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Author-formatted, not peer-reviewed document posted on 29/05/2025

DOI: https://doi.org/10.3897/arphapreprints.e160546

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Gülşah Saç[1*], Sadi Aksu[2], Necmi Aksoy[3], Deniz Anıl Odabaşı[4], Irmak Kurtul[5,6], Sevan Ağdamar[7], Özgür Emiroğlu[8], Şerife Gülsün Kırankaya[9], Özcan Gaygusuz[10], Müfit Özuluğ[1], Ismael Soto[11], Phillip J. Haubrock[6,11,12], Ali Serhan Tarkan[13,14*]

[1]*Department of Biology, Faculty of Science, İstanbul University, Vezneciler-Fatih, Istanbul, Türkiye*

[2]*Vocational School of Health Services, Eskişehir Osmangazi University, Eskişehir, Türkiye*

[3]*Department of Forest Engineering, Faculty of Forestry, Düzce University, Düzce, Türkiye*

[4]*Department of Marine and Inland Water Sciences, Faculty of Marine Science and Technology, Çanakkale Onsekiz Mart University, Türkiye*

[5]*Department of Marine and Inland Waters Sciences and Technology, Faculty of Fisheries, Ege University, İzmir, Türkiye*

[6]*Department of Life and Environmental Sciences, Faculty of Science and Technology, Bournemouth University, Poole, Dorset, UK*

[7]*Department of Forestry, Bayramiç Vocational School, Çanakkale Onsekiz Mart University, Çanakkale, Türkiye*

[8]*Department of Biology, Faculty of Science, Eskişehir Osmangazi University, Eskişehir, Türkiye*

[9]*Department of Biology, Faculty of Science, Düzce University, Düzce, Türkiye*

[10]*Department of Marine and Freshwater Resources Management, Faculty of Aquatic Sciences, Istanbul University, İstanbul, Türkiye*

[11]*Faculty of Fisheries and Protection of Waters, South Bohemian Research Centre of Aquaculture and Biodiversity of Hydrocenoses, University of South Bohemia in České Budějovice, Vodňany, Czech Republic*

[12]*CAMB, Center for Applied Mathematics and Bioinformatics, Gulf University for Science and Technology, Hawally, Kuwait*

[13]*University of Lodz, Faculty of Biology and Environmental Protection, Department of Ecology and Vertebrate Zoology, Lodz, Poland*

[14]*Department of Basic Sciences, Faculty of Fisheries, Muğla Sıtkı Koçman University, Muğla, Türkiye*

***Correspondence:** gulsah.sac@istanbul.edu.tr; serhantarkan@gmail.com

Abstract

Wetlands provide a wealth of ecosystem services essential for human well-being. Despite their importance, wetlands continue to disappear globally and with them, their biodiversity. An additional threat to wetland biodiversity are biological invasions. This study therefore aims to assess the spread and ecological impacts of non-native species in Lake Manyas, Lake Uluabat, and the Kocaçay Delta, all located in the Marmara Region of Türkiye. For this, we used the recently developed Dispersal-Origin-Status-Impact (DOSI) framework, which allows for a holistic analysis of how non-native species are introduced (Dispersal), their origin (Origin), their current population status (Status) and their impacts (Impact) on a given assessment area. A total of sixteen non-native and two translocated species were identified as a result of field studies and literature reviews: ten plants, six fish and two mollusc species. The majority of species were intentionally introduced to the region through human actions such as fisheries, bio-control, and recreational activities. *Carassius gibelio*, *Gambusia holbrooki*, *Physella acuta*, and all plants stand out as the species presenting the highest threat according to the DOSI scoring. These species' effects, such as altering habitat structure, competing with native species and disrupting trophic networks, threaten the ecological integrity of these wetlands. Early intervention and long-term control strategies should be developed, especially for species with high impact levels.

Keywords: *Invasive species, Biological invasions, Life on land, DOSI, Kocaçay Delta, Ramsar sites*

Introduction

Wetlands, known for their ecological and socio-economic productivity, are among Earth's most vital life support systems, supporting a rich biodiversity and providing essential ecosystem functions such as cultural services, including opportunities for recreation, ecotourism, spiritual enrichment, birdwatching, and fishing (MEA 2005; Maltby and Acreman 2011; Wood et al. 2024). Often called the "kidneys of the landscape", wetlands support biodiversity, improve water quality, mitigate floods, replenish aquifers, and regulate global climate and nutrient cycles (Verhooven and Setter 2010; Mitsch et al. 2015; Mitsch and Gosselin 2015). Formally acknowledged for conservation by the Ramsar Convention in the early 1970s, their sustainable use has been emphasized as a matter of international importance, spanning ecology, botany, zoology, limnology, and hydrology (Matthews 1993). However, since the early 20th century, more than half of the world's wetlands have been degraded or lost due to both global change and intense direct and indirect anthropogenic interventions (Davidson 2014; Dervişoğlu 2021). The most common direct interventions include habitat alterations, such as draining for agricultural, industry, and urban expansion,or malaria control, and modified river hydrology through dam construction (Verhooven and Setter 2010; Zhao et al. 2012; Ataol and Onmuş 2021). Moreover, indirect pressures include for instance urbanization and industrialisation, as well as population growth, leading to bio-chemical water pollution and eutrophication (Hong et al. 2020; Alikhani et al. 2021; Ataol and Onmuş 2021).

