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Grant Proposal

GuardIAS – Guarding European Waters from Invasive Alien Species

Stelios Katsanevakis[1], Anastasija Zaiko[2], Sergej Olenin[3], Mark John Costello[4], Belinda Gallardo[5], Elena Tricarico[6], Tim Adriaens[7], Jonathan M. Jeschke[8,9], Maria Sini[1], Nóirín Burke[10], Kosmas Ellinas[11], Stephan Rutten[12], Dimitris Poursanidis[1,13], Agnese Marchini[14], Rein Brys[7], Joost A.M. Raeymaekers[4], Nicolas Noé[15], Virgilio Hermoso[16], Rakel Blaalid[4], Frances E. Lucy[17], Laura N.H.Verbrugge[17], Peter A.U. Staehr[18], Leen Vandepitte[19], Daan de Groot[12], Michael Elliott[20,21], Marieke Reuver[22], Julian Maclaren[23], Mengyu Li[24], Damiano Oldoni[7], Antonios Mazaris[1,27], Vasilis Trygonis[1], Pascal I. Hablützel[19,28] , Teun Everts[7], Jennifer C.A. Pistevos[1], Stefanie Dekeyzer[19], Sophia E. Kimmig[8,9], Fiona S. Rickowski[8,9] and Vadim E. Panov[17,29]

[1]University of the Aegean, Department of Marine Sciences, 81100 Mytilene, Greece; [2]Sequench Limited, Nelson, New Zealand; [3]Marine Research Institute, Klaipėda University, Klaipėda, Lithuania; [4]Faculty of Biosciences and Aquaculture, Nord University, 8026 Bodø, Norway; [5]Instituto Pirenaico de Ecología, IPE-CSIC, Zaragoza, Spain; [6]Department of Biology, University of Florence, 50019 Sesto Fiorentino, FI, Italy ;[7]Research Institute for Nature and Forest (INBO), B-1000 Brussels, Belgium; [8]Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB), 12587 Berlin, Germany; [9]Institute of Biology, Freie Universität Berlin, 14195 Berlin, Germany; [10]Irish Ocean Literacy Network (IOLN), Galway, Ireland; [11]Laboratory of Advanced Functional Materials and Nanotechnology, Department of Food Science and Nutrition, School of the Environment, University of the Aegean, Myrina 81400 Lemnos, Greece; [12]Lobster Robotics, Delft, Netherlands; [13] Institute of Applied and Computational Mathematics, Foundation for Research and Technology Hellas, Heraklion 70013, Greece; [14]University of Pavia, Department of Earth and Environmental Sciences, 27100 Pavia, Italy; Faculty of Biosciences and Aquaculture, Universitetsalléen 11, 8026 Bodø, Norway; [15]The binary Forest / NNIT: Lillois, Belgium; [16]Estación Biológica de Doñana (EBD-CSIC), 41092 Sevilla, Spain; [17]International Association for Open Knowledge on Invasive Alien Species (INVASIVESNET), Finland; [18]Aarhus University, Department of Ecoscience, 4000 Roskilde, Denmark; [19]Flanders Marine Institute (VLIZ), 8400 Ostend, Belgium; [20]School of Environmental and Life Sciences, University of Hull, Hull, HU6 7RX, UK; [21]International Estuarine & Coastal Specialists (IECS) Ltd, Leven, HU17 5LQ, UK; [22]ERINN Innovation, Dublin, Ireland; [23]Nelson AI Institute, Nelson 7010, New Zealand; [24]ISA, School of Physics A28, The University of Sydney, NSW 2006, Australia; [27]Department of Ecology, School of Biology, Aristotle University of Thessaloniki, Thessaloniki, Greece; [28]Vrije Universiteit Brussel, Biology Department, 1050 Brussels, Belgium; [29]Regional Euro-Asian Biological Invasions Centre, Helsinki, Finland

Corresponding author: Stelios Katsanevakis (stelios@katsanevakis.com)

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Abstract

GuardIAS is a three-year Horizon Europe project starting in January 2025, uniting diverse expertise to address aquatic invasive alien species (IAS) management. This multidisciplinary initiative comprises seven interconnected work packages targeting all invasion stages (pre-border, border, post-border) to develop tools for disrupting invasions. GuardIAS will employ Artificial Intelligence and data workflows to enhance biodiversity databases with species distributions, environmental tolerances, traits, and genetic information, thereby improving the European Alien Species Information Network (EASIN) and harmonizing key datasets. The citizen science platform iNaturalist will be enriched with expert-verified images of aquatic IAS for early detection and monitoring of geographic spread. An Early Warning System focused on IAS of EU concern will be developed and integrated into EASIN. To prevent hull biofouling—a major IAS introduction pathway—GuardIAS will explore nanotechnology-based antifouling coatings. The project will also investigate recreational boat movements along European coastlines, an understudied factor in IAS secondary dispersal. An eDNA reference library and assay panel will be developed for effective IAS detection. Advanced models, such as the Nobel Prize winning Multi-Region Input-Output analysis, will assess IAS risks, including impacts on threatened species and critical habitats under current and future scenarios. Systematic conservation planning tools will prioritize IAS monitoring and management actions based on their impacts. GuardIAS will enhance data collection, monitoring, early detection, and public awareness through innovative citizen science initiatives like BioArtBlitz events—where arts serve as a communication vehicle—eDNA sampling, sound analysis projects on Zooniverse, and marina events for boaters. Stakeholder engagement will be fostered through applied games. Collaborating with environmental authorities, industry, and aquatic managers, the project will co-design and implement eradication and control efforts in marine and freshwater environments. By integrating Social Sciences and Humanities, GuardIAS will promote collaborative knowledge creation, understand public perceptions on IAS management, and facilitate exploitation of the project's outcomes.

Key words: aquatic, artificial Intelligence, citizen science, biofouling prevention, early detection, eDNA, biological invasions

Abbreviations used

AB: Advisory Board; **AI**: Artificial Intelligence; **API**: Application Programming Interface; **AUV**: Autonomous Underwater Vehicle; **BCA**: Benefit Cost Analysis; **BHD**: Birds and Habitats Directives; **BS**: Biodiversity Strategy; **BWMC**: Ballast Water Management Convention; **CaSt**: Case study; **CIMPAL**: Cumulative IMPacts of invasive ALien species; **CS**: Citizen Science; **DASCO**: Downscaling Alien Species Checklists using Occurrence data; **DEC**: Dissemination, Exploitation, and Communication; **EASIN**: European Alien Species Information Network; **ESA**: European Space Agency; **EW**: Early Warning; **FAIR**: Findable, Accessible, Interoperable and Reusable; **FAO**: Food and Agriculture Organization; **GA**: General Assembly; **GES**: Good Environmental Status; **GISD**: Global Invasive Species Database; **GloBi**: Global Biotic Interactions; **GPT**: Generative Pre-trained Transformer; **GRIIS**: Global Register of Introduced and Invasive Species; **IAS**: Invasive Alien Species; **IMO**: International Maritime Organisation; **IP**: Intellectual Property; **IPBES**: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services; **IPCC**: Intergovernmental Panel on Climate Change; **IPR**: Intellectual Property Rights; **KCBD**: Knowledge Centre for Biodiversity; **KER**: Key Exploitable Result; **KM-GBF**: Kunming-Montreal Global Biodiversity Framework; **KPI**: Key Performance Indicators; **LLM**: Large Language Model; **MOOCs**: Massive Open Online Courses; **MPAs**: Marine Protected Areas; **MRIO**: Multi-Region Input-Output; **MS**: Member States; **MSFD**: Marine Strategy Framework Directive; **NRL**: Nature Restoration Law; **OA**: Open Access; **OBIS**: Ocean Biodiversity Information System; **ROAM**: Risk and Opportunity Assessment and Management; **RL**: Red List; **RSC**: Regional Sea Conventions; **SC**: Steering Committee; **SDG**: Sustainable Development Goal; **SDMs**: Species Distribution Models; **SEI**: Social-Ecological Interactions; **SSH**: Social Sciences and Humanities; **STEAM**: Science, Technology, Engineering, Arts & Mathematics; **SINAS**: Standardizing and Integrating Alien Species; **TRL:** Technology Readiness Level; **WFD**: Water Framework Directive; **WP**: Work Package; **WoRMS**: World Register of Marine Species; **WRiMS**: World Register of Introduced Marine Species

