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Prioritising Non-Native Crayfish Species for Management in the Rhine-Main Observatory Using the Dispersal-Origin-Status-Impact (DOSI) Scheme

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ABSTRACT

Managing non-native species remains a critical challenge in biodiversity conservation, highlighting the need for effective prioritisation frameworks that integrate ecological, economic and policy considerations. Given that biological invasions are a population-level rather than a species-level phenomenon, more nuanced assessment schemes are needed. The Dispersal-Origin-Status-Impact (DOSI) scheme is such an example. Using the Rhine-Main-Observatory (RMO) Long-Term Ecological Research (LTER) site in Germany as a model system, we applied DOSI to rank the occurring non-native crayfish species to guide conservation actions. Our results classify the signal crayfish *Pacifastacus leniusculus* as the highest priority for management due to its expanding range, autonomous spread and severe ecological and economic impacts. The spiny-cheek crayfish *Faxonius limosus* follows as a medium-high priority species, while the red swamp crayfish *Procambarus clarkii* and the calico crayfish *Faxonius immunis* are ranked lower due to their shrinking or static populations despite their known potential impacts observed at other places. Our study highlights the utility of DOSI as a practical and scalable tool for invasion risk assessment, offering a targeted, data-driven approach to inform decision-making at the population level. By shifting the focus to population-level management, DOSI enhances conservation planning beyond traditional species-based assessments, providing a structured framework for mitigating the risks posed by invasive species in dynamic freshwater ecosystems.

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1 | Introduction

In the Anthropocene, the proliferation of non-native species has become an environmental concern and a global challenge (Simberloff et al. 2013). Biological invasions result from accidental or intentional species introductions and byproduct of human activities such as intensified global trade, tourism, travel and anthropogenic environmental degradation (Lodge et al. 2006). In recent decades, biological invasions have escalated, profoundly impacting the social-ecological aspects that support human well-being worldwide (Seebens et al. 2021; Daly et al. 2023). These invasions have become pivotal in the discourse of biodiversity conservation and environmental management (Hulme 2021; Roy 2023). The impacts of non-native species can vary over space and time and are linked to the consequent modification of ecosystems (e.g. trophic web alterations via predation and competition for resources; structural modifications of habitats) as well as their possible interaction with the effects of other stressors (Haubrock et al. 2020; Soto, Macêdo, et al. 2024). Additionally, non-native species can introduce pathogens or act as hosts, contributing to the proliferation of diseases and threatening native species lacking resistance (Macêdo et al. 2022; Zhang et al. 2022). Owing to these multifaceted impacts, management of biological invasions must focus not only on mitigating the spread of non-native species but also on mitigating their impacts.

Researchers, environmental managers, conservationists, and policymakers are actively devising and deploying strategies to avert additional introductions of non-native species and curb their subsequent establishment, proliferation and effects. Risk analysis, spanning the main phases of the invasion process, plays an important role in guiding management decisions and involves a combination of different methods (e.g. Gallien et al. 2012; Leung et al. 2012; Haubrock et al. 2020; Holman et al. 2022). They are crucial in preventing the introduction of potentially harmful non-native species by identifying high-risk taxa even before they arrive, guiding biosecurity measures, and informing the development of species watch lists. These analyses also support efforts to prevent the transport, establishment, and spread of invasive species and aid in evaluating responses (Hulme 2009; Kumschick and Richardson 2013; Roy et al. 2014). As part of this, they can help determine whether eradication or control measures are necessary (or warranted) for non-native species that arrive and establish populations (Pluess et al. 2012). The assessment of both realised and potential impacts of non-native species assumes prioritising management interventions (Essl et al. 2011). However, managing biological invasions has been hampered by the magnitude of new introductions, inadequate and inefficient investments, as well as a limited understanding of the species' dynamics, owing mainly to cryptic populations and lags between the introduction of a species and its rapid spread (Strayer et al. 2017; Haubrock et al. 2022; Soto et al. 2023). This is especially true in freshwater ecosystems where environmental fluctuations, hydrological connectivity, and complex ecological interactions can delay the recognition of both the presence and impacts of biological invasions (Wagner et al. 2020; Macêdo et al. 2022).