Türkiye is one of the few countries significantly covered by three global biodiversity hotspots—the Caucasus, Irano-Anatolian, and Mediterranean Basin—making it a unique center of biological diversity (Şekercioğlu et al. 2011). Due to the geological evolution of the Anatolian Peninsula and its highly variable topography, Türkiye hosts a wide range of wetlands with distinct characteristics, supporting diverse genetic reserves of flora and fauna (Şekercioğlu et al. 2011; Kantor et al. 2023). Recognising the value of wetland ecosystems and their services, Türkiye has designated 14 wetlands as Ramsar sites, implementing measures to protect these critical habitats and the species they support (Dervişoğlu 2021; Elvan and Birben 2021). The South Marmara region (NW Anatolia) is particularly significant, as it hosts two Ramsar sites—Manyas (Kuş) and Uluabat (Apolyont) lakes— as well as the ecologically valuable Kocaçay (Dalyan) Delta. This region, however, faces increasing pressures from urbanisation. Lake Manyas, protected since 1959 as Türkiye's first wetland conservation area (Özmetin et al. 2017), was designated a Ramsar site in 1994 for its importance to migratory birds (Karadeniz et al. 2009); Lake Uluabat followed in 1998, meeting four Ramsar criteria related to species conservation and ecological function (Yenilmez and Aksoy 2013), while both lakes' rich biota and reed beds support diverse wildlife (Çelik and Ongun 2006; Kurtoğlu et al. 2015); similarly, the biodiverse Kocaçay Delta contributes to regional ecological and cultural value (Ursavaş and Keçeli 2019).

The main threats to Türkiye's wetlands and the services they provide are dam constructions, excessive water use and misguided agricultural water policies, pollution, illegal hunting and fishing, and infrastructure development (Dervişoğlu 2021)—also affecting the wetlands of South Marmara. Over

past decades, these stressors lead to significant losses in ecological and socio-economic benefits but growing concern has been directed toward the devastating effects of biological invasions on wetland ecosystems (Havel et al. 2015; Pathak et al. 2021; Tarkan et al. 2024). Lake Manyas, Lake Uluabat, and the Kocaçay Delta are wetlands identified as particularly vulnerable to a documented growing presence of numerous non-native species (Emiroğlu et al. 2012; Çınar et al. 2013; Keskin et al. 2013; Ağdamar and Tarkan 2019; Saç et al. 2020; Top-Karakuş et al. 2021).

To assess the risks posed by biological invasions and develop effective management strategies, various tools have been developed. These include, among other tools, the numerous Invasiveness Screening Kit (e.g. AS-ISK; Vilizzi et al. 2021, 2022, 2024) and the European Non-native Species in Aquaculture Risk Analysis Scheme (ENSARS) (Tarkan et al. 2020). However, there is growing recognition that biological invasions are context-specific, populations-level phenomena that are influenced by various factors (Soto et al. 2024; Haubrock et al. 2024). As a result, traditional assessments that generalize risks at the species-level may fail to capture these population-level complexities. To address this, the Dispersal-Origin-Status-Impact (DOSI) assessment scheme (Soto et al. 2024) has been developed as a standardized and objective method for evaluating biological invasions at different scales. This structured yet adaptable framework allows for a more accurate assessment of invasion dynamics, making it applicable across different spatial and temporal scales. One of DOSI's key advantages is its use of standardized terminology, avoiding politically sensitive or ambiguous language such as 'non-indigenous' or 'exotic,' thereby facilitating clearer scientific communication and decision-making (Błońska et al. 2024; Tarkan et al. 2024).

Given the increasing threats from biological invasions, this study aims to assess the ecological risks posed by non-native species in the wetlands of the South Marmara region, Türkiye, with a particular focus on their impact on ecosystem functions and services by employing the DOSI scheme (Tarkan et al. 2024; Błońska et al. 2024). Specifically, we aim to (*i*) overarchingly identify and prioritize non-native and translocated species by (*ii*) assessing their ecological impacts, including their role in altering food web structures, habitat stability, and species interactions, and (*iii*) dispersal mechanism, as crucial indicators of the adequate management implications, to finally (*iv*) provide evidence-based recommendations for conservation management and mitigation strategies in Ramsar-listed wetlands and other vulnerable coastal ecosystems. We hypothesize that (1) wetlands with notable presence of non-native and translocated species may show signs of altered ecological dynamics, including potential shifts in trophic interactions and pressures on native biodiversity, (2) species categorised as high priority through the DOSI scheme will show general consistency with those previously identified as high-risk invaders, thereby allowing a comparative validation of the framework, and (3) site-specific environmental characteristics, such as eutrophication and hydrological connectivity, may influence DOSI component scores, reflecting variation in the perceived or actual impacts of non-native species across wetland systems. By integrating ecological assessments with risk prioritization tools, this study

will contribute to the development of targeted management actions aimed at preserving the ecological integrity of Türkiye's wetlands.

Materials & Methods

Study site

This study was conducted in three wetlands located in the South Marmara region of northwestern Anatolia, Türkiye. The area lies along a major migratory flyway connecting Asia, Europe, and Africa, known as "bird paradise" (Fig. 1; see Supplementary Material 1). Lake Manyas (40.204522°N, 27.952728°E), situated in Balıkesir Province, is part of the Susurluk exoreic river basin. The lake covers an area of roughly 160 km² and lies at an elevation of 15 meters above sea level. It is a shallow, freshwater lake of tectonic origin, with a maximum depth of 3.4 meters and an average depth between 1 and 2 meters. The lake is eutrophic, and its waters are typically turbid due to suspended colloidal particles and constant mixing from wind action (Dorak et al. 2023). Its shores and seasonally inundated areas support a rich assemblage of aquatic and semi-aquatic vegetation. Lake Uluabat (40.148308°N, 28.614761°E) is also located within the Susurluk basin, in the neighboring province of Bursa. It spans approximately 140 km² and sits at 9 meters above sea level. Like Lake Manyas, Uluabat is a tectonically formed, shallow freshwater lake. It reaches a maximum depth of 10 meters, but its average depth remains around 1 to 2 meters. The lake is also eutrophic, with persistent turbidity largely resulting from the input of fine sediments via the Mustafakemalpaşa Stream (Değirmenci et al. 2006; Emiroğlu et al. 2012). Both the shores and islands are surrounded by dense wetland vegetation. The Kocaçay Delta (40.385689°N, 28.424936°E) is located where the Susurluk River meets the Sea of Marmara. This deltaic area encompasses a mosaic of habitat types, including floodplain forests, agricultural fields, wetlands, woodlands, shallow lakes, swamps, scrublands, and coastal sand dunes (Ursavaş and Keçeli 2019). The diversity of habitats makes it a particularly dynamic and ecologically valuable site within the region.