Objectives and ambition

The recent IPBES report (IPBES 2023) highlights the significant threat posed globally by invasive alien species (IAS), with over 3,500 of 37,000 introduced species identified as major global threats to biodiversity, economy and health. These species are implicated in 60% of global plant and animal extinctions and cost over $400 billion annually (92% due to damage to nature's contributions to human welfare, 8% due to management costs) (IPBES 2023). In the EU, > 2000 aquatic alien species are reported in the European Alien Species Information Network (EASIN), some with serious impacts on ecosystems and their services to humans. The challenge associated with IAS is likely to intensify in the future due to climate change and increased globalization (Katsanevakis et al. 2023). The EU, through the IAS Regulation and the EU Biodiversity Strategy for 2030, is committed to mitigate these impacts and reduce the threat of IAS. However, the IPBES report notes a general insufficiency in global measures to manage IAS, with only 17% of countries implementing specific laws or regulations. Following the publication of the first report on the application of the IAS Regulation, Virginijus Sinkevičius, Commissioner for the Environment, Fisheries and Oceans, stated: "*Invasive alien species are a major driver of biodiversity loss in Europe. Today's report shows that taking action at EU level has real added value. This Regulation will be an essential tool to continue to address this threat and put biodiversity on the path of recovery under the EU Biodiversity Strategy for 2030*". The EU Biodiversity Strategy encompasses prevention, early detection, eradication, and control of IAS populations, targeting a 50% decrease in the number of Red List (RL) species such IAS populations threaten.

The main goal of GuardIAS is to improve governance and management of aquatic IAS towards fulfilling the objectives of the Biodiversity Strategy for 2030, the Kunming-Montreal Global Biodiversity Framework (KM-GBF), and the IAS Regulation on mitigating IAS impacts on biodiversity, ecosystem services, societal goods and benefits, the economy, and human health. This will be achieved through five strategic operational objectives (Table 1), involving the development of innovative tools and methods to enhance prevention of new introductions, aid early detection and rapid response, as well as promoting the efficient eradication or population control of aquatic IAS in Europe in collaboration with stakeholders and the wider society. GuardIAS will support the implementation of the IAS Regulation at the national, sub-regional, regional, and European level by offering solutions that address every phase of the invasion process (pre-border, border and post-border) for both marine and freshwater ecosystems. GuardIAS will advance tools beyond the current state-of-the-art and forge innovative concepts and methodologies, targeting the most advanced TRLs, namely those where technology has already been demonstrated and/or are already part of an operational system (Table 1) in both freshwater and marine environments.

Methodological approach

The GuardIAS approach targets all steps of the multi-stage invasion process (pre-border, border and post-border), aiming to develop novel tools for appropriate interventions thereby contributing to the disruption of the invasion process (Figure 1). It will be implemented through seven interconnected Work Packages (WPs) (Figure 1).

GuardIAS tools will be co-developed with European, regional and national stakeholders to guarantee fit-for-purpose outcomes, effective end-user uptake and long-term impact of our research. Major groups of stakeholders identified

Table 1. GuardIAS operational objectives and related specific outputs linked to work packages (WP) – the TRL (Technology Readiness Level) at start and by the end of the project are provided for each outcome. fw: freshwater; mar: marine; CaSt: Case Studies. (TRL1: basic principles observed; TRL2: technology concept formulated; TRL3: experimental proof of concept; TRL4: technology validated in lab; TRL5: technology validated in relevant environment; TRL6: technology demonstrated in relevant environment; TRL7: system prototype demonstration in operational environment).

Objectives	GuardIAS Specific Outputs (bSA: beyond the State-of-the-Art, nCT: new concepts and tools)	WP	TRL (start → end)
O1: Develop innovative tools and IAS data integration approaches to underpin effective IAS prevention.	1. Develop a novel biosecurity risk model based on the Nobel-Prize-winning MRIO analysis technique (bSA)	1	5 (previously validated) → 7 (demonstrated at EU scale)
	2. Develop an AI-powered tool using a Large Language Model to boost IAS data search and integration (nCT)	1	2 (New tool; TRL 6/7 in other fields) → 7 (operational system)
	3. Develop state-of-the-art antifouling solutions for vessels based on nanotechnology (bSA)	1	4 (validated in lab) → 6 (demonstrated in vessels)
	4. Quantify the risks associated with recreational vessels through network modelling of vessel movements; prioritize locations for monitoring and management (bSA)	1	5 (previously validated) → 6 (demonstrated in two Case Studies, fw+mar)
	5. Develop a smartphone app to assist officers conducting border controls for recognising and intercepting IAS (bSA)	2	6 (technology demonstrated) → 7 (operational system)
	6. Develop eDNA protocols for the implementation of eDNA metabarcoding for border controls (bSA)	2	5 (validated in lab) → 6 (demonstrated for border control)
O2: Empower IAS early detection and monitoring through developing methods and novel technology.	1. Develop a robot able to efficiently map benthic IAS distribution, combining AUV technology and AI (nCT)	2	2 (New tool – AUV is at TRL 6 – see Fig. 4) → 7 (operational system)
	2. Develop a methodology for using hyperspectral remote sensing observations to map IAS in shallow waters (bSA)	2	5 (previously validated) → 6 (demonstrated in two case studies, fw+mar)
	3. Develop underwater listening hydrophonics for automatic surveillance of aquatic IAS (bSA)	2	5 (previously validated) → 6 (demonstrated for fw+mar IAS)
	4. Upscaling eDNA for monitoring by (a) constructing automated sampling machines and utilising environmental passive samplers, (b) improving accurate quantification of IAS abundances through eDNA (bSA)	2	5 (previously validated) → 6 (demonstrated for fw+mar IAS)
	5. Integrate AI and IT technologies to facilitate fast and easy (through Smartphone App) detection and monitoring of IAS by citizens (bSA)	2	6 (technology demonstrated) → 7 (operational system)
	6. Develop an Early Warning (EW) System building on existing data systems and AI tools focused on IAS of EU concern that can be incorporated in EASIN (bSA)	2	6 (technology demonstrated in Belgium) → 7 (operational system at EU-scale through EASIN)
O3: Develop an operational AI-powered framework and models for improved assessments of IAS impacts on threatened species and prioritization of threats.	1. Develop an AI-based workflow to create a dynamic database of native-invasive interactions, and identify most vulnerable threatened species (nCT)	3	2 (technology concept formulated) → 7 (operational system to support Biodiv. Strategy implementation)
	2. Identify hotspots of IAS impacts on aquatic threatened species at EU-scale through distribution modelling under various future scenarios of invasion (bSA)	3	6 (demonstrated at low scales) → 6 (demonstrated at large scale: EU-wide, all species)
	3. Prioritize IAS management by assessing management costs and societal costs of inaction through Benefit-Cost Analysis (bSA)	3	5 (approach validated) → 6 (demonstrated for fw+mar IAS)
	4. Implement systematic conservation planning approaches to prioritize areas for IAS monitoring and management (nCT)	3	2 (SCP approaches never applied for IAS management prioritization) → 6 (demonstrated EU-wide)
O4: Develop informed strategies and decision support tools for successful and efficient eradication or control of established IAS	1. Using 11 key Case Studies, the project will assess, improve, and demonstrate eradication and control options (bSA)	4	2–6 (depending on CaSt) → 6–7 (management options demonstrated in relevant fw+mar environments)
	2. Conduct cause, consequence and response pathway analysis of IAS management options based on the ten-tenets approach and Bow-tie analysis (nCT)	4	2 (never applied for IAS management; TRL 6-7 in other fields) → 6 (demonstrated in 11 CaSt)
	3. Fostering collaborative networks for the 11 case study species through a Community of Practice model (bSA)	4	5 (validated in other fields) → 6 (demonstrated in 11 CaSt)
	4. Apply a social-ecological network approach to analyse social-ecological interactions for selected freshwater and marine IAS and inform management (bSA).	5	5 (validated in other fields) → 6 (demonstrated for selected IAS)
O5: Use innovative approaches to engage with a diverse range of stakeholders, enhance literacy and awareness about IAS, and bolster support of management actions.	1. Capacity building and literacy enhancement through a range of innovative citizen science (CS) initiatives (BioArtBlitz events, open-lab activities, Zooniverse project to analyse video/sound records) (bSA)	5	2-6 (depending on the activity) → 6 (demonstrated for all CS activities)
	2. Engage researchers, practitioners, and CS networks through collaborative OA publications (bSA)	5	5 (approach validated through *BioInvasions Records*) → 6 (demonstrated at large-scale through a series of OA articles & special issues)
	3. Innovative applied games for stakeholder engagement, co-designing species-specific management strategies and raising public awareness (bSA)	5	5 (games developed in other projects) → 6 (expanded for several IAS & made available for wide use)
	4. Develop an indicator-based framework for measuring the effectiveness of stakeholder engagement activities for IAS management (nCT)	5	2 (never applied before – concept formulated) → 6 (demonstrated for all engagement activities)