Freshwater crayfish play crucial roles in ecosystems (O'Hea Miller et al. 2024). Their diet covers multiple trophic levels, thus influencing energy flow and nutrient cycling. Their activities, such as foraging and burrowing, alter sediment transport dynamics, making them recognised ecological engineers (Statzner et al. 2003; Kouba et al. 2016). However, when introduced and established in non-native ranges, they often pose significant ecological threats, leading to the decline or extinction of native species (Twardochleb et al. 2013). Among others, these impacts arise through competition, predation, disease transmission and reproductive interference, yet research—particularly field studies on competition—remains limited (O'Hea Miller et al. 2024). Invasive crayfish are particularly successful due to their early maturation, high fecundity, rapid growth and generalist feeding habits, alongside their ability to tolerate extreme conditions (e.g. Beatty et al. 2005). Their aggressive behaviour gives them a competitive edge over native crayfish, further driving population declines (Dorn et al. 1999; Fořt et al. 2019). Freshwater crayfish are notoriously known as among the most problematic invasive species once established, given their prominent ecological roles and life history traits they possess (Twardochleb et al. 2013; Vodovsky et al. 2017), impacting native biota and ecosystem (Gherardi et al. 2011; Kouba et al. 2016). Once established, managing non-native freshwater crayfish species is costly and labour-intensive, and effective eradication methods are lacking (Lidova et al. 2019; Manfrin et al. 2019). The challenge is acute in low- and middle-income nations, whose response might be insufficient due to limited resources and available data, further complicating the management of biological invasions (Tobin 2018; Haubrock, Turbelin, et al. 2021). The outcome of targeted and judicious management strategies (Hoddle 2004) is also influenced by social and cultural factors, such as public acceptance and awareness (Courchamp et al. 2017; Roberts et al. 2018). Moreover, interventions attempting to control these species can be controversial and pose risks to native biota and human health (e.g. biocontrol agents and pesticides; Messing and Wright 2006; Layne and Stubbs 2009; Kumschick et al. 2012). As such, the focus is often on species with impacts (potentially observed elsewhere) rather than those that spread and might pose a threat in other locations (Vander Zanden and Olden 2008).

Harmonised risk assessment approaches are crucial for informed decision-making and effective conservation action against non-native species, and in response, the availability of various tools increased considerably (Srėbalienė et al. 2019). However, there is a growing demand for robust and user-friendly assessment protocols that cater to professionals with diverse expertise and knowledge. These protocols are needed to predict the potential impacts of new invaders and evaluate the real impact of established species. However, existing risk identification (e.g. *Aquatic Species Invasiveness Screening Kit*; Vilizzi et al. 2021) and assessment (e.g. *Environmental Impact Classification for Alien Taxa*, Hawkins et al. 2015 and *The European Non-native Species in Aquaculture Risk Analysis Scheme,* Tarkan et al. 2020) frameworks have primarily focused on the species-level across various spatial scales from the continental (Haubrock, Copp, et al. 2021; Haubrock, Oficialdegui, et al. 2021) to national level (Tarkan et al. 2017). There is a growing recognition that biological invasions are context-specific, with spread and impact differing among populations because of variable biotic and abiotic conditions. However, while these tools provide structured approaches, they are often complex and require answering numerous detailed questions, necessitating solid, peer-reviewed literature support (Vilizzi et al. 2021). This can be particularly challenging for lesser-known species or those lacking significant economic or ecological importance, where data availability is limited. Consequently, well-defined and standardised assessment protocols that treat effects (status and impact) differently among populations, even within the same species, are still required. This ensures a judicious allocation of resources (McGeoch et al. 2016) and facilitates the prioritisation of species for subsequent risk assessments (Brunel et al. 2013).

The Dispersal-Origin-Status-Impact (DOSI) assessment scheme (Figure 1) proposed by Soto, Balzani, et al. (2024) recognises that biological invasions are a population-level phenomena, rather than a burden that can be generalised to the entire species. DOSI embraces the intricacies affecting populations of non-native species based on four primary components: (i) **D**ispersal mechanisms (assisted vs. independent), (ii) **O**rigin (allochthonous vs. autochthonous), (iii) current **S**tatus (expanding, stationary or shrinking) and (iv) **I**mpact (ecological, economic, health and/or cultural). This nuanced and granular approach aligns with the requirement for objective, data-driven methodologies in the management of biological invasions (Finley et al. 2023). After confirmation and preliminary testing by Błońska et al. (2024), Tarkan, Emiroğlu, et al. (2024) and Tarkan, Kurtul, et al. (2024), DOSI's strength lies in its ability to provide a comprehensive yet flexible framework

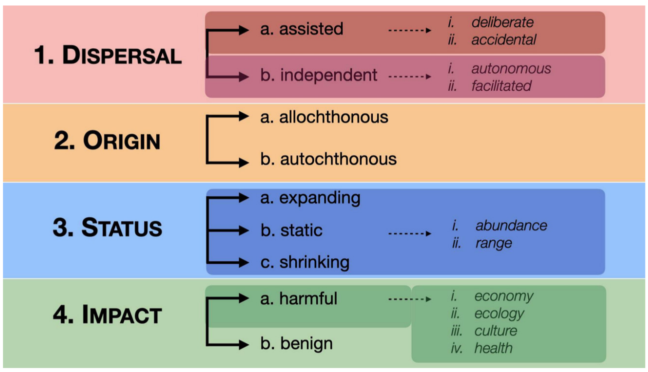

FIGURE 1 | Flow diagram for the proposed classification scheme for species/populations moving into a novel environment. A species' **D**ISPERSAL mechanism can be assisted from its place of origin either *deliberately* ($1a_i$) or *accidentally* ($1a_{ii}$), or it can migrate *independently* of direct human intervention ($1b_i$) or by being *facilitated* ($1b_{ii}$) 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 *allochthonous* (2a) (not from 'here', where the definition of 'here' depends on the spatial scale of interest), or *autochthonous* (2b) (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 and ancient introductions). **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 sectors (ecology, economy and culture, [human] health—such an assessment can cover a gradient from little to extensive harm), or if it is benign (no effect).

