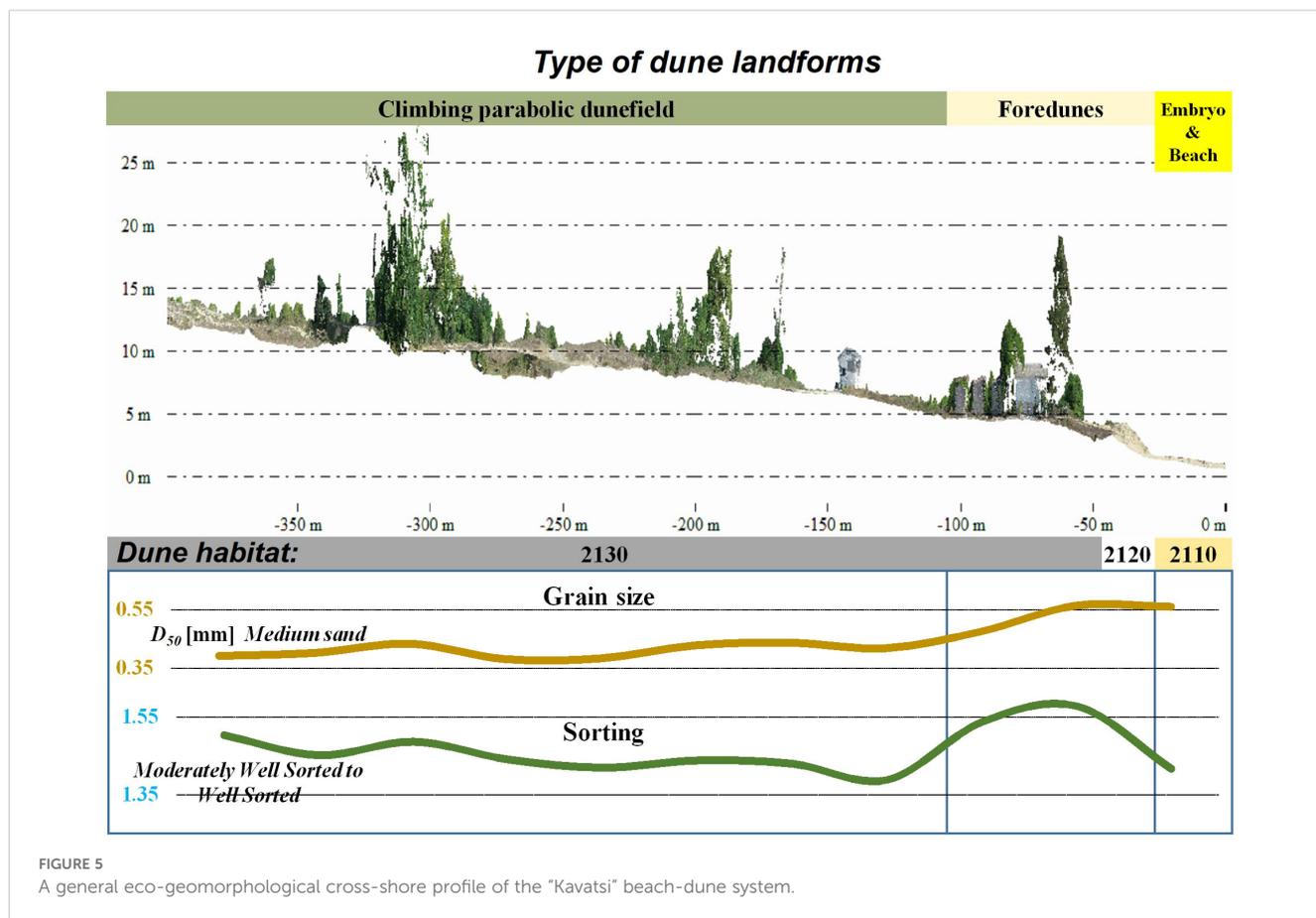
3.4 Stage 4: GIS procedures and analyses

3D modeling and morphometric analysis of DSM/DTM for landform identification using GIS tools (Figure 6);

Orthophoto analysis: Examination of image data from baseline to present time, aiding in understanding temporal changes and texture interpretation.