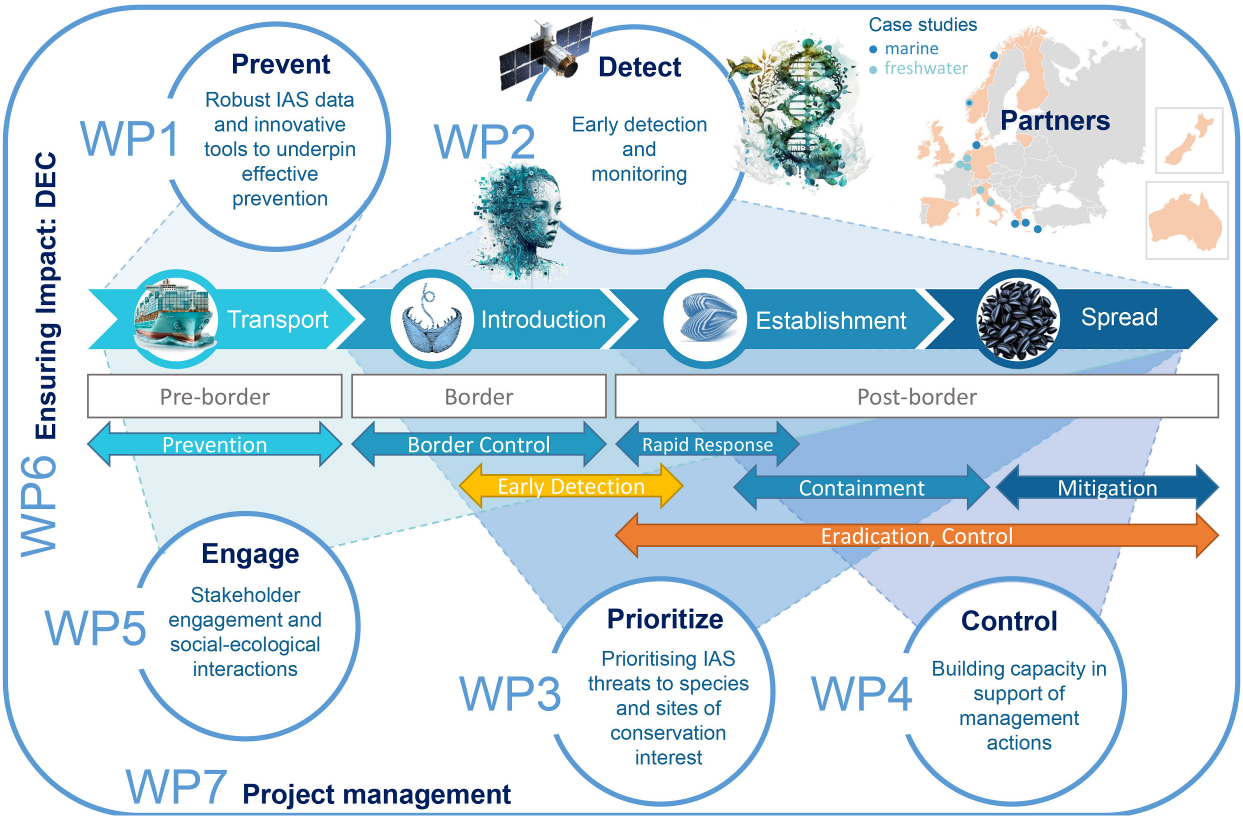


Figure 1. GuardIAS Work Program (WP) structure (WP1-7) linked to the steps of the multi-stage invasion process. DEC: Dissemination, Exploitation, and Communication.

for this project include statutory authorities responsible for the implementation of IAS regulations at various scales, industries related to the introduction and spread of aquatic IAS (e.g., shipping, aquaculture, fisheries, pet and aquarium trade), aquatic managers, border control officers, scientists and the public, with special attention to young people and educators. This stakeholder-centric approach enhances the relevance and applicability of our research outcomes. GuardIAS aligns with key EU policy instruments, such as the IAS Regulation, BS, WFD, MSFD and BHD, reflecting our commitment to contributing to policy and legislative frameworks. The project's seven concurrent WPs are strategically designed to maintain coherence and integration. Well-established communication channels and collaboration strategies ensure seamless integration of outputs from different work streams (Figure 2).

Enhancing prevention (WP1)

WP1 will enhance prevention of IAS introduction in European waters by: (1) deepening the understanding of current IAS distribution and pathways of introduction and spread, (2) modelling and prioritising risk factors, and (3) forecasting future incursions. This involves data integration and improving risk assessments for robust prevention strategies and effective biosecurity measures.