that adapts to varying temporal, spatial and measurement scales, being employed locally for an individual population or at regional or ecosystem scales. DOSI improves on previous approaches for managers and stakeholders who often face limited resources (Adelino et al. 2021) by helping to prioritise populations of non-native species for intervention. Additionally, DOSI values expert opinion and experience, allowing for informed decision-making even in data-limited situations. This emphasis on expert knowledge further enhances its usability and practical application, making it a more accessible tool for risk assessment and management. Finally, by avoiding negatively connoted and politically charged terms like 'invasive', 'non-indigenous', 'exotic' or 'colonised' (see Soto, Balzani, et al. 2024, for further reference), the scheme fosters a more objective and transparent scientific discourse.

In this study, we applied the DOSI scheme for the Rhine-Main-Observatory (RMO) Long Term Ecological Research (LTER) site in Hessia, Germany. The RMO examines the long-term impacts of habitat fragmentation, land use, climate change, and other environmental factors on plant and animal communities in a 'normal' German context. By applying DOSI to populations of different non-native crayfish species, we aim to evaluate its efficacy and reliability in capturing the nuances of biological invasions at the population level and ranking these populations according to the risks they pose to their host ecosystems in the given region. Our methodology encompasses a detailed analysis of each DOSI component, assessing its relevance and applicability across different species and environments. In turn, we aimed to test and refine DOSI as a tool for scientists, policymakers, and conservationists, targeting reproducibility and transparency. We anticipate that this tool will provide a reliable and standardised approach for assessing and managing non-native species globally.

2 | Methods

The RMO (50.2673°N latitude and 9.2691°E longitude) is a LTER site located in central Germany (https://deims.org/9f9ba137-342d-4813-ae58-a60911c3abc1), encompassing the entire 1058-km^2 watershed of the River Kinzig. Specifically, located in the Rhine-Main region—Germany's second-largest metropolitan area—the Kinzig River serves as a natural boundary between three lower mountain ranges: the Rhön, Vogelsberg and Spessart. Established in 2007, the RMO investigates the long-term effects of habitat fragmentation, land-use and climate change on animal and plant communities, with a particular focus on stream, floodplain, and urban ecosystems. The observatory's diverse landscape includes both densely populated urban areas and natural habitats, providing a comprehensive platform for studying biodiversity patterns and ecological processes across varying degrees of human influence, otherwise often underrepresented in existing long-term monitoring efforts.

To apply the DOSI assessment scheme (Figure 1) on the established non-native crayfish species in the RMO, we identified all relevant species of non-native crayfish using the *Species Database Rhine-Main-Observatory* (https://rmo.senckenberg.de/search/home.php) and relevant literature using the RMO's publication repository (https://www.senckenberg.de/en/institutes/senckenberg-research-institute-natural-history-museum-frankfurt/division-river-ecology-and-conservation/section-river

-and-floodplain-ecology/river-and-foodplain-ecology-publications/). We verified that a species was non-native by consulting public databases, including the *Global Biodiversity Information Facility* (GBIF), Henry et al. (2023), and Haubrock et al. (2025). We then assessed each identified non-native crayfish species using DOSI and categorised them based on their dispersal mechanism, origin, status, and impact to provide an objective overview for the prioritisation of each population's characteristics. Because records for these non-native crayfish species are not always accompanied by information on abundance trends or range dispersal, we filled information gaps based on our expert knowledge of the study site. Despite DOSI distinguishing autochthonous (i.e. translocation of native species; e.g. Franco et al. 2022; Tarkan, Kurtul, et al. 2024) from allochthonous (i.e. non-native) species, we decided to focus only on non-native crayfish species. DOSI only considers negative impacts, acknowledging that negative impacts considerably outweigh and are distinct from any potential benefits (Carneiro et al. 2024). Although subjective, the impact classification for species assessed with DOSI presents an expert-based ranking. This means that if no impact assessments have been conducted in the assessment area, assessors can describe a species' impacts by referring to potential impacts observed elsewhere. If impact assessments have been conducted, they should describe locally observed impacts. Since no impact assessments were conducted for non-native crayfish species in the RMO, the authors refer to potential impacts instead. However, the aim of DOSI is 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, the populations' status defining the state of a population within the target site, locally expected impacts, and separating non-native populations that can (a) spread independently and thus can invade areas beyond the invaded site and require targeted population management, from (b) those that rely on human assistance and the existence of pathways and vectors, therefore requiring targeted pathway management or (c) those that are capable of both assisted and independent spread (i.e. assessed for both a and b). For both, non-native species that spread mostly without human assistance and non-native species that spread mainly with human assistance, this results in the following ranking encompassing the priority levels: 'Highest Priority', 'High Priority', 'Medium-High Priority', 'Medium Priority', 'Moderate Priority' and 'Low Priority' (Figure 2).