FIGURE 4
Photogrammetry processing of UAS data (location of aerial images and ground control points) in agisoft metashape software.



3.5 Stage 5: identification and classification of coastal dune landforms

The methodology includes applying a manual object-based image interpretation approach to delineate geomorphological landforms. The process involved visual analysis of high-resolution drone imagery, where similar landform features were identified and digitized based on their shape, texture, pattern, and contextual relationships. Field data are used to support and validate the interpretation. This stage involves classifying the coastal dune landforms (Figures 7A, B) based on their location and geomorphological types (Sloss et al., 2012; Masselink et al., 2014; Prodanov et al., 2023; Hesp, 2011, 2024), such as:

- Primary DS: embryonic dunes/incipient foredune and (established) foredunes;
- Secondary DS: blowouts, transgressive dunes/dunefields, parabolic dunes, cliff-top dunes, and climbing dunes.

3.6 Stage 6: identification and spatial distribution of coastal dune habitats

According to current methodological standards, GIS processing of phytocoenological data must ensure the differentiation of distinct

dune habitat types based on their physiognomic characteristics, biophysical structure, and floristic composition. Habitat polygons are to be delineated through manual interpretation and spatial analysis within GIS environments such as QGIS, ArcGIS Pro, Global Mapper, etc.

Habitat classification is required to follow a hybrid approach, which combines supervised manual object-based image classification with field-verified data. This classification must adhere to the definitions provided in the Interpretation Manual of European Union Habitats (IMEUH, 2013) and Annex I of the Bulgarian Biodiversity Act (BDA). Dune habitat types are to be discriminated using a combination of spectral texture, vegetation structure and species composition, ensuring compliance with EU and national standards for habitat mapping and reporting (Table 1; Figure 7C).

3.7 Stage 7: creation of a high-resolution map of dune habitats

The final stage is the creation of a high-resolution map of the coastal dune habitat at a 1:1000 scale (Figure 7C). This involves integrating all collected data, designing the map layout, accurately representing features, and ensuring the map's clarity and accuracy. Implementing these minimal research requirements in the SDMP significantly enhances data reliability regarding dunes. The



FIGURE 6
Three-dimensional photorealistic tiled model of the heavily modified central sector of the “Kavatsi” beach-dune system.