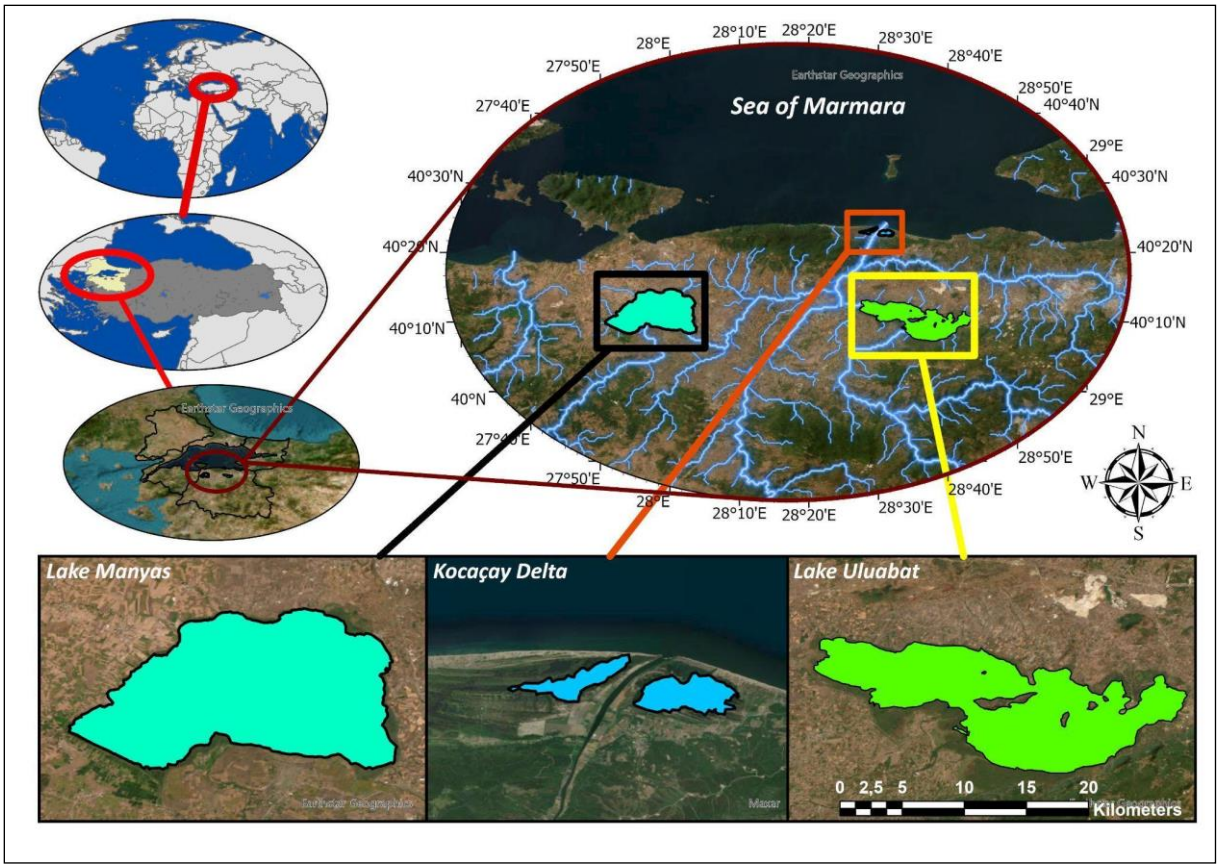

Figure 1. Location of the study areas (Lake Manyas, Kocaçay Delta, and Lake Uluabat) in the South Marmara region of Türkiye.

Species Selection and Verification

To identify non-native species threatening Lake Manyas, Kocaçay Delta, and Lake Uluabat, we first compiled a list of non-native and translocated species in each lake. Their status as non-native was confirmed by referencing databases such as the *Global Biodiversity Information Facility* (GBIF; REF) and relevant literature, including Tarkan et al. (2015, 2017) as well as up-to-date national lists (Tarkan et al. unpubl. data). Examining the literature (see Supplementary Material 2) revealed that three fish and one invertebrate species were recorded in Lake Manyas, four fish and one invertebrate species in Lake Uluabat Lake, and one invertebrate species in the Kocaçay Delta. In addition, some of the species were listed alongside both the authors' previous unpublished studies and their current observations. Finally, a total of 18 non-native and translocated species, including six fish, two mollusks, and ten plant species were evaluated using the DOSI assessment across all study areas (see Supplementary Material 2).

The Dispersal-Origin-Status-Impact (DOSI) assessment scheme and Prioritising

The DOSI framework developed by Soto et al. (2024) is a structured assessment tool that evaluates the potential threats posed by non-native or translocated species at different potential scales. DOSI only includes negative impacts of non-native species, acknowledging that they are often outweighed and

differ significantly from any potential benefits (Błońska et al., 2024; Tarkan et al., 2024). To assess populations of non-native or translocated species in the Manyas, Uluabat, and Kocaçay wetlands, we applied the DOSI framework to all non-native populations.

The DOSI framework evaluates species and populations moving into a new environment based on four key criteria (Fig. 2). The DISPERSAL mechanism determines how a species arrives at a new location. This can occur through deliberate (a_i) or accidental (a_{ii}) human-assisted transport, independent migration without direct human intervention (b_i), or facilitated dispersal (b_{ii}) by exploiting human-induced environmental changes such as canals. The ORIGIN of a species is classified as allochthonous (O_a), meaning it is not from 'here' (non-native), with 'here' defined spatial scale of interest, or autochthonous (O_b), meaning it originates from 'here', but has been translocated within the region of focus. The STATUS of the population describes its trend in terms of abundance (*i*) and range size (*ii*), categorizing it as expanding (S_a), static (S_b), or shrinking (S_c). Finally, the IMPACT category assesses whether the population causes harm (I_a) in one or more vectors—economic (*i*), ecological (*ii*), cultural (*iii*), or human health (*iv*)—or whether it has no detectable impact (I_b). To gather information on each non-native species' local dispersal, status, impact, and origin, we conducted a comprehensive literature review and drew on the author's expert judgment. Since species records, particularly on abundance trends and range expansion, are not always readily available, we addressed these gaps using our expert knowledge of the study site.

