scientific reports

OPEN

Testing the Dispersal-Origin-Status-Impact (DOSI) scheme to prioritise non-native and translocated species management

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Assessing actual and potential impacts of non-native species is necessary for prioritising their management. Traditional assessments often occur at the species level, potentially overlooking differences among populations. The recently developed Dispersal-Origin-Status-Impact (DOSI) assessment scheme addresses this by treating biological invasions as population-level phenomena, incorporating the complexities affecting populations of non-native species. We applied the DOSI scheme to the non-native and translocated species reported in a shallow alluvial lake (Lake Gala) and a reservoir (Sığırcı Reservoir) in north-western Türkiye. DOSI identified 12 established species across both ecosystems, including nine fish, two invertebrates, and one mammal. Most species received *High* and *Medium–High* priority rankings, in both sites. In contrast, *Medium* and *Low* priority rankings were less common, each occurring once in Lake Gala and four times in Sığırcı Reservoir. These high-priority species warrant targeted management interventions due to their established status, autonomous spread, and observed negative impacts. By enabling a more nuanced and context-specific approach, DOSI facilitates the development of targeted strategies for managing species posing the highest risks. Moreover, DOSI's focus on population-level assessment within ecosystems is highly relevant for stakeholders, decision-makers, and environmental managers, because it provides a more detailed and precise unit of evaluation.

Keywords Biological invasions, Invasive species, *Callinectes sapidus*, *Myocastor coypus*, *Gymnocephalus cernua*, Lake Gala, Sığırcı reservoir

Evaluating the real and potential impacts of non-native species is necessary to prioritise their management[1]. However, assessments of non-native species are often done at the species level and can therefore miss important differences among populations[2]. Such assessments can also be inaccurate reflections of potential outcomes

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because many populations (i.e., sleeper populations; Spear et al.[3]) remain cryptic until they enter an exponential growth phase[4–6]. Because eradication is often not feasible[7], managing non-native species remains the only option, but can be challenging due to insufficient and ineffectively allocated funding, as well as incomplete knowledge of the target species' behaviour and life history. These problems are complicated by societal and cultural dynamics, including public acceptance and awareness[8,9]. Limitations can be especially pronounced in low- and middle-income countries where resource constraints[10] and insufficient data exacerbate the difficulty in controlling biological invasions[11]. Extensive interventions using biocontrol agents and pesticides, for example, are often seen as a last resort, but can threaten native ecosystems and worsen human health[12–14].

Problems in managing non-native species are acute in freshwater environments where the ecological consequences are often identified too late when management actions have become less efficient and costly[15,16]. In Türkiye's freshwaters, the spread of non-native species is exacerbated by many pathways, such as angling, aquaculture[17], and a lack of management resources[18]. In 2024, eighty seven non-native species were reported as an economic burden to Türkiye's biodiverse and endemic freshwater ecosystems[19], having incurred a total of US\$4.1 billion to the Turkish economy[20]. In contrast, only US\$0.009 billion (i.e., ~ 0.012% of their estimated total cost) was invested by the Turkish government into controlling pufferfish (*Lagocephalus* spp.) in Turkish seas[20]. The lack of sufficient resources therefore emphasises the need for effective prioritisation and accessible assessment methods suitable for professionals from various backgrounds and with different expertise.

While biosecurity is likely the most effective strategy given limited resources, the management of established non-native species must be based on rigorous prioritisation that selects those species identified as most harmful and those presenting the largest threats[21]. Available risk identification tools (e.g., *Aquatic Species Invasiveness Screening Kit*; Vilizzi et al.[22]) and impact evaluation frameworks (e.g., *Environmental Impact Classification for Alien Taxa*; Hawkins et al.[23]) have been developed to estimate relative potential impacts for species across geographical scales — e.g., continents to countries[24,25]. Early detection and early assessments are essential components of this process because they allow for the timely identification of emerging threats, enabling more effective and efficient resource allocation and management actions before introduced non-native species become more established and difficult to control[26]. Therefore, precise and uniform assessment protocols that account for population-level differences are necessary to allocate resources efficiently toward the highest-priority species[27,28].

The recently developed Dispersal-Origin-Status-Impact (DOSI) assessment scheme proposed by Soto et al.[29] recognises that biological invasions are population-level phenomena and embraces the intricacies affecting populations of non-native species[2]. The scheme is based on four primary components: (*i*) dispersal mechanisms (assisted vs. independent), (*ii*) origin (allochthonous vs. autochthonous), (*iii*) current status (expanding, stationary, or shrinking), and (*iv*) impact (ecological, economic, health, and/or cultural). This detailed strategy is an objective and evidence-based method for managing biological invasions[30]. DOSI's effectiveness comes from its simplicity, standardised terminology and comprehensive, yet adaptable framework that can be tailored to various timeframes, locations, and metrics, making it suitable for specific populations or across broader regional or ecosystem scales. DOSI promotes a more neutral and straightforward communication of scientific results than other protocols because it steers clear of terms with negative or politically sensitive connotations such as, 'non-indigenous', 'exotic', or 'colonised' (see Soto et al.[29]).

We applied the DOSI scheme to the non-native and translocated species (i.e., those moved within the native range to a new location by humans) reported in the shallow alluvial water bodies of Lake Gala (40° 46′ 03″ N, 26° 11′ 03″ E) and the Sığırcı Reservoir (40° 49′ 33″ N, 26° 19′ 19″ E) in north-western Türkiye near the border with Greece. Given the status and characteristics of these ecosystems, they present an ideal opportunity to apply the DOSI scheme to non-native and translocated species. By applying DOSI to non-native and translocated populations in both ecosystems, we aim to assess the scheme's effectiveness and dependability in understanding the population-level subtleties of biological invasions when categorising them based on their ecological threats. Our approach involves an in-depth examination of each component of DOSI, evaluating its relevance and suitability for diverse species and habitats. Consequently, we aim to verify and improve DOSI's functionality as a resource for researchers, policymakers, and conservationists, focusing on consistency and openness in its application.