Populations capable of both assisted and independent spread, as well as those exhibiting increasing changes in both abundance and range, are ranked higher than populations with only one dependency because the former conditions indicate a more extensive and potentially more damaging invasion. The same applies when one dependency is static and the other is expanding. However, the authors prioritise abundance changes over changes in range in confined risk assessment areas (e.g. lakes and reservoirs) and changes in range over changes in abundance in open areas (e.g. rivers or streams). Thus, when a population's status is categorised as shrinking in the RMO, it is demoted in its priority ranking.

3 | Results

The *Species Database Rhine-Main-Observatory* identified four non-native crayfish species: the spiny-cheek crayfish *Faxonius limosus*, the calico crayfish *Faxonius immunis*, the signal crayfish *Pacifastacus leniusculus* and the red swamp crayfish *Procambarus clarkii* (Table 1 and Figure 3). Although all four species have been identified in the RMO, their distribution varied substantially, with *P. leniusculus* occupying the largest area, with established populations found throughout the RMO, and *F. limosus* found only (but widely) distributed in the South-Western area of the RMO. *F. immunis* and *P. clarkii* occurred only in isolated populations in the far South-Western area of the RMO (Oficialdegui et al. 2024).

Using the DOSI scheme, we classified all four species as non-native (i.e. allochthonous) species that relied on comparable dispersal mechanisms, including both assistant (deliberate and accidental) human activities, including the pet trade,

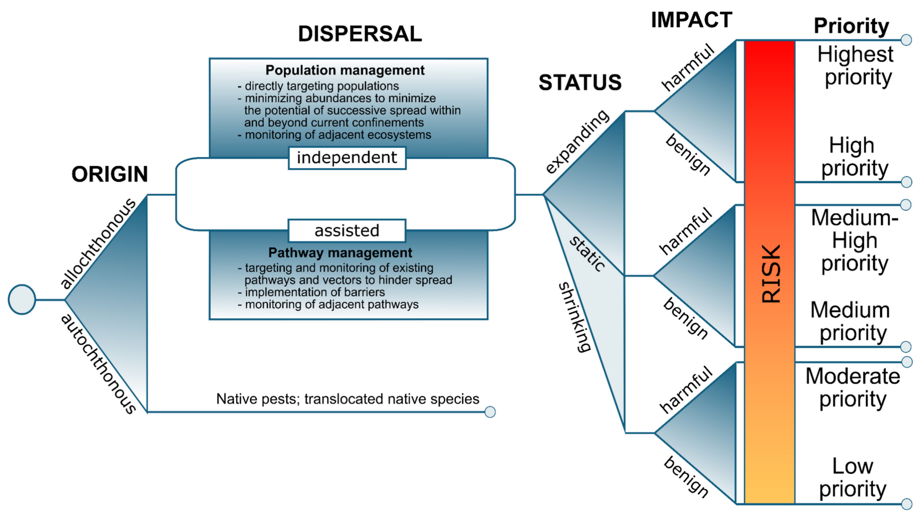

FIGURE 2 | Proposed priority ranking for management interventions of non-native populations following the Disperal-Origin-Status-Impact (DOSI) assessment scheme for populations of non-native species.

TABLE 1 | Classification of non-native fish species using the Dispersal-Origin-Status-Impact (DOSI) classification scheme.