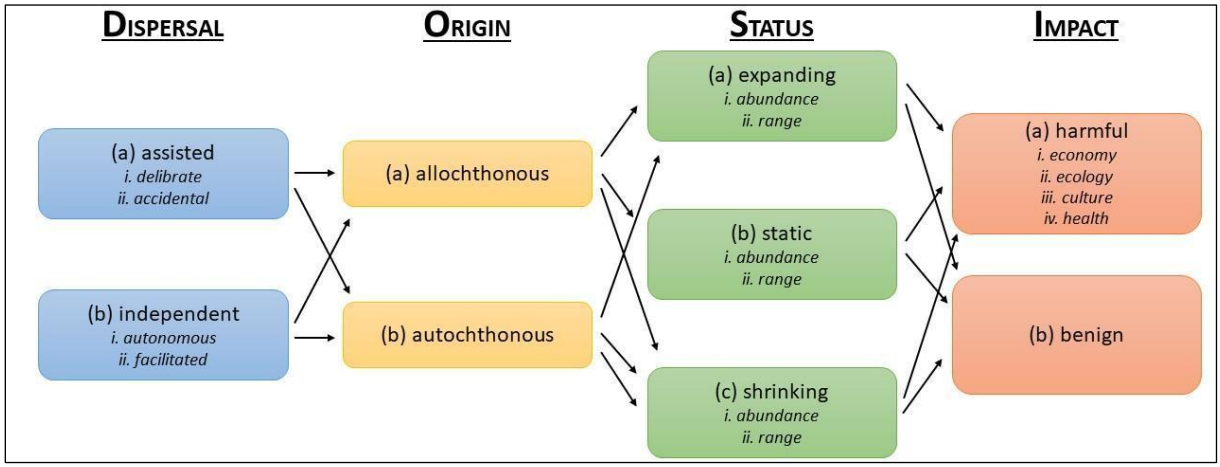

Figure 2. The DOSI flow diagram for the proposed classification scheme for non-native species and populations. Figure adapted from Soto et al. (2024).

Although inherently subjective, the impact classification within DOSI provides an expert-driven ranking system. This allows assessors to characterize a species' potential impact even when direct assessments are lacking in the study area, by drawing on documented impacts from other regions. However, if impact assessments have been conducted locally, they should take precedence. Notably, DOSI's objective is to

prioritize non-native species populations for management interventions, leveraging information on not only local risk levels, but most importantly the species' means of dispersal. This is because a species relying on assisted dispersal would require pathway management to hinder spread, whereas a predominantly independently spreading species would indicate population management. It does not consider the feasibility of mitigation strategies, the existence of management measures, or the species' ability to expand beyond its current range. Our DOSI assessment, therefore, prioritizes from the highest to lowest risk using a structured decision tree (Fig. 3). For both allochthonous (non-native) and autochthonous (native) populations, management recommendations depend on the identified risk level and dispersal mechanism. If there is evidence of direct human-assisted or independent spread in the introduction area, either pathway or population management is advised. Pathway management focuses on monitoring and controlling existing dispersal routes and vectors to prevent further spread, including erecting barriers or tracking adjacent pathways. Population management, on the other hand, aims to directly control populations by reducing their abundance, thereby minimising the potential for further expansion within and beyond current boundaries, while also monitoring adjacent ecosystems (Tarkan et al. 2024).

Populations capable of both assisted and independent dispersal, as well as those showing increases in both abundance and range, are assigned higher priority than those dependent on only one factor. This is because the former scenario suggests a broader and potentially more harmful invasion. The same prioritization applies when one factor remains static while the other is expanding. However, in confined risk assessment areas (e.g., lakes, reservoirs), abundance changes are generally given greater weight than range expansions in open systems (e.g., rivers, streams). Consequently, populations categorized as shrinking are lowered in priority rankings.

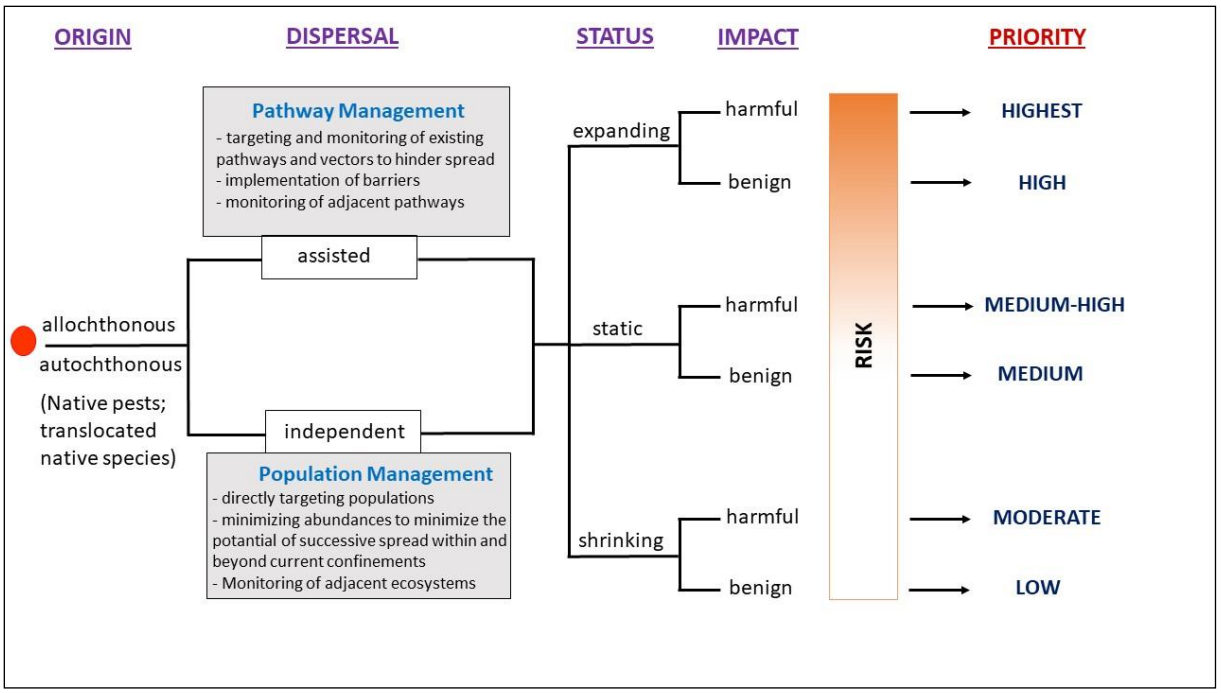

Figure 3. Proposed "Decision Tree" to prioritise ranking for management actions for non-native and translocated populations based on the DOSI assessment scheme. Figure adapted from Soto et al. (2024).