Results

We identified seven non-native and five translocated species of nine fishes, two macroinvertebrates, and one mammal. Among the non-native fish species were gibel carp *Carassius gibelio*, and topmouth gudgeon *Pseudorasbora parva* from East Asia, the mosquitofish *Gambusia holbrooki*, ruffe *Gymnocephalus cernua*, and pumpkinseed *Lepomis gibbosus* from North America, common carp *Cyprinus carpio*, perch *Perca fluviatilis*, pikeperch *Sander lucioperca*, and roach *Rutilus rutilus*; the latter three are considered native in other parts of Türkiye (Table 1). Additionally, we identified two non-native macroinvertebrate species — the blue crab *Callinectes sapidus* in Lake Gala, and the zebra mussel *Dreissena polymorpha*, native to the Ponto-Caspian region, in Sığırcı Reservoir. The mammal species was the nutria *Myocastor coypus* from South America that occurs in both lakes (Table 1).

DOSI ranked *C. sapidus*, *M. coypus*, and *G. cernua* as the species of highest priority in Lake Gala due to assisted spread ($\mathrm{Da}_{i,ii}$) and increasing abundances ($\mathrm{Sa}_{i,ii}$) throughout the entire lake (Fig. 1). In contrast, the fish species *C. gibelio* and *G. cernua* were prioritised in Sığırcı Reservoir due to their capacity to spread independently (Db_{ii}; Fig. 1). The four aforementioned species have increasing population sizes ($\mathrm{Sa}_{i,ii}$), are already established throughout the lakes ($\mathrm{Sb}_{i,ii}$), and cause economic and ecological damage ($\mathrm{Ia}_{i,ii}$). In Lake Gala, two common cyprinids, *C. carpio,* and *C. gibelio*, and the mosquitofish *G. holbrooki*, were ranked *Medium–High* due to static ranges and abundances ($\mathrm{Sb}_{i,ii}$), even though they cause negative ecological impacts (Ia_{i}), but with *C. gibelio* also being culturally and economically important ($\mathrm{Ia}_{i,ii,iii}$) (Fig. 1). Similarly, *P. fluviatilis*, along with *C. carpio* and *G. holbrooki*, were classified *Medium–High* in Sığırcı Reservoir due to the continuous influx of individuals

Priority ranking	Definition
(a) Non-native species that spread without human assistance	
Highest	A population that is expanding and has an impact on the studied system. These populations are considered the most important to manage due to their active expansion and demonstrated negative effects.
High	A population that is expanding but has currently no observed or only benign impacts. These populations can spread and exert impacts elsewhere.
Medium–high	A population that is not expanding but is static while having a locally observed impact that warrants monitoring.
Medium	A population that is currently not spreading and has no documented impacts. Due to environmental change, these populations could eventually expand or cause impacts and become problematic and so should be monitored.
(b) Non-native species that spreads mainly via human assistance	
Moderate-medium	A population that is expanding due to human activities with possible invasive impacts. These populations rely on human facilitation, and thus, their spread can be hindered by the management of current pathways.
Moderate	A population that is expanding due to human activities but currently has no observed impacts. These populations rely on human facilitation and, thus, could exert impacts elsewhere. Their spread can be hindered by managing current pathways.
Low-moderate	A population with a local impact but is not expanding due to the reliance on human assistance. These populations rely on human facilitation and, thus, could exert impacts elsewhere. Their local impacts warrant monitoring and potential management interventions.
Low	A population that has no local impact and is not expanding. These populations rely on human facilitation but could develop impacts elsewhere.

Table 1. Priority rankings of non-native and translocated species in Lake Gala and Sığırcı Reservoir using the Dispersal-Origin-Status-Impact (DOSI) classification scheme.