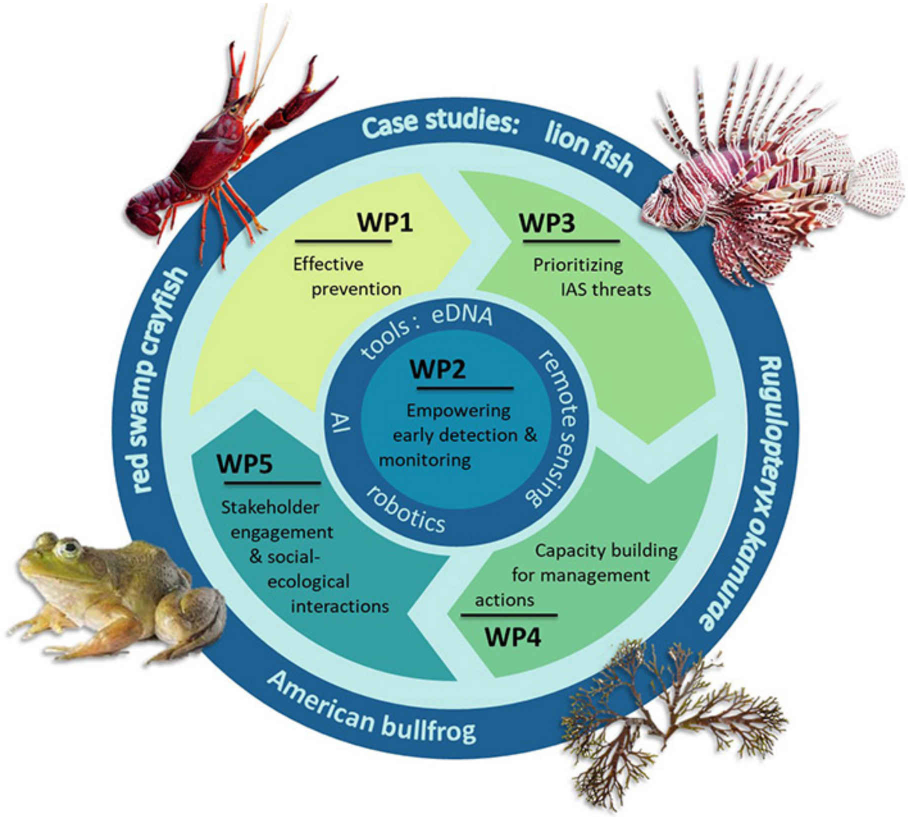


Figure 2. Schematic representation of the interconnection and coherence between the GuardIAS work packages and case studies. Not all case studies are depicted for clarity; for the full list see Table 2.

WP1 will capitalise on GuardIAS partnership and direct involvement in the development and/or management of major alien species databases, i.e. EASIN, AquaNIS, and WRiMS. These databases, integrated with the taxonomic nomenclature offered by WoRMS, maintained by VLIZ (Vandepitte et al. 2018) and consistently updated by ~300 taxonomic editors, will be synchronised to enhance alien species data, leveraging the unique strengths of each database. A pivotal task in WP1 will involve coordinating efforts to achieve a synergistic effect in improving data collection, processing, and user-oriented dissemination, including pathway information, species georeferenced data, mapping services and IAS risk assessment.

WP1 introduces a ground-breaking approach to alien species data integration through the application of AI and developing a tool that uses a LLM and multi-modal model. This AI tool will efficiently query databases and other on-line resources for species distribution, environmental tolerances, key biological traits, and molecular references, enhancing efficiency in horizon scanning for novel IAS. Through better integration of species trait information (e.g., from WoRMS, SeaLifeBase, FishBase, AquaNIS, and OBIS), and other attributes such as threatened status in IUCN Red Lists and interactions between native and invasive species (GloBi; Global Biotic Interactions), the tool will enable better IAS impact profiling and risk assessments. As a proof of concept, we will use SinAS (Seebens et al. 2020)

Table 2. Species-centric case studies addressed by GuardIAS. EW: Early Warning; fw: freshwater; mar: marine.