Results

A total of 18 species were assessed, seven of which found in three ecosystems, two in two ecosystems, and nine in a single ecosystem each, resulting in a total of 34 assessments. Species were classified following the DOSI framework (see Supplement Material 1). Overall, 15 species (83%) were classified as highest priority, three species as medium-high (17%), and two as moderate (11%). In Lake Manyas, eight species (*C. gibelio*, *G. holbrooki*, *P. parva*, *P. acuta*, *A. negundo*, *A. altissima*, *A. donax*, *G. triacanthos*, and *R. pseudoacacia)* were identified as Highest priority species (Table 1), two as Medium-High priority (*P. parva* and *C. carpio*) and one (*L. gibbosus*) classified as Moderate priority. In Lake Uluabat, ten species (*G. holbrooki*, *C. carpio*, *P. antipodarum*, *A. negundo*, *A. altissima*, *A. verlotiorum*, *B. frondosa*, *M. azedarach*, *P. quinquefolia*, and *R. pseudoacacia*) were ranked as Highest priority species, two (*C. gibelio* and *P. parva*) as Medium-High priority status, one (*L. gibbosus*) as Moderate priority and finally one (*T. tinca*) as Moderate priority. In the Kocaçay Delta, six species (*C. gibelio*, *G. holbrooki*, *P. acuta*, *A. altissima*, *R. pseudoacacia* and *Y. gloriosa*) were also categorized as Highest priority species, two (*L. gibbosus* and *P. parva*) as Medium-High priority, and one (*C. carpio*) as Moderate priority (Fig. 4; Table 1).

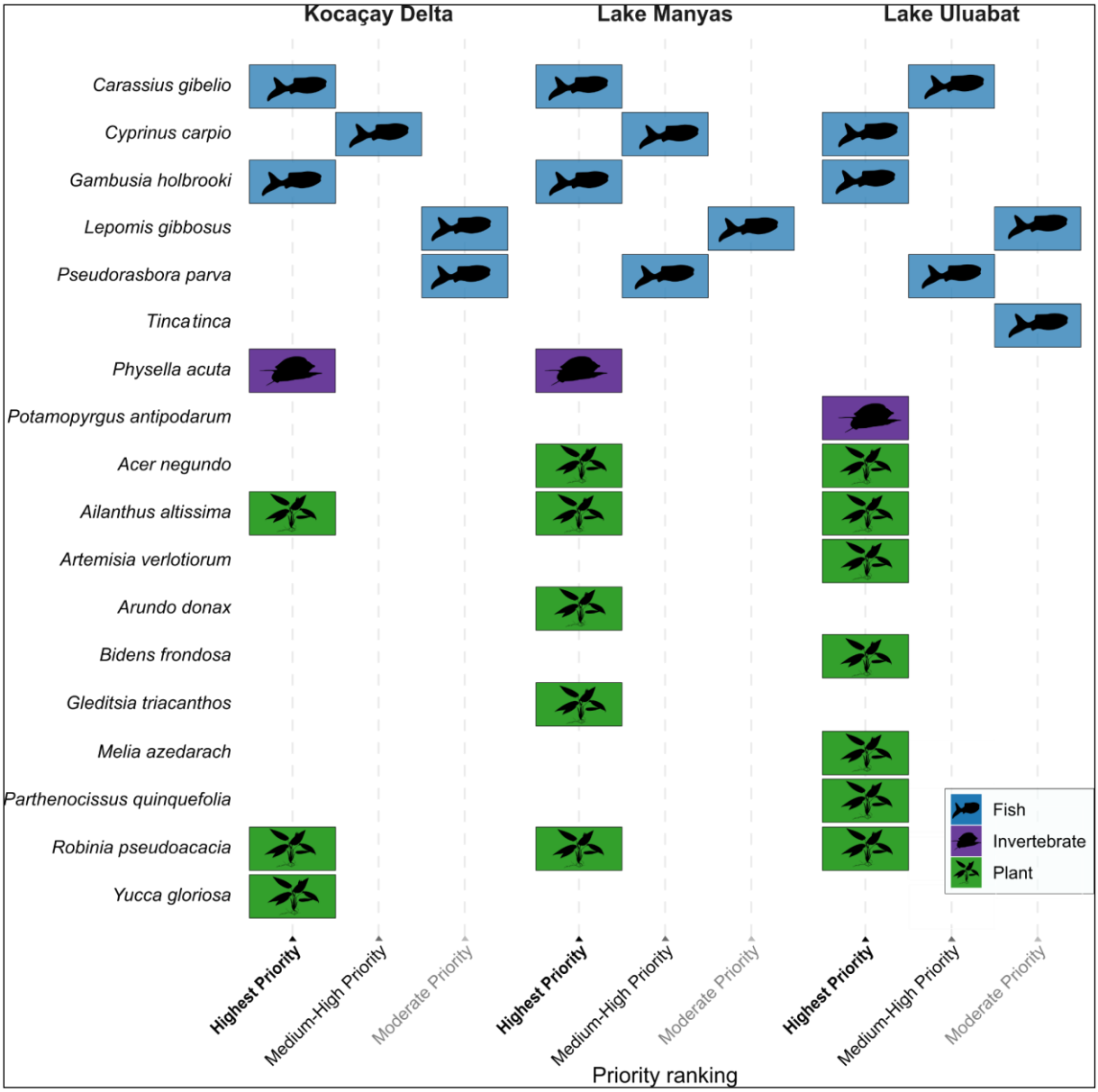

Figure 4. Assessment of non-native and translocated species for management prioritization in Manyas and Uluabat Lakes and the Kocaçay Delta, based on assessment using the Dispersal-Origin-Status-Impact (DOSI) scheme.