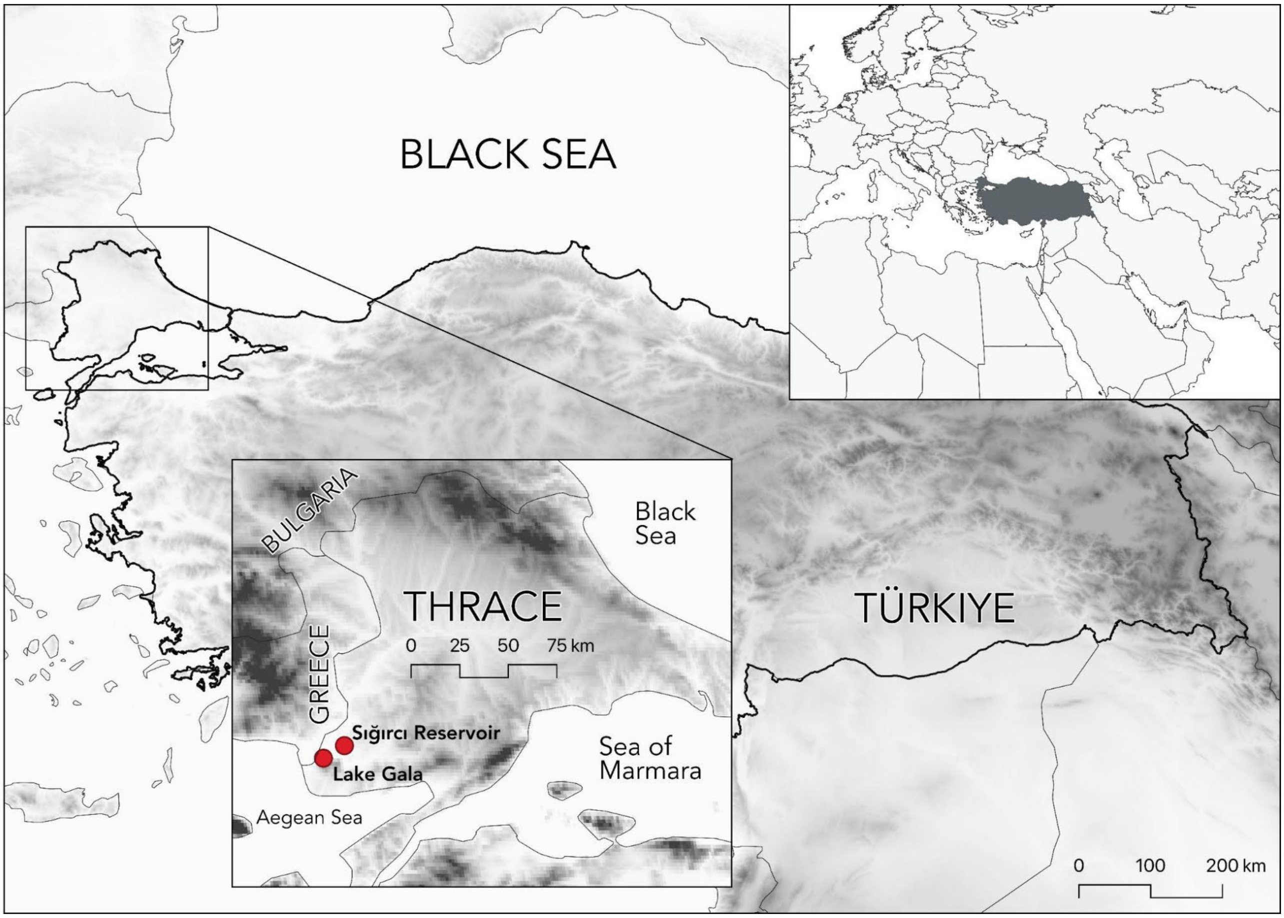

Fig. 1. Location of the study sites—Lake Gala and Sığırcı Reservoir—in the Thrace region of Türkiye.

from Lake Gala (Db_{ii}; Fig. 1). *L. gibbosus* and *P. parva* were ranked *Medium* and *Low* priority in Lake Gala, respectively, reflecting their declining or static abundances and ranges ($Sb_{i,ii}$,$c_{i,ii}$), with no apparent ecological impacts observed for either species (Ib; Fig. 1). In Sığırcı Reservoir, four species received a *Medium* ranking — *D. polymorpha*, *M. coypus*, *L. gibbosus*, and *R. rutilus* — due to their static ranges (Sb_{ii}), stable abundances (Sb_i), and lack of observed impacts (Ib). Only *S. lucioperca* was ranked *Low* priority in Sığırcı Reservoir due to its declining abundance (Sc_i) and a lack of observed impacts (Ib; Fig. 1).

Discussion

We aimed to assess the risks posed by populations of non-native species in two distinct yet interconnected aquatic environments in north-western Türkiye: Lake Gala and Sığırcı Reservoir. Our investigation encompassed twelve species identified as established in one or both ecosystems, comprising nine fishes, two invertebrates, and one mammal. The *Highest* and *Medium-Highest* priority rankings dominated, with six instances observed in Lake Gala and five in Sığırcı Reservoir. Conversely, *Medium* and *Low* priority rankings were less prevalent, each occurring only once in Lake Gala and four times in Sığırcı Reservoir. DOSI identified the fish *C. gibelio* and *G. cernua*, the invertebrate *C. sapidus*, and the mammal *M. coypus* as ranking highest. These species are considered high-priority targets for management interventions due to their established status, independent spread, and observed negative impacts (Table 1).

In Sığırcı Reservoir, where translocated species are prevalent, priority rankings were more variable than in Lake Gala. While all categories were equally represented across the species from both lakes, a *Low*-priority ranking occurred only in the Sığırcı Reservoir (Table 1). The designation of higher-priority rankings for *C. sapidus* and *M. coypus* aligns with their globally recognised invasiveness[31,32]. Both species have wide-ranging impacts in both lakes, except *M. coypus* in Sığırcı Reservoir, where it is less widespread, and its impacts are primarily ecological (predation, competition, habitat degradation) and economic (by damaging fishing resources and increasing parasite transmission) (Table 1). The species is abundant and ubiquitous in Lake Gala, making population control by trapping and reducing density the only feasible management action.

Assessing the impact of non-native species at the population level is essential for understanding their ecological effects and for developing effective management strategies, because it allows for a more precise evaluation of how these species interact with native populations and local ecosystems[2]. Controlling *C. gibelio*, widely recognised as the most invasive freshwater fish species in Türkiye[33], is also challenging due to its competitiveness and reproductive interference with native fish species[34]. Its priority rankings varied between Lake Gala and Sığırcı Reservoir, highlighting the impact of local factors on species distribution and spread, and hence the value of a population-level assessment. Although *P. parva* is recognised as one of the most invasive freshwater fishes in the world[35], its population in Lake Gala only received a *Low* priority ranking due to its low abundance and decreasing range with no apparent impact (e.g., Copp et al.[36]). The observed patterns stress the importance of considering population-specific characteristics and local context in risk assessments (e.g., Copp et al.[36]). Our findings also shed light on the complex dynamics of introduced native populations, such as *P. fluviatilis* and *R. rutilus*, within the reservoir ecosystem (Table 1). Despite differing priority rankings, these species warrant further attention given their potential ecological implications. This is especially true for *P. fluviatilis*, with increasing concern over its rapid spread[37] facilitated by intentional introduction by anglers and its predation impact on native fauna[38].