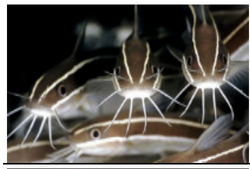
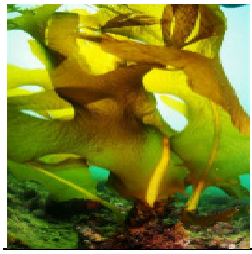
Case studies (CaSt) – description of GuardIAS activities	
	**CaSt1**: marbled crayfish *Procambarus virginalis* (fw). **Where?** Belgium and The Netherlands. **Who?** INBO. **Description:** This crayfish, listed as an IAS of Union Concern since 2016, is parthenogenetic, so a single individual can establish a new population. It reproduces rapidly, achieving high densities, is a carrier of crayfish plague, and can inhabit various freshwater environments. Recent discoveries in Belgium and the Netherlands, in regions with species-rich amphibian habitats, have raised concerns. At both sites, population control and eradication are still feasible through coordinated efforts. At both regions, GuardIAS will (i) **determine the species distribution range**, (ii) **prioritise areas of highest concern** for **eradication** or **conservation actions**, and (iii) **assess the impact** of this IAS **on local amphibian communities** in infected versus uninfected ponds, based on eDNA ddPCR and metabarcoding analyses (T2.4 and T4.2).
	**CaSt2**: Red swamp crayfish *Procambarus clarkii* (fw). **Where?** Italy. **Who?** UNIPV, UNIFI. **Description:** An IAS of Union concern, it is widespread but can potentially be controlled or eradicated in areas where it is abundant, especially with community support. In Northern Italy, preliminary efforts show that trapping can effectively reduce crayfish populations below viable levels. GuardIAS plans to enhance this approach by **engaging local communities in CS activities** for higher impact (Task 5.1.1). The use of **static underwater cameras** will be tested in northern-central Italy to detect the species in protected areas (Task 2.1.2).
	**CaSt3**: African clawed frog *Xenopus laevis* (fw). **Where?** Belgium. **Who?** INBO. **Description:** Listed as an IAS of Union Concern (with entry into force on 2/8/2024), it has been introduced via the pet trade and biomedical laboratories. Its capacity to disperse both through water and over land poses significant management challenges. In 2018, the discovery of a new population at the France-Belgium border triggered urgent response actions. GuardIAS will assist in (i) **monitoring its main distribution** range in this border region (T2.4), (ii) **selecting breeding ponds** for eradication based on eDNA concentrations (T2.4), and (iii) **evaluating eradication or control efforts and success** of targeted ponds using eDNA (T4.2-4.3). The feasibility assessment (WP4) will consider the suite of measures that can be applied in the invaded pond and river systems to **prioritize sites for management** (T4.2) based on **biodiversity estimates** from generated eDNA data (T2.4).
	**CaSt4:** American bullfrog *Lithobates catesbeianus* (fw). **Where?** Belgium. **Who?** INBO. **Description:** In Belgium, the American bullfrog (an IAS of Union concern), introduced in the late 1990s, has spread across 360 km^2, forming eight metapopulations. Management is notoriously complex due to many inaccessible private ponds and the river acting as a dispersal corridor. Management is taking a holistic approach, combining active removal with native predator introduction to increase ecosystem resilience. GuardIAS will map **its distribution, abundance, and spatial spread** through species-specific ddPCR eDNA analyses, and eDNA metabarcoding for **assessing its impact on native species and communities** (T2.4).
	**CaSt5:** Parrot's feather *Myriophyllum aquaticum* (fw). **Where?** Italy. **Who?** UNIFI. **Description:** An IAS of Union concern, native to S. America, it has both an emergent and submerged leaf form and thrives in slow-flowing and standing waters. Introduced to Europe for ornamental purposes, it reproduces asexually in invaded areas, leading to rapid spread. It can displace native species, reduce biodiversity, limit recreation, lower aesthetic value, and decrease water quality and flow. In GuardIAS, **the species will be managed in zones around a protected wetland area in Central Italy, in collaboration with local authorities and stakeholders**.
	**CaSt6:** Humpback (pink) salmon *Oncorhynchus gorbuscha* (mar-fw). **Where?** Norway. **Who?** NORD. **Description:** Since its introduction into the Russian coast, this Pacific American species has spread through Norway into Britain, Finland, Ireland, Iceland, Faroes, and Greenland. It shares dietary needs, diseases, and competes with already threatened native salmonids both at sea and in rivers. In 2021, over 20,000 fish were caught in one Norwegian river. Post-spawning, their rotting bodies cause offensive odours. However, whether positive impacts in terms of fishing will outweigh negative impacts on native species is uncertain. In GuardIAS, we will review current knowledge on the **spread, ecological and economic impacts, and existing control measures** in Europe and conduct a **stakeholder survey** (T4.2, T5.3), involving ecologists, salmon farmers, fishers, and government agencies to assess how they value the impact of the species and how it should be managed.
	**CaSt7:** Lionfish *Pterois miles* (mar). **Where?** Greece. **Who?** AEGEAN. **Description:** Lionfish, a species of MS concern, has invaded Cyprus, Greece, Italy, and other non-EU Mediterranean countries with potentially severe impacts on biodiversity and ES. GuardIAS will assess, prioritize, and implement **population control options,** such as removal campaigns **engaging citizens**, promotion of human consumption, and targeted commercial fishing in two Aegean Sea islands, with two nearby islands serving as controls (T4.2, T5.3). The effectiveness of these control efforts will be evaluated over two years through a dedicated monitoring program.
	**CaSt8:** Striped eel catfish *Plotosus lineatus* (mar). **Where?** Greece. **Who?** AEGEAN. **Description:** An IAS of Union concern, it recently (2022) reached the EU (Cyprus) and is expected to arrive in Greece. GuardIAS will set up an **EW mechanism** in the SE Aegean Sea (the likely entry point from Turkey), by engaging fishers, divers, and NGOs. Upon detection, coordinated **eradication** efforts will be initiated (Article 17, IAS Regulation). S. Katsanevakis, member of the Greek National IAS Committee, will ensure effective coordination with competent authorities.
	**CaSt9:** Red king crab *Paralithodes camtschaticus* (mar). **Where?** Norway. **Who?** NORD. **Description:** Introduced to the Barents Sea in the 1960s, this large crab (nearly 2 m leg span) has formed a valuable fishery but is also likely to be impacting benthic fauna significantly through predation. It has reportedly spread to southern Norway and northern Britain and, preferring cold waters (less than 12°C), may continue to spread by living at depth. GuardIAS will review its **spread, ecological and economic impacts and existing control measures** in Norway and conduct a **stakeholder survey** (T4.2, T5.3), involving ecologists, fish farmers, fishers, and government agencies to evaluate their perspectives on its impact and preferred management approaches.

Table 2. (continued).

	**CaSt10:** Wakame *Undaria pinnatifida* (mar). **Where?** Denmark, Germany **Who?** AU. **Description:** A worldwide known IAS that occurs in most European Seas. It is now present at the southern limits of the Danish North Sea. With the introduction of hundreds of **offshore wind farms** (OWF) in this area, it is very likely to spread further northwards. This case study will **develop management options regarding OWF's as stepping-stones** for this and other highly potential IAS. We will model its dispersal and impacts to biodiversity in Danish Natura 2000 areas (distance between offshore wind farms, reduce risk of IAS spreading from neighbouring countries – cross-border IAS spreading).
	**CaSt11:** brown algae *Rugulopteryx okamurae* (mar). **Where?** Greece. **Who?** AEGEAN. **Description:** This IAS of Union Concern is invasive in Spain's Alboran Sea, is established in France, and has the potential to inhabit Portugal, Italy, Greece, Croatia, Slovenia, Cyprus, and Malta. GuardIAS will implement an **EW system** in Greece, involving divers and NGOs, and conduct regular eDNA monitoring at potential entry points (e.g., ports, marinas) (Task 2.4). Upon detection, coordinated **eradication** efforts will be initiated (Article 17, IAS Regulation). S. Katsanevakis, member of the Greek National IAS Committee, will ensure effective coordination with competent authorities.

(generates checklists of IAS) and DASCO (Seebens and Kaplan 2022) (retrieves occurrences) as a starting point and AI to optimise the process. This will involve: (1) Identifying information sources and determine obtainable variables; (2) Standardising terminology and names across databases; (3) Homogenizing data types from different sources and reconcile differences in scales/units; (4) Optimizing search queries by enhancing search efficiency, merging and synthesising results; (5) Integrating data into major IAS inventories (i.e., EASIN, AquaNIS, WRiMS, GRIIS) and enhancing safety, searchability, and user experience; (6) Improving Quality Control by developing cross-validation algorithms to assess the model's performance and calculate uncertainty; (7) Developing the end-tool as a customised GPT (Generative Pre-trained Transformer), database plugin, or API (Application Programming Interface), adhering to FAIR (findable, accessible, interoperable and reusable) principles for accessibility to IAS researchers, aquatic managers, and practitioners. This approach will ensure that the newly developed AI system is technically robust, accurate and reproducible, and able to deal with and inform about possible failures, inaccuracies, and errors. The AI system will complete and update information available in EASIN and will be used to identify potential IAS (not yet in Europe) based on characteristics of known IAS. Macroecological studies indicate that species common in their native range are more likely to become invasive, indicating that IAS can be predicted (Karatayev et al. 2009). We will test this by analysing the range and abundance of about 500 aquatic IAS, classifying them by traits related to dispersal and impact. This will assist in identifying pathways and potential impact, and in focusing monitoring for early detection of potentially new IAS (WP2) and provide critical information for refining Species Distribution Models (SDMs) and predicting future species spread (link to WP3).

WP1 focuses on shipping-mediated IAS introduction, increasingly relevant due to global political and trade changes and climate-induced shifts in maritime routes, including the Arctic, affecting biosecurity risks (Christie et al. 2022). To enhance and future-proof quantification of the shipping-related risk, WP1 will use a novel biosecurity risk modelling approach utilising 20 years of international trade data and a Nobel-Prize-winning Multi-Region Input-Output analysis (MRIO) technique to identify high-risk IAS source regions (Lenzen et al., 2023) and predict the future biosecurity risk patterns in Europe. MRIO analysis, integrating economic and environmental data, is well-suited for assessing invasion risks amidst climate change, geopolitical shifts, and supply-chain challenges. MRIO models benefit from extensive OA input datasets, such as the UN National Accounts Main Aggregates, the OECD Inter-Country Input-Output tables, FAO AgStat (Agricultural Statistics) and FishStat (Fisheries Statistics) data, and UN data on trade in commodities. The proof-of-concept model has been validated against observed IAS spread data (Lenzen et al. 2023). GuardIAS will leverage the existing model prototype and build a MRIO model, including additional risk factors affecting IAS survival and establishment in European waters. We will also expand it for assessing freshwater IAS risks by incorporating information on freshwater shipping hubs. The model will retrospectively identify the riskiest combinations of region of origin, commodity, and ship type. This will refine future IAS predictions and inform management strategies for enhanced pre-border control and early detection (contributing to WP2, WP3 and WP4). The model also offers risk estimates for regions lacking IAS baseline data.