Table 1. Ranking of non-native and translocated species for management targeting populations in Manyas and Uluabat lakes and the Kocaçay Delta following the assessment using the Dispersal-Origin-Status-Impact (DOSI) scheme for identified fish (f), invertebrates (i) and plants (p).

Wetland	Ranking	Species	Group	Status	Classification
Lake Manyas	Highest Priority	*Carassius gibelio*	Fish	Non-native	Da_i Oa $Sa_{i,ii}$ $Ia_{i,ii,iii,iv}$
		Gambusia holbrooki	Fish	Non-native	Da_i Oa $Sa_{i,ii}$ $Ia_{ii}b_{i,iii,iv}$

		Physella acuta	Invertebrate	Non-native	$Da_ibi,ii\ Oa\ Sa_{i,ii}\ Ia_{ii,iv}b_{i,iii}$
		Acer negundo	Plant	Non-native	$Da_ib_i\ Oa\ Sa_ib_i\ Ia_{ii,vi}b_{i,iii}$
		Ailanthus altissima	Plant	Non-native	$Da_{ii}b_i\ Oa\ Sa_ib_i\ Ia_{i,ii,iii,iv}$
		Arundo donax	Plant	Non-native	$Da_{ii}b_i\ O_a\ Sa_ib_i\ Ia_{i,ii,iv}b_{iii}$
		Gleditsia triacanthos	Plant	Non-native	$Da_{ii}b_i\ Oa\ Sa_ib_i\ Ia_{i,ii,iii,iv}$
		Robinia pseudoacacia	Plant	Non-native	$Da_{ii}b_i\ Oa\ Sa_ib_i\ Ia_{i,ii,iii,iv}$
	Medium-High Priority	*Pseudorasbora parva*	Fish	Non-native	$Db_i\ Oa\ Sb_ia_{ii}\ Ia_{ii}b_{i,iii,iv}$
		Cyprinus carpio	Fish	Translocated	$Da_i\ Ob\ Sb_{i,ii}\ Ia_{ii}b_{i,iii,iv}$
	Moderate Priority	*Lepomis gibbosus*	Fish	Non-native	$Da_i\ Ob\ Sc_ia_{ii}\ Ia_{ii}b_{i,iii,iv}$
Lake Uluabat	Highest Priority	*Gambusia holbrooki*	Fish	Non-native	$Da_i\ Oa\ Sa_{i,ii}\ Ia_{ii}b_{i,iii,iv}$
		Cyprinus carpio	Fish	Translocated	$Da_i\ Ob\ Sa_ib_{ii}\ Ia_{ii,iv}\ b_{i,iii}$
		Potamopyrgus antipodarum	Invertebrate	Non-native	$Db_{i,ii}\ Oa\ Sa_{i,ii}\ Ia_{ii,iv}\ b_{i,iii}$
		Acer negundo	Plant	Non-native	$Da_ib_i\ Oa\ Sa_ib_i\ Ia_{ii,iv}b_{i,iii}$
		Ailanthus altissima	Plant	Non-native	$Da_{ii}b_i\ Oa\ Sa_ib_i\ Ia_{i,ii,iii,iv}$
		Artemisia verlotiorum	Plant	Non-native	$Da_{ii}b_i\ Oa\ Sa_ib_i\ Ia_{ii,iv}b_{i,iii}$
		Bidens frondosa	Plant	Non-native	$Da_{ii}b_i\ Oa\ Sa_ib_i\ Ia_{ii,iv}b_{i,iii}$
		Melia azedarach	Plant	Non-native	$Da_{ii}b_i\ Oa\ Sa_ib_i\ Ia_{ii,iii,iv}b_i$
		Parthenocissus quinquefolia	Plant	Non-native	$Da_{ii}b_i\ Oa\ Sa_ib_i\ Ia_{i,ii,iii,iv}$
		Robinia pseudoacacia	Plant	Non-native	$Da_{ii}b_i\ Oa\ Sa_ib_i\ Ia_{i,ii,iii,iv}$
	Medium-High Priority	*Carassius gibelio*	Fish	Non-native	$Da_i\ Oa\ Sb_i\ a_{ii}\ Ia_{i,ii,iii,iv}$
		Pseudorasbora parva	Fish	Non-native	$Db_i\ Oa\ Sb_ia_{ii}\ Ia_{ii}b_{i,iii,iv}$
	Moderate Priority	*Lepomis gibbosus*	Fish	Non-native	$Da_i\ Oa\ Sc_ib_{ii}\ Ia_{ii}b_{i,iii,iv}$

		Tinca tinca	Fish	Translocated	Db_i Oa Sc_ia_{ii} $Ia_{ii}b_{i,iii,iv}$
Kocaçay Delta	Highest Priority	*Carassius gibelio*	Fish	Non-native	Db_i Oa $Sa_{i,ii}$ $Ia_{i,ii,iii}b_{iv}$
		Gambusia holbrooki	Fish	Non-native	Da_i Oa $Sa_{i,ii}$ $Ia_{ii}b_{i,iii,iv}$
		Physella acuta	Invertebrate	Non-native	$Da_{ii}b_{i,ii}$ Oa $Sa_{i,ii}$ $Ia_{ii,iv}b_{i,iii}$
		Ailanthus altissima	Plant	Non-native	$Da_{ii}b_i$ Oa Sa_ib_i $Ia_{i,ii,iii,iv}$
		Robinia pseudoacacia	Plant	Non-native	$Da_{ii}b_i$ Oa Sa_ib_i $Ia_{i,ii,iii,iv}$
		Yucca gloriosa	Plant	Non-native	$Da_{ii}b_i$ Oa Sa_ib_i $Ia_{ii,iv}b_{i,iii}$
	Medium-High Priority	*Cyprinus carpio*	Fish	Translocated	Da_i Ob $Sa_{i,ii}$ $Ia_{ii}b_{i,iii,iv}$
	Moderate Priority	*Lepomis gibbosus*	Fish	Non-native	Da_i Oa Sc_ib_{ii} $Ia_{ii}b_{i,iii,iv}$
		Pseudorasbora parva	Fish	Non-native	Db_i Oa Sc_ia_{ii} $Ia_{ii}b_{i,iii,iv}$