The DOSI assessment underscores the importance of prioritising management based on a population's risk profile and local context. Including population-level assessments in conservation strategies offers a more nuanced understanding of impacts and aids in formulating targeted management tailored to specific habitats and ecological contexts. Existing risk identification and assessment tools such as the A*quatic Species Invasiveness Screening Kit* (AS-ISK) and *Environmental Impact Classification for Alien Taxa* (EICAT) are predominantly species-focused. In contrast, DOSI offers several advantages by incorporating the number of impact categories within classes while employing a more nuanced approach by evaluating populations individually. DOSI also allows multiple assessments of several populations of one species to calculate an average for management applications at broader scales. Furthermore, establishing standardised guidelines for applying DOSI across different taxonomic groups and ecosystems could improve consistency and comparability among assessments done by different researchers or in various regions. Incorporating a more quantitative approach to assigning weights in the ranking system could enhance the objectivity and reproducibility of the prioritisation process, potentially through a scoring system that ranks priorities from highest to lowest. This approach could benefit from integrating the quantitative formula described by Parker et al.[39], which considers population range, abundance, and per-capita effects on native species, providing a robust framework that complements DOSI by addressing its limitations and emphasising a population-level perspective. Doing sensitivity analyses to assess the robustness of DOSI-based prioritisation outcomes to changes in input data or expert judgment could help identify areas of uncertainty and guide future refinements of the scheme. Additionally, collaborating with stakeholders, decision-makers, and environmental managers to develop case studies demonstrating how DOSI-based assessments inform real-world management actions and policy decisions for the two studied lakes could further validate its utility and promote its adoption. Integrating DOSI with other risk screening and assessment tools or frameworks, such as AS-ISK or EICAT, would capitalise on the strengths of each approach and provide a more comprehensive understanding of the risks posed by non-native species. DOSI also addresses the shortcomings of expert-based assessments, which can vary among assessors, by being transparent and evidence-based. Unfortunately, because we often lack evidence of impact, spread, or even the origin of species (e.g., cryptogenic species) at the local scale, DOSI relies not only on quantitative information from empirical studies, but also on qualitative information regarding non-native species in the recipient ecosystem.

While our study demonstrates the utility of the DOSI scheme for assessing the ecological risks posed by non-native species and informing management priorities, we recognise that socio-economic considerations are not systematically integrated into the current DOSI framework. Although we briefly discuss the economic impacts of certain species, such as *C. sapidus* and *G. cernua* damaging fishing nets and traps, and *M. coypus* impacting habitats for economically important fish populations and acting as vectors for parasites, these examples only scratch the surface of the broader socio-economic challenges. The cultural perception of some species, such as *C. gibelio* being desirable to anglers and *M. coypus* being viewed as a pest further highlights the complex trade-offs that managers face. These trade-offs depend on management goals, which can range from prioritising ecological integrity to maximising economic gain. The challenge lies in how we assign value to these different objectives — how do we weigh the preservation of a natural ecosystem against the benefits of a popular non-native species?

This difficulty in ascribing monetary value to ecological and socio-economic factors is a nuance that the DOSI framework must address to be more holistic. For instance, the economic impacts on local fisheries, aquaculture, and tourism can be substantial, requiring including these sectors in decision-making processes. Furthermore, the costs of implementing management strategies for high-priority species identified by DOSI should be considered with their potential socio-economic impacts. The integration of socio-economic considerations into the DOSI framework, including both direct economic costs and intangible cultural values, could lead to a more balanced approach that aligns ecological and socio-economic priorities. This approach would also support more effective management decisions, particularly in cases where stakeholders have conflicting interests. Future research could explore ways to refine DOSI by incorporating methods from existing socio-economic assessment tools, ensuring that each element within DOSI is comprehensive and reflects both ecological and socio-economic impacts.

Conclusion

Our study demonstrates the utility of the DOSI scheme in assessing the risks posed by non-native and translocated species in two interconnected aquatic environments in north-western Türkiye. By applying DOSI to 12 established species across Lake Gala and Sığırcı Reservoir, we identified high-priority species, such as *C. gibelio*, *G. cernua*, *C. sapidus*, and *M. coypus*, which warrants targeted management interventions due to their established status, independent spread, and observed negative impacts. Moreover, DOSI provides the advantage of ranking non-native populations based on management urgency, independent of national lists or recommendations from overarching political jurisdictions. This autonomy in assessment is important, particularly given the diverse ecological, economic, and cultural contexts across regions. However, we acknowledge that the current application of DOSI does not systematically integrate socio-economic considerations, which can shape management decisions. Future research should explore ways to integrate socio-economic assessments with DOSI, potentially by drawing on existing risk- assessment tools and frameworks. This integration could provide a more comprehensive understanding of the risks and benefits associated with non-native species and support the development of management strategies that balance ecological and socio-economic priorities. As DOSI continues to be refined and applied in diverse settings, it has the potential to become a valuable tool for researchers, decision-makers, and environmental managers working to address the complex challenges posed by biological invasions and promote effective conservation and management of aquatic ecosystems in Türkiye and beyond. By prioritising populations, DOSI enables a more nuanced and context-specific approach to management, allowing for the development of targeted strategies for species posing the highest risks. Additionally, DOSI evaluates populations within ecosystems, a smaller unit of assessment that holds considerable relevance for stakeholders, decision-makers, and environmental managers.