Guided by biological invasion scenarios from the Alien Challenge project (Roura-Pascual et al. 2021) and recent outputs from AlienScenarios and InvasiBES (Understanding and managing the impacts of Invasive alien species on Biodiversity and Ecosystem Services) projects, and in collaboration with the Advisory Board and relevant stakeholders (e.g., industries, governmental organizations, statutory authorities), we will apply the most pertinent future scenarios (hereafter "GuardIAS scenarios" – to be developed in WP3) to the MRIO model. This will be the first time that predicted shifts in trade connections will serve to forecast future dynamics of biosecurity risks. The outcomes will inform the development of a future-proof IAS management strategy for Europe, contributing significantly to WP4.

After the ban of toxic biocides such as Tributyltin (TBT) in 2008, many products have been marketed that reduce biofouling without biocides, including silicone-based materials (e.g., HEMPASIL and INTERSLEEK) and biomimetic surfaces (e.g., SHARKLET). GuardIAS will advance these technologies by pioneering hierarchical micro-nanotextured surfaces with appropriate 'green' chemistry, inspired by the "lotus leaf" phenomenon where water droplets roll off easily due to the air trapped within its hierarchical micro-nanostructure (Bhushan 2011). The added benefits of such surfaces include sustaining high pressure (Ellinas et al. 2015) and maintaining a surface air layer that ensures prolonged low friction (Dragatogiannis et al. 2015; Xu et al. 2014). This air layer acts as a physical barrier, preventing organism attachment, reducing biofouling, and lowering fuel consumption. We will implement such "passive" biomimetic coating concepts, significantly decreasing or even eliminating biofouling. We will develop solutions beyond the state-of-the-art using two scalable technologies: (1) micro-nano-imprinting on self-adhesive polymeric sheets and (2) spray coating of hydrophobic materials to create superhydrophobic surfaces with optimal pre-designed micro- and nano-topography. These coatings will be designed to maintain an air layer for extended periods, to overcome the main limitation of existing solutions. They will be demonstrated on vessel hulls (TRL 6) and evaluated for industrial scalability and economic viability in collaboration with the shipping industry.

Through a web-based survey (https://www.maptionnaire.com/), the project will develop a network model, mapping recreational vessel movements in the Mediterranean. This survey will allow collecting data on vessel homeports, travel destinations and durations for 2023–24. Structural analysis of the resulting network, using established metrics like degree, betweenness centrality and ego-neighbourhoods, will identify critical nodes for IAS transmission (Ashander 2022). This will pinpoint marinas, anchorages and coastal areas as potential hotspots or stepping-stones for IAS, guiding monitoring and management strategies. The methodology will also be applied to freshwater environments, assessing the role of recreational vessel movements in IAS transport across rivers, canals and lakes, similar to studies conducted in Minnesota's (USA) 9,100 freshwater lakes (Ashander 2022).

Overall, the outcomes of WP1 will guide the identification of risks for IAS introductions and spread, establishment of national early warning stations, prioritisation of border control efforts, and ultimately underpin the effective prevention measures at the pan-European scale.

Improving early detection and monitoring (WP2)

GuardIAS will harness citizen science (CS) in biodiversity data collection. Despite the increasing use of AI in CS applications for species identification, challenges remain in accurately recognizing introduced species. Therefore, GuardIAS will enhance species identification through iNaturalist, a platform that uses AI trained recognition with verified photographs, documenting 1 million weekly observations and contributing to 4,400 scientific papers. It allows users to upload species images for expert verification of AI-based identifications. These "research grade" verified records are then uploaded weekly to GBIF. We will establish a "project" within iNaturalist, compiling >100 photographs for each of >200 aquatic IAS to train the AI for accurate, automated identification. This initiative will bridge gaps in species identification aids, involve both experts and enthusiasts, and provide a valuable tool to border control officers for easily identifying and intercepting IAS.

Field managers and policymakers require rapid access to information on new IAS occurrences. WP2 will create tools to harvest records from multiple sources to detect trends in aquatic IAS distribution. We will adapt existing data analysis pipelines that can reveal early signals of invasion, generating