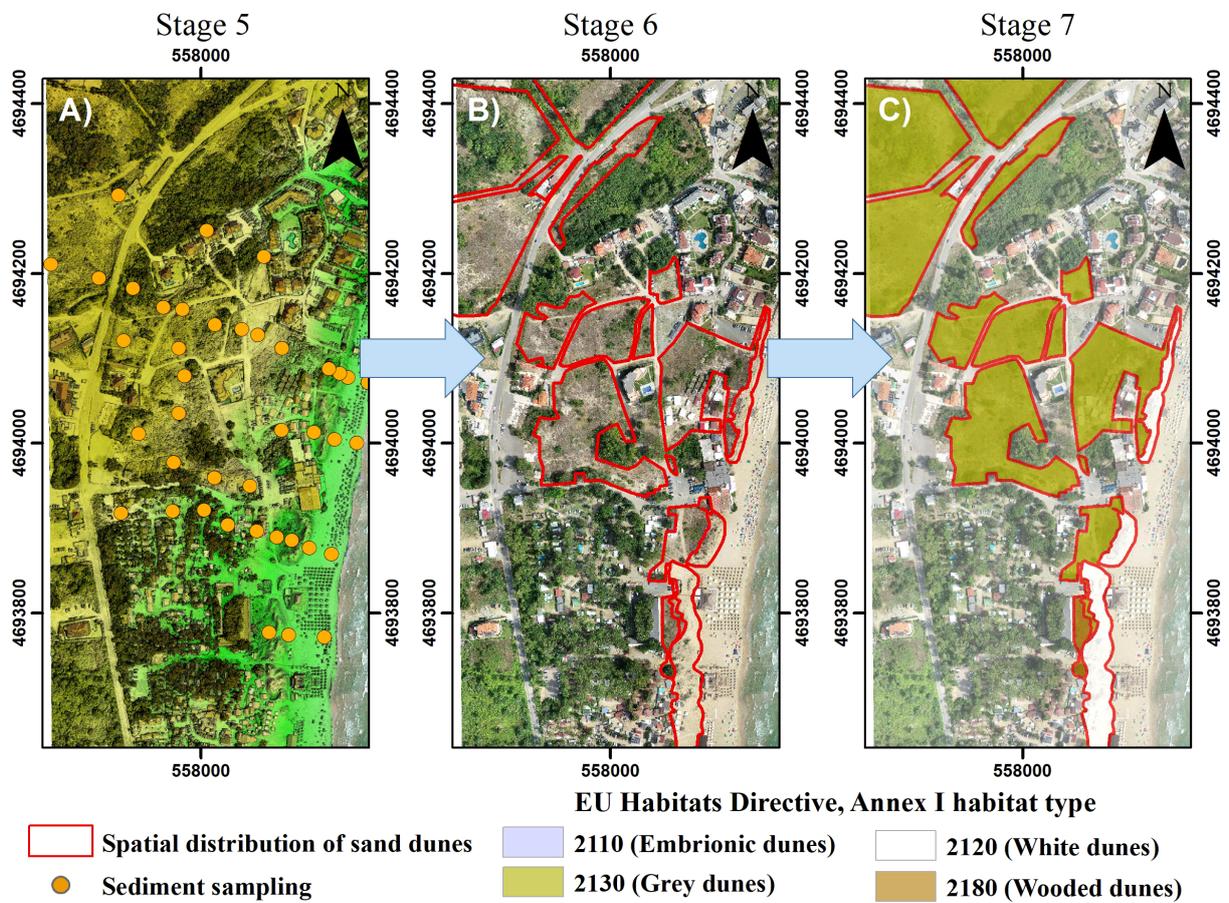


FIGURE 7
Producing data for the spatial distribution of coastal dune landforms and dune habitat for the creation of a special cadastral map along the BBSC. (A) Digital surface model from UAV photogrammetry; (B) Identified coastal dune landforms; (C) Map of dune habitat types.

implementation of these research requirements ensures the authenticity of data, contributing to a more informed and involved society in coastal management and conservation efforts. The creation of high-resolution maps of dune forms and habitats, as guided by the SDMP, serves crucial purposes, including cadastral mapping and habitat protection. By establishing a comprehensive and systematic approach, this workflow facilitates accurate and detailed mapping and fosters greater public trust in the scientific community and the process of dune cartography.

4 Results

The implementation of the SDMP, employing a drone-based methodology, facilitated the acquisition of a digital elevation model and orthophoto mosaic at a very high resolution. This approach ensured the acquisition of precise geospatial data concerning the distribution of CD. Supervised by coastal geomorphologists and botanist-phytocoenologists, the procedure consisted of multiple important stages aimed at investigating both geomorphological conditions and dune habitat types. The efficacy of this approach was evident as it emerged as an indispensable tool for the mapping and re-mapping of dunes, particularly in contentious dune areas, to address and offer sustainable solutions to dune maintenance challenges.

4.1 Pilot showcase: the Kavatsi dune system

The selection of the “Kavatsi” dune system as a pilot area for applying the methodology was proposed by MoEW under cadastral procedure within the region. This dune system is a prominent example of the profound modifications induced by human activities. Geomorphologically, the study area stands out due to its unique climbing type of DS, which is characteristic of the Medni Rid coastal region. The dune field’s climbing transgressive type is influenced by complex geomorphological and geological conditions, with the coastal settings comprising Middle Jurassic neointrusions to the south and Upper Cretaceous volcanic formations to the north. The beach strip primarily consists of Holocene and Quaternary fluvial materials (Petrova et al., 1994a, 1994b), with the sand composition being predominantly carbonate-quartz. The genesis of the beach is attributed to the movement of carbonate sand from adjacent underwater coastal slopes, as well as abraded material from cliff sections at Budjaka and St. Agalina localities.

In the Kavatsi DS area, dunes have been observed in the forefront of a foredune zone, which has long been anthropogenized by buildings, housing estates, restaurants, etc. (Figures 1C–F, 6). This dune system is a contact zone of interaction of natural processes and habitats, especially those of nature-conservation significance, human interventions, and economic and recreational interests. Unfortunately, different types of constructions or other placement of tourist infrastructure on the dunes, as well as the development of roads and parking lots, have been permitted for numerous years, leading to a loss of over 23% of its area in the past

century (Prodanov et al., 2023). Following numerous alerts to the Ministry of Environment and Water regarding mapped secondary dunes, an initiative was undertaken to update the “Specialized cadastral map and registers” for the “Kavatsi-North” DS.