Methods

Study sites

The Evros Delta Wetland, located where the Evros River flows into the Aegean Sea, is a Class A wetland of international importance located within the territories of Türkiye and Greece[40]. Lake Gala is a natural lake, while the Sığırcı Reservoir is formed from Lake Gala by a dam, but remains connected to Lake Gala. The two water bodies are approximately 11.5 km straight-line distance apart (Fig. 2). Over several decades, both lakes have undergone ecological succession and have transitioned into meso-eutrophic environments[33]. In both ecosystems, *P. fluviatilis* and *S. lucioperca* are the dominant piscivorous species. Additionally, native and non-native cyprinids exhibit dominance[41]. For instance, the stocking of *C. carpio* has inadvertently led to the release of other non-native cyprinid species, such as the trophically similar *C. gibelio*, which has spread widely through this pathway[33]. These non-native species have since established populations, often causing ecological disruptions and impacting native fish species through competition and predation[34,42]. Due to the increase in industrialisation and agriculture in recent years, the water quality of Sığırcı Reservoir and Lake Gala has been deteriorating.

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

We adapted (Soto et al.[29]) and tested the recently developed DOSI assessment scheme (Fig. 3), we used expert knowledge (regarding locally exerted Impacts, Dispersal, and Status) paired with a scoping literature review focusing on the Origin of non-native species and possibly additional information relevant for these non-native species in Lake Gala and Sığırcı Reservoir unknown to the expert (Fig. 3; Table S1). The prime focus was on fish and macroinvertebrates but was open to other taxa. We assessed each identified non-native (six species in Lake Gala; five in Sığırcı Reservoir) and translocated species (one in Lake Gala; five in Sığırcı Reservoir) using DOSI to provide an objective overview for the prioritisation of each population's characteristics (Table 2). Because records for non-native species are not always accompanied by information on changes in abundance or range, we filled information gaps based on our expert knowledge of the study sites.

DOSI only considers negative impacts (i.e., potential threats), acknowledging that negative impacts considerably outweigh and are distinct from any potential benefits[43]. After the DOSI assessment, we developed a weighted ranking to prioritise populations of non-native and translocated species for potential management interventions (Table 2). However, DOSI aims to prioritise populations of non-native species for management interventions based on local risks, disregarding the feasibility or existence of adequate approaches and the species' ability to spread beyond current confinements. We therefore based the DOSI prioritisation on a hierarchy of primary dispersal mechanisms, separating non-native populations that can (a) spread independently and therefore invade areas beyond the introduction site from those (b) that rely primarily on human assistance and the existence of pathways and vectors, or (c) that are capable of both assisted and independent spread (i.e., assessed for both a and b), and (d) the population's status defining the state of a population within the target site and the locally exerted impact.

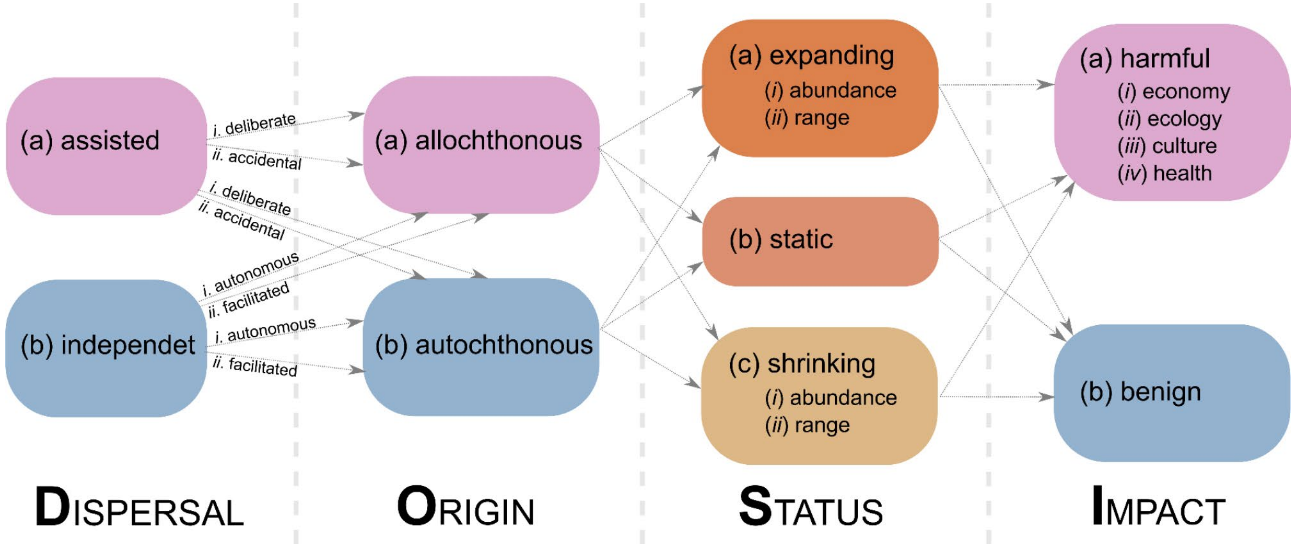

Fig. 2. Proposed DOSI classification scheme for species/populations moving into a novel environment. A species' **D**ISPERSAL mechanism can be assisted from its place of origin either *deliberately* (a_i) or *accidentally* (a_{ii}), or it can migrate *independently* of direct human intervention (b_i) or by being *facilitated* (b_{ii}) by exploiting a human-driven change to the environment (e.g., canals). The **O**RIGIN of a species that has its distribution shifted according to the mechanisms described in 1 can either be introduced, *allochthonous* (Oa) (not from 'here', where the definition of 'here' depends on the spatial scale of interest) or indigenous, *autochthonous* (Ob) (from 'here', as in the case of local species moving within the region of focus). The definition of *allochthonous* or *autochthonous* can also depend on how much time has elapsed since the species arrived (e.g., events in geological time, ancient introductions, etc.). **S**TATUS refers to the state of the population(s) of the species, defined either/both in terms of *abundance* or/and *range* size (*expanding*, *static*, or *shrinking*)—these assessments depend on the time that the species has been present, how much measurement effort has been applied to assess population change, and whether interventions (if any) have been effective. The **I**MPACT category assesses whether the species causes harm to ≥ 1 sector (ecology, economy, culture, [human] health—such an assessment can cover a gradient from little to extensive harm), or if it is benign (no effect). Figure adapted from Soto et al.[29].