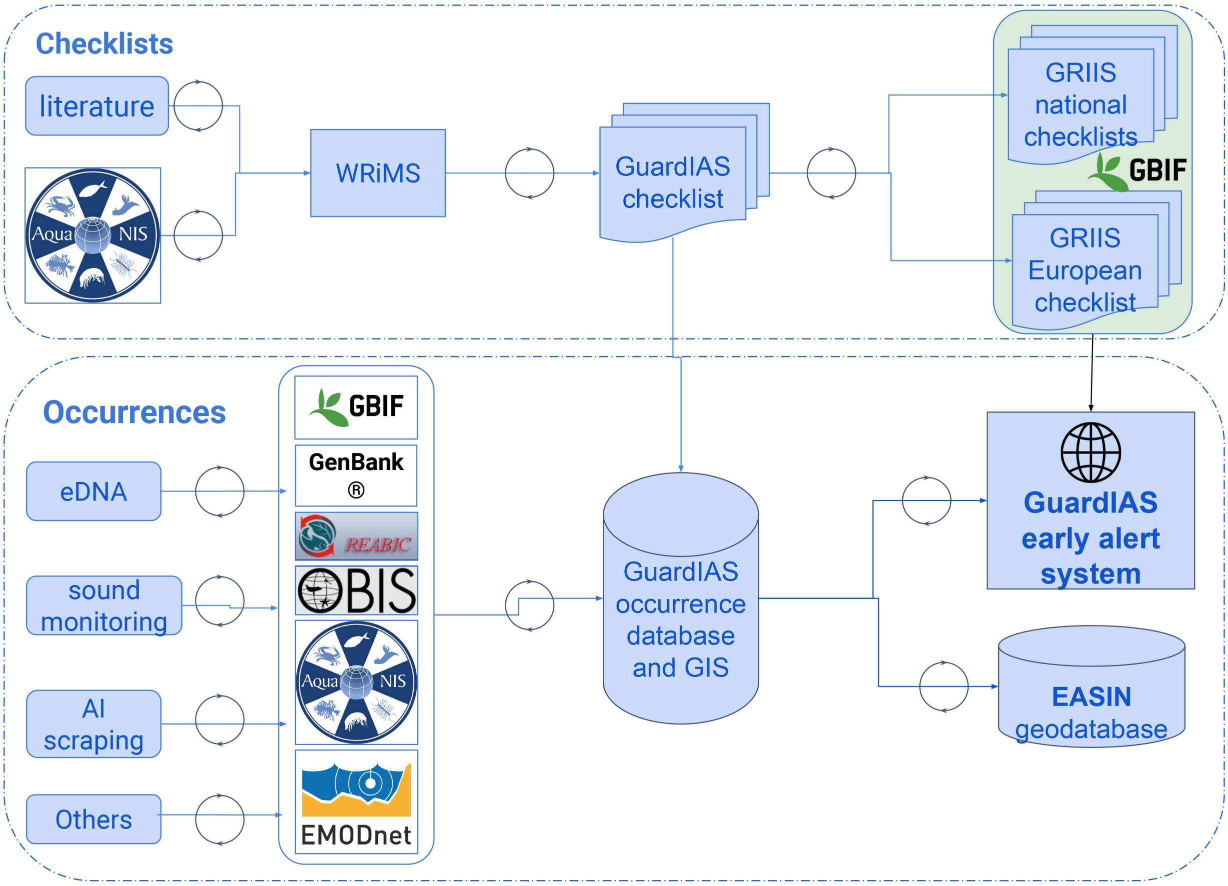


Figure 3. Data flow in GuardIAS, including on the top panel: taxonomic nomenclature and biogeography from WRiMS (subset of WoRMS), expert validated information (including pathways, vectors, and species traits) from AquaNIS and the literature; feeding into GRIIS national and regional checklists (countries' contributions as part of international commitments under the CBD). The lower panel illustrates data pulling on species distributions in space and time to inform trends and Alerts necessary for a European IAS Early Warning System to be hosted by EASIN.

prioritised lists of alien species for horizon scanning and risk assessment. The Tracking Invasive Alien Species (TrIAS) project has developed such a workflow for Belgium using statistically sound time series analysis. GuardIAS will adapt TrIAS to the European scale using species occurrence cubes from the Building Blocks for Biodiversity B3-project, in which GuardIAS partners are active. This will ensure the developed workflow adheres to the Essential Biodiversity Variable (EBV) for invasions approach (McGeoch and Squires 2015). The resulting trend analysis for alien species will be integrated into the EASIN portal, and the workflow will be openly available. A kick-off workshop will explore the data flow system (Figure 3) routes for additional data mobilisation to the early GuardIAS-alert tool and a subsequent interactive workshop for EASIN integration. At this workshop, scenarios will be discussed to integrate data relevant to early warning from EASIN data providers (e.g. using the EASIN API) into the alert tool, as well as strategies to mobilise additional detection data from the WP2 innovative detection technologies (robotics, remote sensing, eDNA) through the Marine Data Archive. Additionally, in the workshop, participants will discuss necessary adaptations for upscaling to the European level. Leveraging the LIFE RIPARIAS

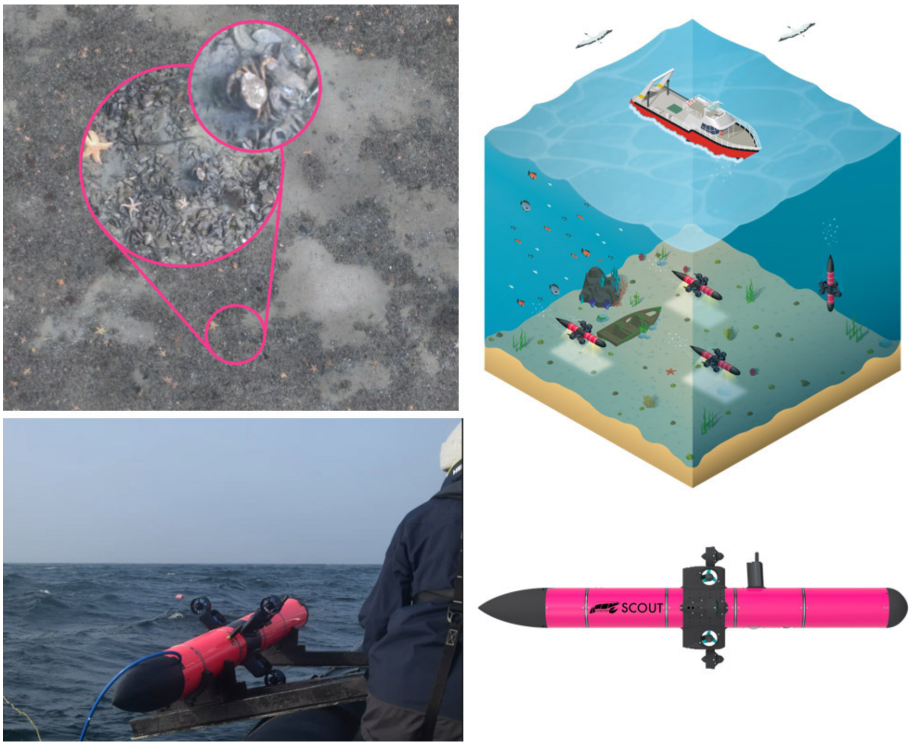


Figure 4. Examples of a seabed video taken by the robot in the North Sea habitat with native flat oysters and introduced Pacific cupped oysters and a mussel bed.

(https://alert.riparias.be/) web service, which automatically draws on occurrence data from GBIF mostly for freshwater IAS, GuardIAS will develop a similar tool for Europe and extend it with observations from marine and brackish datasets (WRIMS, AquaNIS). The system can be hosted by VLIZ as part of LifeWatch, EMODnet Biologyand EurOBIS and linked to the EASIN geodatabase.

Robotics are poised to advance IAS detection methods, overcoming limitations of traditional techniques like diving, baited traps and sampling, which are depth-limited, species-specific, or habitat-destructive. Underwater robotics, becoming more feasible due to decreasing costs and advancing technology, offer non-intrusive observation and digital archiving for later analysis. Emerging robotics excel in surveying larger areas rapidly and at greater depths, adjusting to water clarity and potentially utilizing AI for *in situ* IAS recognition. *In-situ* detection will enable robots to adjust sampling design on the fly, e.g. to collect more detailed data to confirm IAS detection. GuardIAS partner Lobster Robotics (LR) is developing a portable (~ 2 m long) autonomous underwater robot for high-resolution seabed imaging to detect and map IAS (Figure 4). The robot flies between 0.8 m and 3.0 m above the seabed depending on the turbidity of the water and captures about 650 m^2/h of the seabed at the lowest altitude with full resolution, resulting in an orthophotomosaic (high-resolution, geometrically corrected composite image created by stitching together multiple overlapping photographs). WP2 will go beyond the state-of-the-art by expanding the operating scope (turbidity, current, depth) at which large scale (10.000–

100.000 m^2 per day in 4K resolution) IAS mapping can be done, based on LR's current prototype. GuardIAS will enhance the camera system for increased mapping efficiency and real-time AI-driven IAS detection and mapping and develop a governance system for managing multiple robots simultaneously, optimizing the detection process. The terabyte (TB) of data generated per day will feed into next generation AI models that are robust and efficient, trained by consortium species identification experts, streamlining IAS detection over extensive areas and saving significant human effort. This technology will be demonstrated in the North Sea and eastern Mediterranean Sea at sites known to have IAS algae (such as the locally invasive *Stypopodium schimperi* and *Caulerpa cylindracea* in MPAs of the Aegean Sea) and molluscs (e.g. *Magallana gigas* in the North Sea). Maintaining FAIR principles, the project will develop a robust data processing pipeline to which third-party AI services can be integrated, showcasing a significant advancement in IAS detection and mapping technology.