Species	Common name	Origin	Dispersal mechanism	Status*	Potential impacts**
Faxonius immunis	Calico crayfish	(North America) **Oa**	Assisted (deliberate and accidental) and independent (autonomous) possible but currently not observed in the RMO Pathway: unknown, possibly accidentally introduced with fish stocking in angling ponds and when used as bait $\mathbf{Da_{i,ii}b_i}$	Shrinking abundance Static range $\mathbf{Sb_{ii}c_i}$	Economy: Low Ecology: Moderate Culture: low Health: Low $\mathbf{Ia_{ii}\ b_{i,iii,iv}}$
Faxonius limosus	Spiny-cheek crayfish	(North America) **Oa**	Assisted (deliberate and accidental) and independent (autonomous) possible but currently not observed in the RMO Pathway: unknown, possibly accidentally introduced with fish stocking in angling ponds or when used as bait due to their smaller size $\mathbf{Da_{i,ii}b_i}$	Static abundance Expanding range $\mathbf{Sa_{ii}b_i}$	Economy: low to moderate Ecology: High Culture: Low Health: Moderate $\mathbf{Ia_{i,ii,iv}\ b_{iii}}$
Pacifastacus leniusculus	Signal crayfish	(North America) **Oa**	Assisted (deliberate and accidental) and independent (autonomous) likely occurring in the RMO Pathway: unknown, possibly accidentally introduced with fish stocking in angling ponds or through bucket introductions when misidentified $\mathbf{Da_{i,ii}b_i}$	Expanding abundance Expanding range $\mathbf{Sa_{i,ii}}$	Economy: High Ecology: Very high Culture: Moderate Health: High $\mathbf{Ia_{i,ii,iii,iv}}$
Procambarus clarkii	Red swamp crayfish	(North America) **Oa**	Assisted (deliberate and accidental) and independent (autonomous) possible but currently not observed Pathway: Ornamental; pet trade, bait (sportfishing) $\mathbf{Da_{i,ii}b_i}$	Shrinking abundance Shrinking range $\mathbf{Sc_{i,ii}}$	Economy: High Ecology: Very high Culture: High Health: High $\mathbf{Ia_{i,ii,iii,iv}}$

*Information established based on the assessors' experience and local knowledge.
**Based on impacts inferred not necessarily locally, but globally.

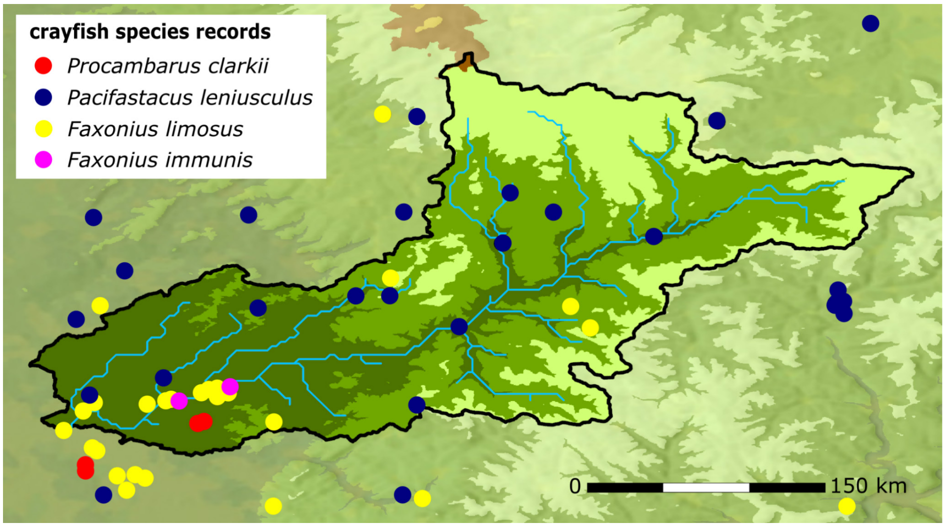

FIGURE 3 | Distribution of crayfish species in the Rhine-Main-Observatory and in the Main-Kinzig district (delimited area in grey) in central Germany following the Rhine-Main-Observatory species database https://rmo.senckenberg.de/search/home.php and the World of Crayfish (Ion et al. 2024).

ornamental use and bait for sportfishing, as well as independent spread (Table 1). *P. leniusculus* was the most widespread, with both its range and abundance expanding due to assisted and autonomous dispersal. *F. limosus* was also increasing in range but maintained a static abundance. In contrast, *P. clarkii* and *F. immunis* existed in isolated populations, both experiencing a shrinking range and declining abundance, whereas *P. leniusculus* continues to spread. Furthermore, we identified varying potential impacts of the four non-native crayfish species in the RMO region of Germany. *P. leniusculus* and *P. clarkii* potentially exert the most severe effects, including high economic damage—*P. leniusculus* harming fisheries and *P. clarkii* causing infrastructure damage through burrowing. Both species are known for high ecological impacts, altering habitats and displacing native species (Svoboda et al. 2017). Moreover, although all of these non-native species pose significant health risks as vectors of the crayfish plague, *P. leniusculus* is the the most likely species that can reach the habitats occupied by noble crayfish *Astacus astacus* (Ercoli et al. 2014, 2025). *F. limosus* has a high ecological impact due to competition and habitat modification, a moderate economic threat and moderate health risks. With a more restricted range, *F. immunis* has the lowest potential impact, contributing moderately to ecological disruption and associated risks. Potential cultural impacts were highest for *P. clarkii* due to its previous presence in the pet trade (despite now being outlawed; Lipták et al. 2023), while *P. leniusculus* has some importance in fisheries and gastronomy.