Populations capable of both assisted and independent spread, and those exhibiting changes in both abundance and range, are ranked higher than populations with only one dependency because the former conditions indicate a more extensive and damaging invasion potential. The same is applied when one dependency is static and the other is expanding. When a population is deemed to have only benign known impacts, which are set as equal to no relevant or measurable impact, it is demoted in its priority ranking (Fig. 4). All introduced and established non-native species have some form of impact by occupying space and using resources; however, these impacts currently are not considered relevant by the DOSI assessment (Soto et al.[29]).

Because DOSI is an assessment scheme that focuses on prioritising non-native populations within individual ecosystems, it ranks expanding (both in terms of abundance and range) populations over those that are static, even if these have reached the maximum carrying capacity and/or already occupy the entire ecosystem. This is because expanding populations pose a greater risk of additional spread and potential invasion into adjacent ecosystems, thereby increasing their overall impacts on biodiversity and ecosystem functioning[44]. In contrast, static populations, even if they have saturated their current habitats, can exert a consistent threat even if they are less likely to exacerbate their impact through additional expansion. Thus, DOSI prioritises expanding populations for management intervention because they represent a dynamic and potentially escalating threat, while static populations, although still of concern, might require a more maintenance-oriented approach. This focus on expansion helps ensure that resources are allocated to populations that could cause the most harm if left unchecked.

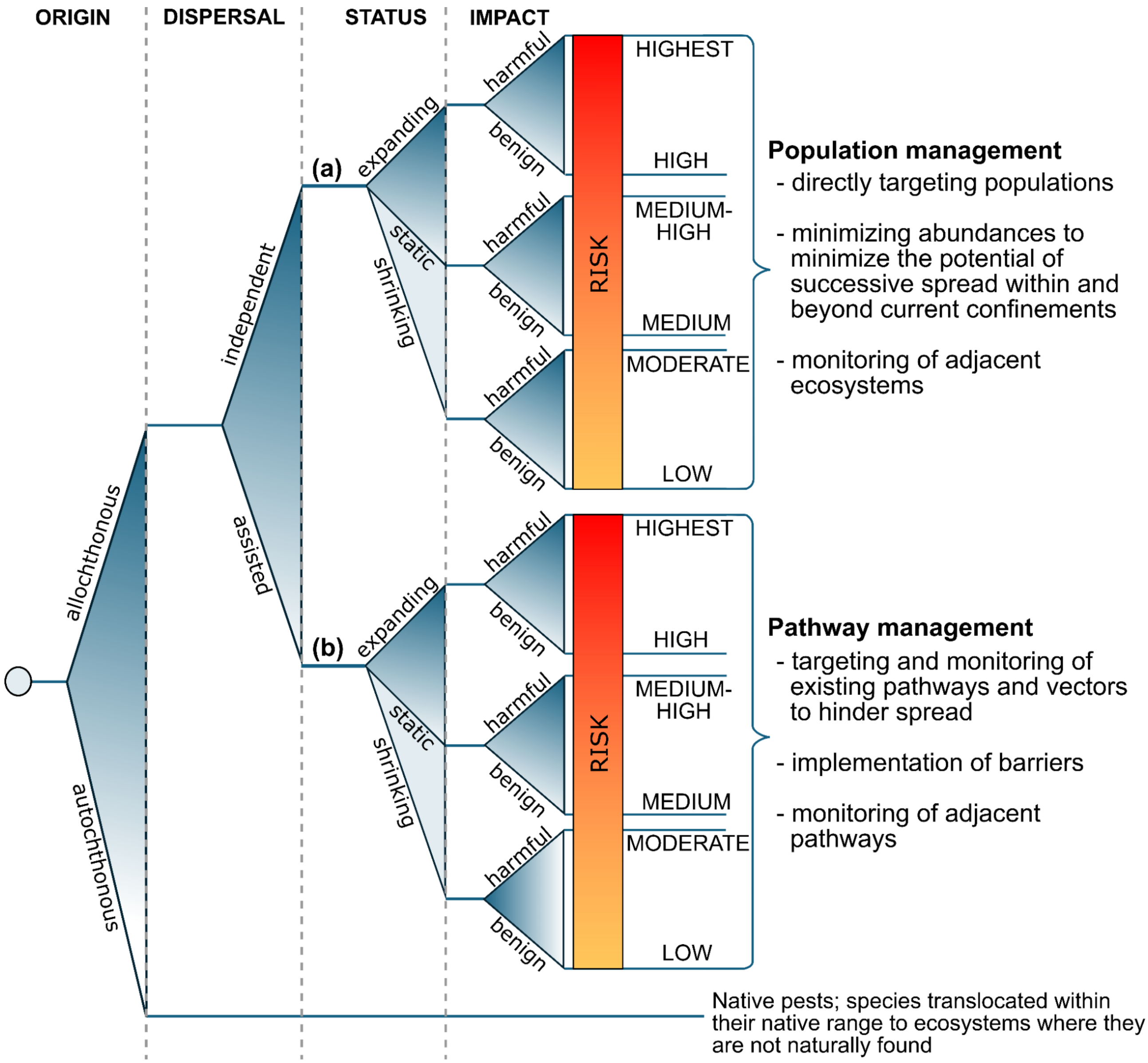

Fig. 3. Proposed "Decision Tree" priority ranking for management interventions of non-native populations following the Disperal-Origin-Status-Impact (DOSI) assessment scheme (Fig. 2) for (**a**) non-native populations dispersing mainly without human assistance, or (**b**) populations that rely on human assistance to spread.