Discussion

The strength of the DOSI framework lies in its ability to parse out these localized dynamics at the population level, enabling more precise prioritization of management actions based on both impact and dispersal mechanisms. Applying the Dispersal-Origin-Status-Impact framework offers a valuable and structured approach for assessing invasion risk and guiding conservation and management actions (Błońska et al. 2024; Tarkan et al. 2024). Applying it for the first time to three Ramsar-designated wetlands in Türkiye, DOSI was used to evaluate ecological risk of 18 non-native and translocated species. This application yielded a total of 34 species–ecosystem assessments, offering a robust test of the framework's capacity to capture ecological variability and prioritization needs across systems.

The majority of species (83%) were classified as Highest priority, indicating widespread and substantial perceived or documented ecological threats. Medium-High and Moderate priority classifications were assigned to a smaller subset, reflecting either lower impact scores or reduced evidence of spread. Notably, several species—such as *C. gibelio*, *G. holbrooki*, and *R. pseudoacacia*—were consistently ranked as Highest priority across all wetlands, demonstrating a high degree of alignment between DOSI classifications and known invasive profiles from previous studies, thus supporting Hypothesis 2. Furthermore, differences in DOSI component scores between wetlands highlight the influence of local environmental conditions, such as eutrophication and hydrological connectivity (supporting Hypothesis 3). For example, Lake Uluabat—with higher anthropogenic influence and complex hydrological

inputs—had a broader range of Highest priority species compared to the Kocaçay Delta, which is more spatially isolated.

Ecosystem-Based Interpretation of Invasion Dynamics and Management Priorities

Our assessment of three Ramsar-listed wetlands in the South Marmara region—Lake Manyas, Lake Uluabat, and the Kocaçay Delta—highlights how varying degrees of ecological disturbance, hydrological modification, and anthropogenic pressure influence the establishment and impact of non-native and translocated species. Although two sites benefit from international protection, Ramsar designation alone offers limited resilience against the ecological inertia of legacy degradation and ongoing biological invasions (Klejin et al. 2013; Batanjski et al. 2016). In practice, protection status often fails to mitigate the effects of pollution, eutrophication, or land-use change that facilitate species introduction and establishment. Moreover, the dominant invasion vectors differ among these wetlands—ranging from fisheries enhancement and bio-control to recreational infrastructure and urban landscaping (Kurtoğlu et al. 2015; Saç et al. 2020)—require tailored and context-sensitive management strategies (Tarkan et al. 2023; 2024).

Lake Manyas exhibits advanced eutrophication, shoreline degradation, and persistent nutrient loading, which collectively reduce ecosystem resistance and promote the establishment of tolerant invaders such as *C. gibelio*, *G. holbrooki*, and *Physella acuta* (Öktener and Georgiev 2019; Saç et al. 2020). These taxa are known to benefit from degraded conditions and for their ability to disrupt food webs through competition, habitat modification, and direct predation (Pyke 2008; Tarkan et al. 2012; Vinarski et al. 2017). The widespread presence of non-native riparian trees like *A. negundo* and *A. altissima*, likely facilitated by tourism infrastructure and altered hydrological regimes, reflects a broader pattern of human-mediated secondary invasions (Sikorska et al. 2019; Montecchiari et al. 2020). While Lake Manyas was among Türkiye's first formally protected wetland areas, persistent ecological stressors have continued to erode biotic integrity, enabling invasive populations to expand (Saç et al. 2020). In Lake Uluabat, similar pressures are exacerbated by sediment inflows, canalized watercourses, and intensive shoreline development (Değirmenci et al. 2006; Emiroğlu et al. 2012). The co-occurrence of *C. carpio* and *G. holbrooki*, both historically introduced, creates compounding ecological pressures through bioturbation, predation on larval stages of native fish and amphibians, and direct competition for resources. The presence and apparent spread of *P. antipodarum*, a high-risk invader with considerable reproductive capacity and tolerance to disturbance, is especially concerning given its potential to alter native invertebrate communities and sediment dynamics (Alonso and Castro-Díez 2012; Gérard et al. 2003). Along urbanized shorelines, especially near the Gölyazı Peninsula, invasive plants such as *R. pseudoacacia* and *B. frondosa* dominate, their expansion likely tied to recreational development and archaeological tourism. Finally, the Kocaçay Delta, while less urbanized, is a dynamic and

hydrologically connected wetland complex that functions as both a recipient and source of propagules (Ursavaş and Keçeli 2019). Its diverse habitat types and seasonal water fluctuation patterns facilitate species dispersal, making it especially prone to invasions by taxa that exploit transitional zones. *Gambusia holbrooki*, *C. gibelio*, and *P. acuta* dominate aquatic habitats, while *Y. gloriosa*, typically associated with ornamental plantings, was found invading natural dune ecosystems—suggesting a terrestrial-coastal invasion pathway rarely documented in Türkiye. Agricultural expansion, unmanaged grazing, and tourism-related land conversion continue to create corridors of disturbance that facilitate the spread of both aquatic and riparian invaders (Ursavaş and Keçeli 2019).