Based on the DOSI framework ranking prioritising species based on their potential for spread, status and potentially exerted impacts (Figure 4), *P. leniusculus* ranked as the highest priority for direct management due to its dual dispersal mechanisms (assisted and autonomous), combined with expanding abundance and range, and significant harmful impacts (Economy: High, Ecology: Very High, Culture: Moderate and Health: High). *F. limosus* was assigned a medium-high priority as it exhibited an expanding range, albeit with static abundance and exerting high ecological impacts alongside moderate risks to the economy and health. *P. clarkii*, despite its severe harmful impacts (Economy: High, Ecology: Very High, Culture: High and Health: High), was ranked with moderate priority because of its shrinking range and abundance, indicating reduced current threats. Finally, *F. immunis* was categorised as low-moderate priority due to its static range, shrinking abundance, and relatively low impacts (Economy: Low, Ecology: Moderate, Culture: Low and Health: Low), along with its reliance on human-assisted dispersal. The final ranking prioritises species based on their potential for spread, status and locally exerted impacts, with *P. leniusculus* posing the most urgent management concern.

For management strategies under the DOSI framework, directly applied population-level management was found to be most suitable for *P. leniusculus* and *F. limosus*, as both species have active or expanding populations that require direct interventions to limit their spread and impacts. Pathway management is most appropriate for *F. immunis* and *P. clarkii*, as their spread relies heavily on human assistance, and controlling pathways and vectors could effectively mitigate their impact. For *P. leniusculus*, a combination of both population management and pathway management is advisable due to its dual dispersal mechanisms and significant negative impacts on local ecosystems.

4 | Discussion

The DOSI assessment represents a significant advancement in the management of non-native species populations by providing an objective and comprehensive classification across the core dimensions of biological invasions (Soto, Balzani, et al. 2024). Here, we applied the DOSI framework to assess four non-native crayfish species in the RMO in Hessia, Germany: *P. leniusculus*, *F. limosus*, *P. clarkii* and *F. immunis*. Our findings highlight the utility of the DOSI scheme in providing context-specific insights and advancements in the assessment of populations of non-native species through objective classification across all