Site	Species	Dispersal mechanism	Origin	Status	Impact	Priority	References
Lake Gala	*Callinectes sapidus*	Ballast waters are the most probable introduction vector [Da_{ii}]	South America [Oa]	Range: static (entire ecosystem); abundance: increasing [sa_ib_{ii}]	Ecological: predation, habitat degradation; economic: damaging traps and nets; cultural: considered pest, undemanded; health: *na* [$ia_{i,ii,iii}$]	*Highest*	
	Carassius gibelio	Unintentional introductions with common carp stocking and intentional introductions by fishermen [$Da_{i,ii}$]	Asia, Eastern Europe [Oa]	Range: static (entire ecosystem); abundance: stable [$sb_{i,ii}$]	Ecological: reproductive interference, habitat alteration, competition; economic: replacing economic species; cultural: fisher relocation; health: *na* [$ia_{i,ii,iii}$]	*Medium–High*	Aydin et al.[45], Tarkan et al.[20,33,34]
	*Cyprinus carpio**	Repeatedly introduced for fisheries enhancement [Da_i]	Eastern and Central Asia, and Eastern Europe [Ob]	Range: static (entire ecosystem); abundance: stable [sa_ib_i]	Ecological: competition, habitat alteration; economic: *na*; cultural: *na*; health: *na* [ia_{ii}]	*Medium–High*	Aksu et al.[41]
	Gambusia holbrooki	Accidental release, and intentional introductions by the public [$Da_{i,ii}$]	North America [Oa]	Range: static (widespread); abundance: stable [$sb_{i,ii}$]	Ecological: competition with native fish; economic: *na*; cultural: *na*; health: *na* [ia_{ii}]	*Medium–High*	Kurtul et al.[46,47]
	Gymnocephalus cernua	Accidental release from nearby basins [Da_{ii}]	Eurasia [Oa]	Range: increasing; abundance: increasing [$sa_{i,ii}$]	Ecological: competition, predation; economic: damaging fishnets; cultural: *na*; health: *na* [$ia_{i,ii}$]	*Highest*	Tarkan et al.[48]
	Lepomis gibbosus	Unintentional introductions with common carp stocking and intentional introductions for ornamental purposes [$Da_{i,ii}$]	North America [Oa]	Range: static; abundance: stable [$sb_{i,ii}$]	Ecological: no information available. But competition is possible; economic: *na*; cultural: *na*; health: *na* [ib]	*Medium*	Toutain et al.[49]
	Myocastor coypus	Natural spread, possibly human-mediated [Db_i]	South America [Oa]	Range: increasing; abundance: increasing [$sa_{i,ii}$]	Ecological: food web, consuming wetland plants; Economic: damaging fishnets and reducing economic fish Cultural: pest & undesired; health: parasite transmission [$ia_{i,ii,iii,iv}$]	*Highest*	Pamukoğlu[50], Tarkan et al.[20]
	Pseudorasbora parva	Unintentional introductions with common carp stocking [Da_{ii}]	East Asia [Oa]	Range: shrinking; abundance: shrinking [$sc_{i,ii}$]	Ecological: *na*; economic: *na*; cultural: *na*; health: *na* [ib]	*Low*	Tarkan et al.[17]
Continued							

Site	Species	Dispersal mechanism	Origin	Status	Impact	Priority	References
Sığırcı Reservoir	*Carassius gibelio*	Spread from Lake Gala [D_ib_{ii}]	Asia, Eastern Europe [Oa]	Range: increasing; abundance: increasing [$sa_{i,ii}$]	Ecological: reproductive interference, habitat alteration, competition; Economic: replacing economic species Cultural: fisher relocation; health: *na* [$ia_{i,ii,iii}$]	*Highest*	Tarkan et al [20,33,34]
	Cyprinus carpio	Repeatedly introduced for fisheries enhancement and natural spread from Lake Gala [Da_i,b_{ii}]	Eastern and central Asia, and Eastern Europe (west to the Danube basin, Black, Caspian and Baltic Sea drainages) [Ob]	Range: static (entire ecosystem); abundance: stable [$sb_{i,ii}$]	Ecological: competition, habitat alteration; economic: *na*; cultural: *na*; health: *na* [ia_{ii}]	*Medium–High*	Aksu et al.[41]
	Dreissena polymorpha	Spread from Lake Gala [Db_{ii}]	Black, Caspian and Aral Sea drainages [Ob]	Range: static; abundance: stable [$sb_{i,ii}$]	Ecological: *na*; economic: *na*; cultural: *na*; health: *na* [ib]	*Medium*	Aydın et al.[51]
	Gambusia holbrooki	Spread from Lake Gala [Db_{ii}]	North America [Oa]	Range: static; abundance: stable [$sb_{i,ii}$]	Ecological: competition with native fish; economic: *na*; cultural: *na*; health: *na* [ia_{ii}]	*Medium–High*	Kurtul et al.[46,47]
	Gymnocephalus cernua	Spread from Lake Gala [Db_{ii}]	Eurasia [Oa]	Range: increasing; abundance: increasing [$sa_{i,ii}$]	Ecological: competition, predation; economic: damaging fishnets; cultural: *na*; health: *na* [$ia_{i,ii}$]	*Highest*	Tarkan et al.[48]
	Lepomis gibbosus	Unintentional introductions with common carp stocking and spread from Lake Gala [$Da_{ii}b_{ii}$]	North America [Oa]	Range: static; abundance: stable [$sb_{i,ii}$]	Ecological: *na*; economic: *na*; cultural: *na*; health: *na* [ib]	*Medium*	Toutain et al.[49]
	Myocastor coypus	Spread from Lake Gala [Db_{ii}]	South America [Oa]	Range: static; abundance: stable [$sb_{i,ii}$]	Ecological: *na*; economic: *na*; cultural: *na*; health: *na* [ib]	*Medium*	
	Perca fluviatilis	Spread from Lake Gala [Db_{ii}]	Europe, Thrace and Black Sea region of Türkiye [Ob]	Range: static (entire ecosystem); abundance: stable [$sb_{i,ii}$]	Ecological: competition, predation; economic: *na*; cultural: *na*; health: *na* [ia_{ii}]	*Medium–High*	Tarkan et al.[37]
	Rutilus rutilus	Spread from Lake Gala [Db_{ii}]	Europe, Türkiye [Ob]	Range: static; abundance: stable [$sb_{i,ii}$]	Ecological: *na*; economic: *na*; cultural: *na*; health: *na* [ib]	*Medium*	
	Sander lucioperca	Spread from Lake Gala [Db_{ii}]	Europe, Thrace [Ob]	Range: shrinking; abundance: shrinking [$sc_{i,ii}$]	Ecological: *na*; economic: *na*; cultural: *na*; health: *na* [ib]	*Low*	