Dune landforms are integral components of specialized maps and are subject to mapping at a scale finer than 1:1000. The SDMP was executed with a specific focus on mapping the highly anthropogenized section within the secondary dunes (Figure 8). During the pilot application of SDMP in 2023, minimal variations in sediment grain size were observed. The primary dune system exhibited small width and dune size, with substantial anthropogenization of the foredunes, where numerous structures were differentiated. Embryonic dunes were found in a narrow strip in front of the foredune toe, susceptible to annual destruction due to sand rake-up activities and tourist foot traffic on the beach. The secondary dune system comprised a climbing transgressive dunefield spanning from 6 meters above sea level to 61 meters above sea level (Figure 8).

For the first time along the BBSC, an interdisciplinary team successfully mapped CD at a scale of 1:1000 using a very high-resolution UAS orthophotomosaic. The completion of this ambitious task has led to the development of a comprehensive map that accurately outlines the unique and diverse dune habitats (Figure 8).

4.2 Assessment advantages and limitations of methods

The proposed SDMP for the BBSC represents a significant step forward in addressing the urgent need for accurate and comprehensive mapping of coastal dune habitats along the BBSC. Based on analyses of the showcase results, this assessment aims to analyze the methods integrated into the SDMP and their goals, strengths, weaknesses, advantages, and limitations.

4.2.1 UAS Photogrammetry

The use of UAS photogrammetry in RTK mode aims to achieve high-accuracy and high-resolution imagery of beach-dune systems for detailed mapping. This method enables rapid data acquisition, facilitates timely mapping efforts and provides detailed visual data for analysis and interpretation. It offers flexibility in survey planning and execution, allowing for adjustments based on real-time observations. Additionally, it can be integrated with other survey techniques like LiDAR for comprehensive analysis. This method is cost-effective and efficient for data collection over large areas, allowing for the creation of detailed digital surface models (DSM) and orthophotomosaics. However, it is restricted by regulations governing drone usage and airspace restrictions. Challenges may arise in areas with dense vegetation or complex terrain, affecting data coverage and accuracy. Accurate georeferencing and model generation require careful consideration of data processing techniques. Weather conditions, such as high winds, can impact drone stability and data quality. Skilled personnel for operation and data processing are required.