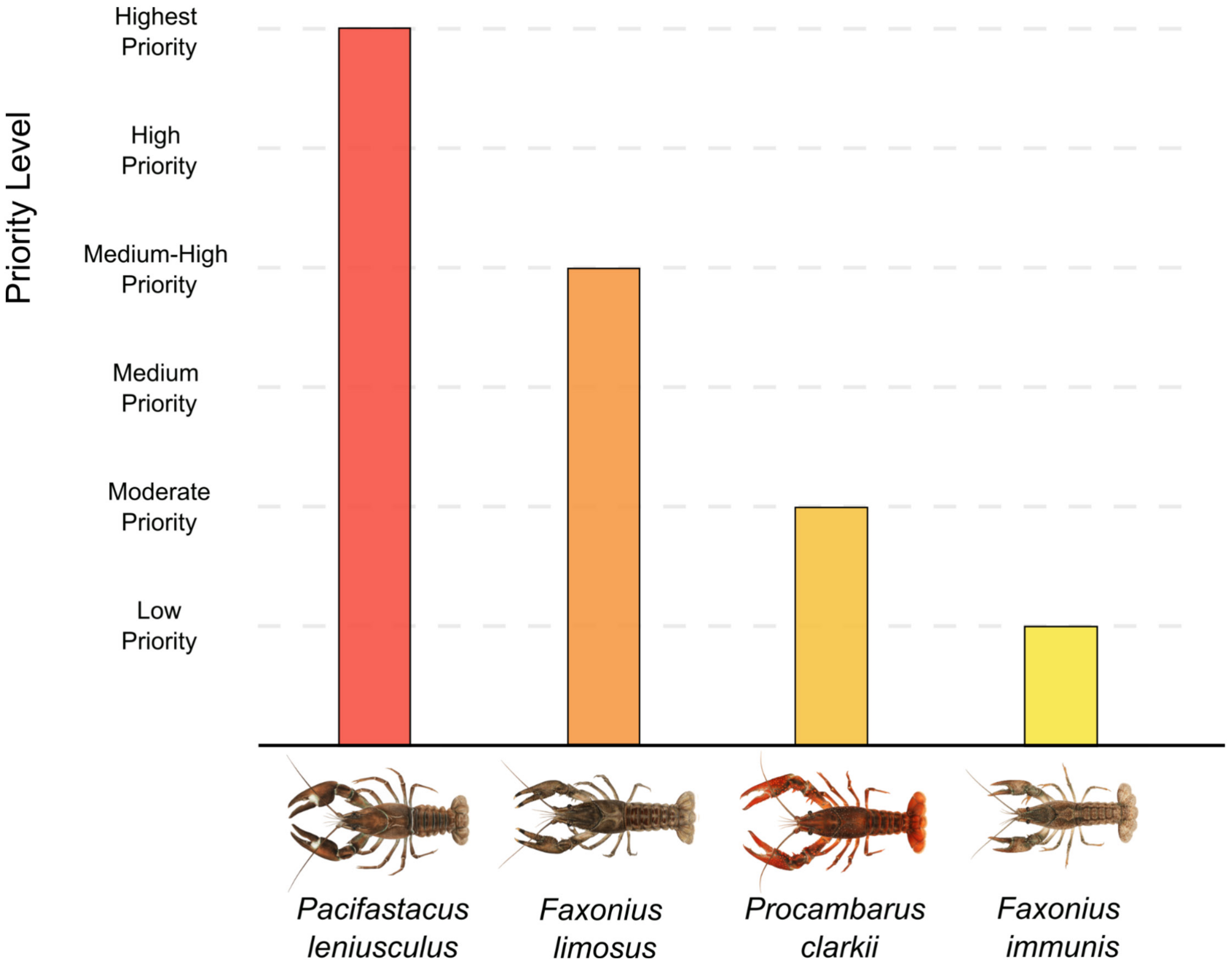

FIGURE 4 | Priority level ranking of non-native crayfish in the Rhine-Main Observatory in Hessia, Germany, following the assessment with the Dispersal-Origin-Status-Impact (DOSI) scheme. The used crayfish illustrations are in the possession of the University of South Bohemia in České Budějovice, Czech Republic, and drawn by the MgA. Radka Bošková.

core dimensions of biological invasions, ultimately improving decision-making and prioritisation, even in regions facing complex ecological challenges.

4.1 | Dispersial-Origins-Spread-Impact

DOSI's novelty lies in its ability to rank populations of non-native species for their respective management urgency, independent of national lists or recommendations from broad political jurisdictions (Fabbrini 2010). This autonomy in assessment is important, especially given the varying ecological, economic and cultural contexts across different regions (Henry et al. 2023). By focusing on the population level, DOSI provides a more nuanced and context-specific prioritisation, allowing for more targeted management strategies for species of highest risk. Moreover, DOSI shifts the focus of resources and efforts directly to populations of non-native species with the highest risks, either for those that (*i*) might spread independently or those that (*ii*) rely on vectors, providing a clear framework for conservation practitioners and policymakers.

Moreover, the DOSI's focus on the negative aspects of non-native populations is intentional and justified. The general experience in ecological management suggests that the harm caused by non-native species, particularly those not under controlled conditions, often outweighs their benefits (Carneiro et al. 2024). Thus, DOSI's approach ensures that the primary focus remains on mitigating risks and potential impacts on ecosystems and species. Nevertheless, positive effects could be considered, particularly when balancing costs and benefits among different actors. For example, the *Environmental Impact Classification for Alien Taxa* (EICAT+) framework explicitly accounts for benefits at the species-level for environmental impacts (Vimercati et al. 2022), and a similar premise could be used to consider benefits at the population level. In this sense, current risk-identification and assessment schemes such as *Aquatic Species Invasiveness Screening Kit* and *Environmental Impact Classification for Alien Taxa* are limited because they operate primarily at the species level. In contrast, DOSI adopts a more nuanced approach by considering populations individually. This shift towards population-level assessments has the potential for more effective conservation and management by providing practical and straightforward ways to prioritise both aquatic and terrestrial non-native species at the local scale.

4.2 | Species-Specific Findings and Implications

Ranked as the highest priority for management, *P. leniusculus* demonstrates both autonomous and assisted dispersal mechanisms, coupled with an expanding range and growing abundance, as well as ecological impacts (including displacement of native crayfish populations, habitat alteration, and acting as a vector for crayfish plague; Ercoli et al. 2014; Dobrzycka-Krahel et al. 2017; Svoboda et al. 2017). Its potential economic impacts on fisheries and moderate cultural significance further underscore its importance as a management target. The RMO region's waterways are currently not managed and therefore particularly vulnerable to its spread, making this species a prime candidate for both population and pathway management. Without intervention, the proceeding expansion of *P. leniusculus* could result in the extinction of *A. astacus* populations in the RMO (Oficialdegui et al. 2024). *P. leniusculus*'s significant reliance on human-assisted dispersal, while generally being known for the ability to spread independently (i.e. secondary spread; Usio et al. 2016), combined with damaging infrastructure (Sanders et al. 2021) and spreading the crayfish plague pathogen (Svoboda et al. 2017), suggests that a mixture of both pathway and population management is an urgently needed strategy.