Hidden Risks and Management Trade-offs

Pseudorasbora parva—despite not ranking among the most visibly dominant invaders—represents a significant risk due to its role in pathogen transmission, particularly *S. destruens*, which has been linked to dramatic declines in native fish populations across Europe (Ercan et al. 2015; Spikmans et al. 2020). Its ecological footprint is further amplified by its capacity to establish in degraded environments and evade detection due to its small size and schooling behavior. The continued stocking of translocated but economically important species such as *C. carpio* compounds these risks. While long used to support inland fisheries in Türkiye, *C. carpio* is known to disturb sediments, uproot vegetation, and alter trophic structures, contributing to water quality decline and loss of native macrophyte habitats (Tarkan et al. 2012; Paulovits et al. 2014). These outcomes underscore how fisheries management decisions—when not aligned with ecosystem health goals—can perpetuate ecological degradation.

Among aquatic invertebrates, *P. acuta* exemplifies a highly adaptable and underappreciated invader. With its broad ecological tolerance, rapid reproductive cycle, and ability to colonize both polluted and pristine waters, this gastropod poses a persistent challenge to freshwater biodiversity (Vinarski et al. 2017; Brand et al. 2024). Its dominance in multiple wetlands in this study suggests a capacity for both passive and active spread, and its presence has been associated with shifts in periphyton communities and native invertebrate assemblages (Scherer et al. 2017; Cieplok and Spyra 2020; Taybi et al. 2024). Effective control options are limited, particularly in eutrophic or hydrologically modified systems where habitat conditions favor its proliferation.

In terrestrial and riparian zones, *A. altissima* presents a different but equally pressing management dilemma. Widely planted for its fast growth and ornamental appeal, the species is now naturalized in many regions of Türkiye, where it outcompetes native vegetation, alters successional dynamics, and reduces soil microbial diversity (Motard et al. 2015; Medina-Villar et al. 2016; Ulus et al. 2021). Despite these ecological costs, its removal is often contested due to its use in urban greening and erosion control. Its deep root system and prolific seed production make mechanical removal challenging, while chemical

treatments carry risks for adjacent native flora and wetland water quality (Kowarik and Säumel 2007; Sladonja et al. 2015).

Integrating Policy and Management: Türkiye's Gaps and Opportunities

Despite mounting evidence of the ecological and economic threats posed by non-native species, Türkiye lacks a national regulatory framework or centralized authority to coordinate early detection, risk assessment, and rapid response. While frameworks like DOSI offer a transparent and standardized method for prioritizing action, their implementation depends on long-term monitoring infrastructure, reliable baseline data, and legislative integration—elements currently fragmented or absent at the national level (Uludağ et al. 2017; Hulme 2009). Compounding this, public resistance to managing species with perceived economic or recreational value—such as *C. gibelio*—undermines control efforts and stalls policy progress (Simberloff et al. 2013; Lovell et al. 2006). To address these challenges, Türkiye must not only adopt structured risk assessment tools like DOSI more widely, but also embed them within a broader non-native species strategy that includes targeted outreach, cross-border cooperation, and habitat-based conservation planning. Research initiatives should support this by developing species-specific impact models, applying climate-driven risk forecasting, and leveraging genetic methods to trace introduction pathways and assess hybridization risks (Keskin et al. 2013; Ağdamar and Tarkan 2019). Community-based monitoring and citizen science can further complement formal efforts, especially in under-resourced regions. Ultimately, any effective response will require aligning ecological science with enforceable policy, stakeholder engagement, and long-term investment in ecosystem resilience.

Conclusion

This study represents the first application of the Dispersal-Origin-Status-Impact (DOSI) framework to Ramsar-listed wetlands in Türkiye, offering a nuanced assessment of invasive and translocated species at the population level. By integrating structured risk assessment with ecological context and field-based insights, we demonstrate that biological invasions in these wetlands are not isolated events but are deeply embedded in broader patterns of habitat degradation, hydrological alteration, and socio-economic use. The findings underscore that legal protection alone is insufficient; effective mitigation requires locally adapted, evidence-based strategies that account for both ecological and human dimensions of invasion dynamics. Such strategies should also be flexible enough to accommodate region-specific socio-political constraints, including land-use conflicts, resource limitations, and governance challenges. Expanding the use of frameworks like DOSI, coupled with long-term monitoring and coordinated action among researchers, practitioners, and policymakers, is essential to preserving the integrity and resilience of Türkiye's freshwater ecosystems. The framework established herein holds potential for broader applicability across global wetland systems, particularly in regions where invasive species dynamics coincide with ongoing environmental changes and complex management contexts.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Author contributions

GS: Concept and design of the study, data collection, data analysis and interpretation, manuscript preparation. SA: Data collection, data visualization. NA: Data collection, manuscript preparation. DAO: Data collection, manuscript preparation. IK: Data collection, manuscript preparation. SA: Data collection, manuscript preparation. ÖE: Data collection. ŞGK: Data collection. ÖG: Data collection. MÖ: Data collection. IS: Manuscript preparation. PJH: Manuscript preparation, data visualization. AST: Concept and design of the study, data collection, data analysis and interpretation, manuscript preparation.

Author ORCIDs

Gülşah Saç https://orcid.org/0000-0001-9988-1116

Sadi Aksu https://orcid.org/0000-0003-2770-561X

Necmi Aksoy https://orcid.org/0000-0002-2153-922X

Deniz Anıl Odabaşı https://orcid.org/0000-0003-0738-2606

Irmak Kurtul https://orcid.org/0000-0002-3566-9172

Sevan Ağdamar https://orcid.org/0000-0002-1268-0379

Özgür Emiroğlu https://orcid.org/0000-0002-4433-4286

Şerife Gülsün Kırankaya https://orcid.org/0000-0002-5171-9256

Özcan Gaygusuz https://orcid.org/0000-0001-6861-6221

Müfit Özuluğ https://orcid.org/0000-0002-1437-3890

Ismael Soto https://orcid.org/0000-0002-7288-6336

Phillip J. Haubrock https://orcid.org/0000-0003-2154-4341

Ali Serhan Tarkan https://orcid.org/0000-0001-8628-0514

Data availability

The dataset used in the manuscript is available in Supplementary Material 2.

Acknowledgments

PJH acknowledges the Marie Skłodowska-Curie Postdoctoral Fellowship from the European Commission Project DIRECT (Grant No. 101203662). We would like to thank local fishermen for their kind help.

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