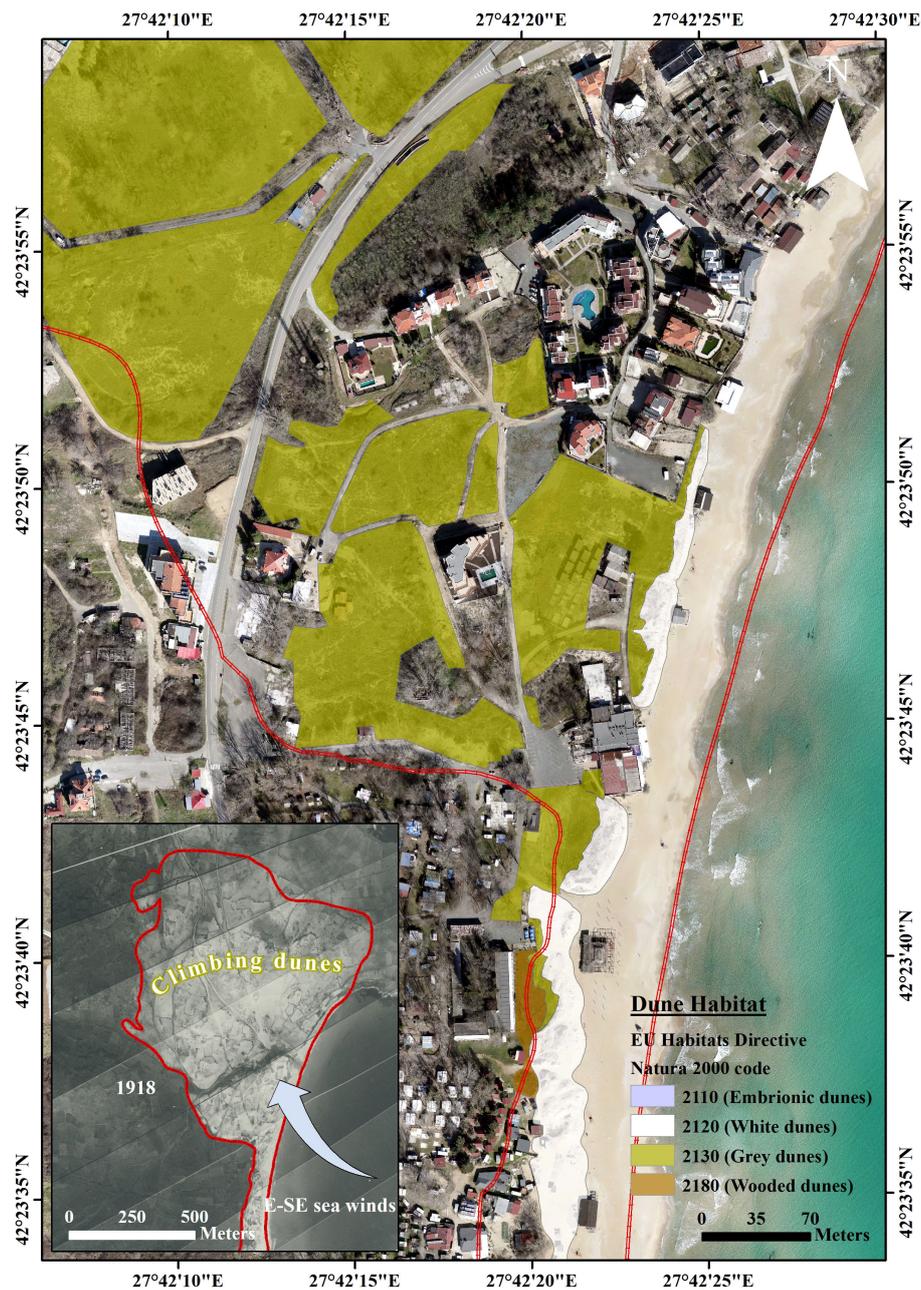


FIGURE 8

A final high-resolution map at a scale of 1:1000 of the remaining coastal dune habitats at the Kavatsi dune system, southern BBSC (archive data – [Aerial photographs, 1918](#), present undisturbed dune area).

4.2.2 Geomorphological survey

The geomorphological survey aims to identify and document various characteristics of beach-dune systems to understand their morphological characteristics. The method uses direct visual observation and documentation of landforms and sedimentary features, providing ground truth data for validating digital results from remote sensing. It provides detailed insights into the geomorphological features of CD, facilitating the identification of basic landforms and their spatial distribution. This method supports the assessment of dune stability and vulnerability to environmental changes. On the other hand, it relies on field personnel with expertise in

geomorphology and sedimentology. Accurately delineating subtle landform boundaries may be challenging, and the scale and resolution of observations may limit spatial precision. This method is labor-intensive and time-consuming, particularly for large study areas, and subjectivity is possible in the interpretation of field research, as evidenced in previous mappings in Bulgaria. Accessibility constraints in remote or hard-to-reach terrain may also pose limitations.

4.2.3 Geological sampling

Geological sampling aims to characterize sediment properties and define the spatial boundaries of sand substrates within beach-

dune systems. This method offers quantitative data for granulometric, mineralogical, or geochemical analysis, enabling comparisons with regional sedimentary records to infer broader environmental trends. It supports the assessment of sedimentological controls on coastal dune formation and evolution, providing essential data on sediment composition, grain size distribution, and stratigraphy. This method also supports the identification of sediment sources, transport pathways, and depositional environments, facilitating the interpretation of past environmental conditions and depositional settings. However, field sampling techniques may disturb or alter sediment structures. Challenges may arise in distinguishing between primary and reworked sedimentary deposits, and the availability of sampling equipment and logistical constraints may limit the method. Careful selection of sampling locations is necessary to ensure representative coverage, and sampling biases, such as preferential collection of certain sediment types, may occur. Additionally, the depth of sedimentary deposits accessible for sampling may be limited.