Table 2. Impact classification of non-native and translocated fish species in Lake Gala and Sığırcı Reservoir using the Dispersal-Origin-Status-Impact (DOSI) classification scheme. **Dispersal** mechanism: a species is assisted from its place of origin either deliberately (Da_i) or accidentally (Da_{ii}), or it can migrate independently of direct human intervention (Db_i) or by being facilitated (Db_{ii}) by exploiting a human-driven change to the environment. **Origin**: a species that has its distribution shifted according to the mechanisms described in Table 1, can either be allochthonous (Oa) (not from 'here', where the definition of 'here' depends on the spatial scale of interest) or autochthonous (Ob) (from 'here', as in the case of local species moving within the region of focus). **Status**: the status of the population(s) of the species, defined either/both in terms of abundance or/and range size (expanding, static, or shrinking). **Impact**: whether the species causes harm to ≥ one sector (ecology, economy, culture, [human] health) or if it is benign (no effect); assessed based on the assessors' expert knowledge. See Table 1 for priority ranking.

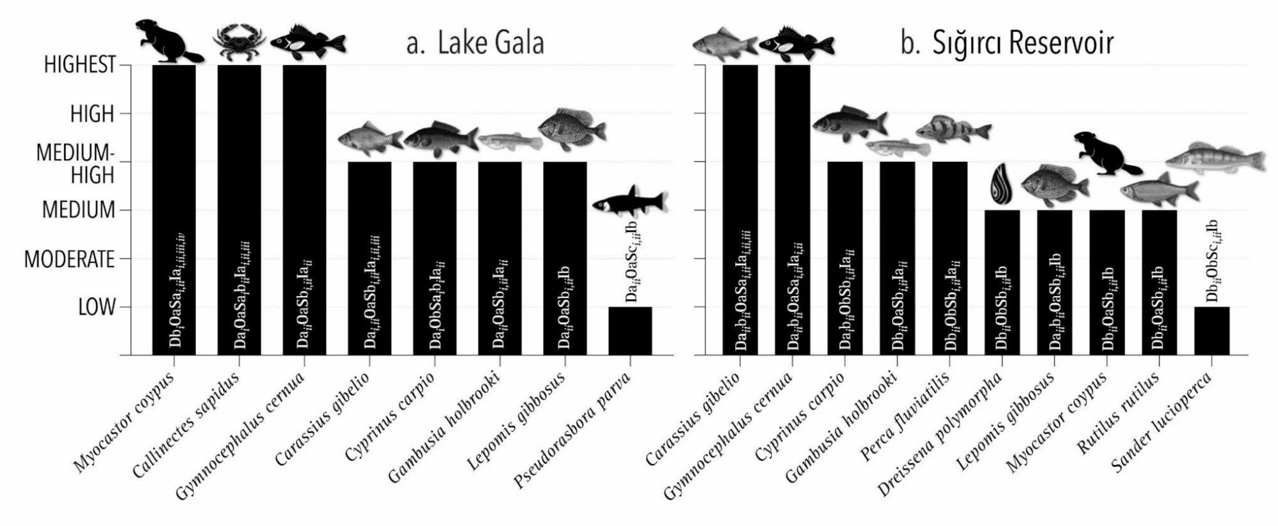

Fig. 4. Ranking of established non-native species for management targeting populations in Lake Gala and Sığırcı Reservoir following the assessment with the Dispersal-Origin-Status-Impact (DOSI) scheme. See Table 2 for the explanations of the text inside the bars.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files.

Received: 15 June 2024; Accepted: 4 December 2024
Published online: 28 December 2024

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AST—conceptualization, data curation, formal analysis, investigation, writing- original draft; OE—data curation, investigation; SA—data curation, investigation; IK—data curation, investigation, writing—review and editing; DB—writing—review and editing, visualization; EB—writing—review and editing; IS—conceptualization, methodology, visualization, writing—review and editing; SSC—writing—review and editing; PJH—conceptualization, methodology, formal analysis, visualization, writing—review and editing; CJAB—conceptualization, methodology, formal analysis, visualization, writing, supervision—review and editing.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-024-82284-z.

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