In contrast to *P. leniusculus* and *F. limosus*, *P. clarkii* and *F. immunis* exhibited potential impacts across all domains (ecology, economy, culture and health) but a static or shrinking range and abundance in the RMO, thus reducing their respective management priorities. This ranking may appear counterintuitive given *P. clarkii*'s high-profile global impacts (Oficialdegui et al. 2019; Oficialdegui et al. 2020), but the DOSI scheme evaluates populations based on local spread and risk, and in the RMO, this species shows a decline rather than expansion. *F. immunis*, in particular, showed a static range and shrinking abundance, alongside relatively low impacts on the economy, ecology, culture and health known for this non-native crayfish compared to other known crayfish invaders (Kouba et al. 2022; O'Hea Miller et al. 2024). *F. limosus* was assigned a medium-high priority due to its expanding range and notable potential ecological impacts, despite a static abundance. *F. limosus* can compete with native species (Chucholl and Chucholl 2021) and is known to modify habitats (Albertson and Daniels 2018; Dobrzycka-Krahel and Fidalgo 2023) but has lower economic and cultural impacts compared to, for example, *P. leniusculus* (Kouba et al. 2022). Yet, similar to *P. leniusculus*, its dual dispersal mechanisms highlight the need for a mixed management approach, with emphasis on population management to contain its range expansion. A word on *P. clarkii*, like being a very problematic species elsewhere (Loureiro et al. 2015), but this has not yet been observed in RMO.

4.3 | Broader Implications of the DOSI Framework in the RMO

One might perceive that managing a non-native species that 'occurs everywhere' might be futile and that limited resources could better be focused on those on the doorstep (Adams and Pearl 2007; Gherardi et al. 2011). While there is truth in the importance of implementing biosecurity measures aimed at hindering successive introductions (Hulme 2011), this argument is inherently flawed because (a) those non-native species that are already established could possibly spread beyond current confinements or assessment areas and (b) can cause unexpected and unpredictable impacts once environmental conditions change (Simberloff and Von Holle 1999; Simberloff 2006a). It should rather be argued that it is equally important to manage both those at the boundaries of an area and their respective pathways to prevent their further introductions and those that are already established to mitigate potential impacts. However, in the context of non-native crayfish, this conceptualisation can yet become even more complex: As species like *F. immunis* and *F. limmosus* are often overlapping, conceptually, managing such places will target both species and minimise the potential of one species to establish if the other is already established.

The DOSI framework's strength thus lies in its ability to prioritise management actions for non-native species based on locally relevant risks, independent of broader political jurisdictions. At the same time, DOSI is not intended to replace species-level systems for, for example, the creation of 'black lists' (Simberloff 2006b); but to complement them. DOSI can be integrated alongside existing national or regional prioritisation schemes—including those with legal mandates by—offering finer granularity at the population level (Haubrock et al. 2024). While tools like EICAT are rigorous and well-established (Bacher et al. 2018), they are often data-intensive, species-wide and not well suited for local implementation or rapid assessment. In contrast, DOSI is pragmatic, lightweight and flexible, making it easier to adopt by local authorities, conservation managers, or NGOs. By filling a practical gap, DOSI could thus serve as an operational tool to prioritise action even within the bounds of existing regulatory frameworks. For the RMO region, where diverse waterways and aquatic ecosystems provide habitats for both native and non-native species, DOSI enables targeted interventions that align with ecological, economic and cultural contexts. For instance, the RMO's vulnerability to the impacts of *P. leniusculus* and *F. limosus* highlights the importance of prioritising species capable of autonomous dispersal and severe ecological impacts (Pyšek and Richardson 2010). Conversely, species like *F. immunis*, with so far limited spread, exemplify the value of low-intensity pathway management. However, while the latter species currently poses minimal threats in the RMO, it still warrants the awareness of potential pathway management to prevent new introductions or facilitated spread (Hulme 2015). It should be noted that, regionally, it has a potential to outcompete even other non-native species such as *F. limosus* (Chucholl et al. 2008); hence, its recognition might increase in the future, which also applies to *P. clarkii* (Kouba et al. 2022; Veselý et al. 2021).

Our assessment underscores the need for practical tools to streamline the DOSI framework for conservation practitioners, potentially with a unified questionnaire similar to the *Aquatic Species Invasiveness Screening Kit* (AS-ISK) to facilitate the standardisation of assessments. While the management of non-native species is not a focus in the RMO as its aim is to monitor rather than to intervene, it is important to note that the application of such a tool could guide future efforts to manage not only crayfish species but also other non-native species that, once spread across the RMO, might pose notable threats to adjacent areas and protected species like the *A. astacus*, which has taken refuge in the higher elevated streams of the RMO (Oficialdegui et al. 2024).

5 | Conclusion

The application of the DOSI framework to the non-native crayfish species of the RMO demonstrates its utility in identifying high-priority management targets, such as *P. leniusculus* and *F. limosus*, while also delineating currently lower-priority species like *F. immunis* and *P. clarkii*. By focusing on both dispersal mechanisms and locally observed impacts, DOSI provides a nuanced approach to invasion biology that is both actionable and adaptable to regional needs. Future iterations of DOSI could further benefit from integrating dependencies between dispersal, status, and impact, as well as the development of standardised assessment tools to promote widespread adoption and implementation. For the RMO and similar regions, DOSI offers a clear pathway to more effective and sustainable invasive species management.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

There are no data underlying this study. All relevant data have been cited in the references and, where applicable, repository access information has been provided (e.g. https://rmo.senckenberg.de/search/home.php).

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