4.2.4 Phytocoenological survey

The phytocoenological survey aims to characterize plant communities within coastal dune habitats and assess their spatial distribution and ecological dynamics. This method observes ecosystem functioning, resilience, and response to environmental changes. It supports habitat mapping and conservation planning efforts and successfully integrates with remote sensing data for landscape-scale analysis. The survey provides valuable information on plant species composition, diversity and abundance, supporting the identification of habitat types. However, field observations may be biased by sampling methods or observer subjectivity, and accurately delineating vegetation boundaries in heterogeneous landscapes may be challenging. Good floristic and taxonomic expertise is required for accurate species identification and vegetation classification. The temporal variability in vegetation phenology and community dynamics may affect the survey. Site-specific factors, such as microclimate and substrate properties, may influence the results and the availability of reference datasets for species identification and habitat classification may be limited.

4.2.5 GIS procedures and analyses

GIS procedures and analyses aim to integrate spatial data from various sources, conduct morphometric analysis and create high-resolution maps of coastal dune habitats. It enables the creation of customized maps for specific applications and stakeholders, supporting 3D modeling and morphometric analysis for landform identification. GIS procedures provide orthophoto analysis and temporal change detection tools, enabling spatial data integration and analysis for multi-layered mapping. However, this method relies on the availability of high-quality spatial datasets for accurate analysis and may require substantial computational resources for processing large datasets. The spatial resolution and accuracy of input data sources may limit the method, and specialized software and technical expertise for data processing and analysis are required. Data interoperability and compatibility challenges between different formats may occur, and errors introduced during data manipulation and geoprocessing may affect the results.

5 Discussion

5.1 Applicability of the procedure

The proposed procedure for mapping beaches and dunes along the BBSC was developed within the framework of the Black Sea Coast Spatial Development Act of the Republic of Bulgaria (BSCSDA, 2007) and its associated regulation (Ordinance No. 1/2008). This legal and methodological foundation is essential for the production and maintenance of authoritative spatial data for coastal DS. The procedure not only aligns with national objectives for spatial data standardization and conservation but also meets interdisciplinary and cross-sectoral requirements. Its integration of geomorphological and phytocoenological methods reflects best practices in coastal habitat mapping, where both physical form and ecological function are essential for the correct classification (Laporte-Fauret et al., 2020; Innangi et al., 2025). Given the dynamic nature of coastal dunes and their status as priority habitats under both national and European legislation, robust, legally compliant mapping is indispensable. Furthermore, as Bulgarian legislation is harmonized with EU directives like the Habitats Directive, the adoption of standard procedures such as SDMP promotes international coherence in coastal governance.

5.2 Evaluating the adaptability and impact of the SDMP

5.2.1 Effectiveness of used methods in SDMP

The successful pilot application of the SDMP on the heavily human-impacted “Kavatsi” DS demonstrates its robustness and adaptability. By integrating multidisciplinary methods, including UAS photogrammetry, geomorphological field surveys, and GIS-based analysis, the SDMP is capable of capturing the complex interactions among physical landscape features, vegetation patterns, and human pressures. High-resolution UAS photogrammetry has proven to be an efficient, non-invasive, and cost-effective tool for producing spatially accurate data even in challenging terrain (Suo et al., 2019). These outcomes are consistent with international best practices in coastal dune monitoring, as evidenced by Cruz et al. (2023), who highlight the potential of UAVs for fine-scale habitat classification and temporal monitoring. In parallel, Ma et al. (2024) developed a comprehensive method that integrates LiDAR, GNSS, and remote sensing for evaluating coastal dune evolution, an approach methodologically aligned with the SDMP. This compatibility not only validates the SDMP’s interdisciplinary structure but also highlights its potential for integration into broader frameworks for coastal zone monitoring and management.

Moreover, the SDMP reflects emerging ecological perspectives on dune morphology and function. The emphasis on species-level vegetation assessments and structural-functional characteristics, such as those discussed by Hacker et al. (2019), aligns with a growing body of evidence that dune-building vegetation plays a critical role in sediment dynamics and dune stability. By incorporating these insights, the SDMP enhances its ecological

relevance and paves the way for its further development through the integration of functional trait-based mapping and vegetation-climate-sediment interactions.

5.2.2 Replicability of SDMP

A central strength of SDMP is its standardization, enabling consistent application across over 46 beach-dune systems, separated into 250 cadastral maps on the BBSC. By ensuring uniform methods for UAS data collection, geomorphological and vegetation analysis, and GIS-based interpretation, the procedure facilitates not only temporal monitoring but also spatial comparisons critical for coastal management (Guisado-Pintado et al., 2019; Almonacid-Caballer et al., 2025). This level of standardization also aligns with international trends toward scalable dune monitoring (Cruz et al., 2023; Marzietti et al., 2021), though site-specific calibration may be necessary for geomorphologically distinct regions (Tysi ac et al., 2025). Alarming losses documented in recent years along the BBSC, driven by urban expansion, recreational overuse, and tourism, underscore the urgent need for updated dune mapping (Prodanov et al., 2023). As seen in other European regions, high-resolution drone monitoring can uncover subtle but ecologically significant degradation patterns (Laporte-Fauret et al., 2020; Pinton et al., 2022). Moreover, multi-temporal drone surveys enhance the detection of dune mobility and vegetation succession, supporting restoration planning (James et al., 2024).

5.2.3 Addressing human-induced impacts

In examples like “Kavatsi” DS, where human pressures are acute, fine-scale UAV data and field-based surveys enable precise detection of unauthorized development, vegetation degradation, and habitat fragmentation. The SDMP output integrating species-level vegetation data and landform characterization forms a solid base for targeted interventions and enforcement. Numerous recent studies have documented the wide range of anthropogenic pressures on coastal dunes across Europe and beyond, including tourism infrastructure, road and parking construction, and recreational trampling, all of which alter vegetation composition and hinder dune mobility (Foti et al., 2021; Defeo et al., 2009; Malavasi et al., 2014; Innangi et al., 2025). These impacts are often exacerbated by the introduction of invasive species and the fragmentation of native vegetation patches, especially in urban settings (Aguilera et al., 2022). Thus, accurate spatial data combined with ecological field indicators are indispensable for planning restoration and mitigating ongoing degradation.

5.2.4 Future opportunities

The modular structure of SDMP allows for the integration of emerging technologies. For example, UAV-LiDAR systems provide enhanced penetration of vegetated areas and enable accurate ground elevation modeling even in complex terrain (Lin et al., 2019; Pinton et al., 2022). Additionally, machine learning techniques, such as Random Forest classifiers, have demonstrated strong performance in coastal vegetation mapping (James et al., 2024; Laporte-Fauret et al., 2020). Algorithms combining multispectral imagery and functional trait data (e.g., supervised classification of eco-functional units) also show the potential to enhance habitat mapping precision

(Innangi et al., 2025; Belcore et al., 2024). As demonstrated by Almonacid-Caballer et al. (2025), the reuse of historical aerial imagery offers another promising avenue for generating long-term baselines of dune morphology, contributing to sediment budget assessments and erosion forecasting.

6 Conclusion

The SDMP for the BBSC represents a significant advancement in coastal dune conservation. By integrating various scientific methods and leveraging modern technology, the SDMP provides a robust framework for accurate mapping and effectively managing coastal dune habitats. The pilot application on the “Kavatsi” dune system highlights the procedure’s potential to address anthropogenic impacts and support sustainable coastal management. Future efforts should focus on scaling the procedure, integrating new technologies, and using the data to inform climate resilience strategies and policy development. The SDMP not only aids in preserving the ecological integrity of DS but also contributes to the broader goal of sustainable coastal zone management.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: Data may be provided with the consent of the Ministry of Environment and Water of the Republic of Bulgaria. Requests to access these datasets should be directed to bprodanov@io-bas.bg.

Author contributions

BP: Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing. CG: Conceptualization, Writing – original draft, Writing – review & editing. DS: Conceptualization, Writing – original draft, Writing – review & editing. MV: Conceptualization, Writing – original draft, Writing – review & editing. RB: Writing – original draft, Writing – review & editing. AB: Conceptualization, Writing – original draft, Writing – review & editing. RT: Writing – original draft, Writing – review & editing. JP: Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2025.1579724/full#supplementary-material>

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