Satellite remote sensing, while effective for terrestrial habitats, faces challenges in large-scale mapping and monitoring of IAS in shallow aquatic environments, particularly in distinguishing native and invasive species with similar spectral traits. Previous uses of optical imagery from drones and satellites have shown potential in identifying specific IAS such as the EU-listed marine alga *Rugulopteryx okamurae* (Roca et al. 2022) and the freshwater hyacinth *Pontederia* (*Eichhornia*) *crassipes* (Mouta et al. 2023). WP2 will leverage the frequent revisits and high-resolution data from Copernicus Sentinel 2 (5-day repeatability; 10-m pixel size; https://dataspace.copernicus.eu/explore-data/data-collections/sentinel-data/sentinel-2) and Planet Labs (daily revisit; 3-m pixel size) and harness the capabilities of satellite hyperspectral imaging to improve IAS mapping and monitoring in aquatic settings. Field data collection through seashore observations at low tide, snorkelling, scuba diving and aerial drones at selected sites will help build a database of spatiotemporal observations to support the creation of spectral libraries essential for spectral unmixing workflows (i.e., quantitative analysis of pixel-level data to estimate the relative abundance of target species depicted in multispectral or hyperspectral imagery based on their spectral characteristics). Open-source tools like the EnMAP Toolbox (Van der Linden et al. 2015) will be used for analysis. Combining spectral unmixing and machine learning regressions will generate fractional cover maps for both marine and freshwater target species across different locations. This work paves the way for utilising upcoming hyperspectral missions, such as ESA's CHIME (European Space Agency's Copernicus Hyperspectral Imaging Mission) and NASA/USGS's SBG (NASA and US Geological Survey's Surface Biology and Geology program), in IAS monitoring. Ultimately, these advancements will contribute to operational monitoring of specific IAS, offering crucial data for decision support systems and EW programs.

GuardIAS will explore underwater sound as a non-invasive method for monitoring sound-emitting aquatic IAS. While passive acoustics are primarily used for marine mammals (Parsons et al. 2022), some fish and invertebrates are also acoustically active (Ladich 1998). However, the sound signatures of aquatic IAS remain largely unknown. GuardIAS will pioneer the potential of current hydroacoustics for monitoring sound-emitting aquatic IAS. The first step will be identifying aquatic IAS with distinctive sound profiles, utilizing existing sound libraries such as GLUBS (Parsons et al. 2022). Autonomous recorders will be used to capture low-frequency sounds, paired with baited remote underwater video to link specific IAS to their sound signatures. Such data collection will be organized in the Aegean Sea for marine species and in northern-central Italy wetlands for freshwater species. Field data will be supplemented with recordings from public aquariums or laboratory tanks. A CS project (within Task 5.1) will assist in analysing extensive audio and video datasets. Existing sounds from Mediterranean and Red Sea studies will be used to enrich the sound library. Animal sounds ranging from infrasound (low frequency, < 20 Hz) to ultrasound (high frequency, > 20 kHz) will be analysed using a computational bioacoustics approach to validate sound sequences. A machine learning algorithm will then be trained for automatic sound recognition (Huang 2009), with extensive environmental audio recordings tested for automatic detection of IAS signatures (De Camargo et al. 2017). Finally, the project will evaluate the feasibility of using passive acoustics for IAS surveillance in terms of the number of sound signatures of alien species identified per unit of sampling effort.

eDNA methods offer higher species detection probabilities than traditional methods, especially for elusive species and where habitats are inaccessible (Bommerlund et al. 2023). Despite the exponential increase in eDNA-based studies since its origin in 2007, practical applications in biomonitoring have lagged until relatively recently (Yao et al. 2022). However, advancements in eDNA-based detection techniques now make them more viable for aquatic IAS management (Sepulveda et al. 2020). GuardIAS aims to bridge this gap by upscaling eDNA techniques for detecting and monitoring aquatic invaders focusing on (i) back-end methodology, (ii) sampling and (iii) applicability. Key to this approach is developing robust molecular assays. GuardIAS will build on recent advances in eDNA-based assays and protocols and their validation. GuardIAS will adhere to the best practices in the field (De Brauwer et al. 2023) to ensure consistency, reliability and reproducibility, to facilitate their routine adoption for IAS monitoring.

Large-scale eDNA sampling is crucial for early detection of IAS. GuardIAS will upscale eDNA sampling surveys by implementing automatic sampling machines and passive samplers over vast areas. Beyond mere detection, quantification of eDNA has emerged as a critical aspect in IAS monitoring. GuardIAS will advance quantitative methods like digital droplet PCR (ddPCR) to infer abundances or biomasses of target species (Everts et al.

2022) to better understand population dynamics, aiding in assessing impacts and management effectiveness. Whereas exact quantification of IAS populations remains challenging, we will leverage probabilistic modelling, such as occupancy modelling, to extract critical insights from presence-absence eDNA data (Doi et al. 2019). We will apply the occupancy model approach to eDNA data from selected case studies integrated with relevant variables from the database integration in WP1, to elucidate population dynamics, infer the likely pathways of introduction and secondary spread, and identify invasion hubs.

Prioritizing IAS threats (WP3)

WP3 will develop models and scenarios to identify priorities for management towards achieving the EU Biodiversity Strategy Target on IAS, to "decrease the number of Red List species threatened by IAS by 50% by 2030". IAS have often been overlooked in the formulation of future biodiversity scenarios, which have mostly focused on climate and land use changes. Addressing this gap, a research team with several GuardIAS partners developed 16 contrasting future IAS narratives on a global scale, considering various environmental, economic, demographic, technological, and social drivers (Roura-Pascual et al. 2021). Subsequently, the AlienScenarios and InvasiBES projects, both with participation of GuardIAS partners, collaboratively downscaled four major global future invasion narratives to the European level (Pérez-Granados et al. 2024) and developed a generic management strategy for IAS considering these future trajectories in Europe (Roura-Pascual et al. 2022). Leveraging the new information to be generated by GuardIAS of the occurrences, pathways, tolerance and impacts of IAS (WP1), we will translate these four future invasion narratives into quantitative, spatial representations of potential alternative futures for biological invasions (GuardIAS Scenarios).

The IUCN recently identified 162 continental aquatic or amphibian native species threatened by at least 67 aquatic IAS and has recognized southern Europe and islands as vulnerable areas (Smith et al. 2022). This report did not incorporate marine species and based its spatial prioritization on coarse 50x50 km grid data, lacking detail for freshwater habitats. The IUCN assessments, while valuable, rely on expert consultation, are resource-intensive, based on assumptions that limit their suitability to inform decision-making and present challenges in updating. Meanwhile, diverse technologies, from remote sensing to eDNA and AI, are generating new information at unprecedented rates. This influx of data holds untapped potential to improve predictive modelling and proactive IAS management. By combining traditional sources of information on species interaction and impacts with novel knowledge generated in WPs 1 & 2, GuardIAS models and scenarios will transition from expert-based to more efficient data-driven impact assessments.

The outcomes will optimise the limited resources available for management by focusing on species and sites, with the highest risk reduction potential today and in the future. WP3 will enhance and complement existing initiatives like the IUCN (Smith et al. 2022) by developing SDMs at much higher resolution (1x1 km, more appropriate to address small aquatic habitats) and including marine species overlooked in previous reports. Moreover, the spatial priorities derived from WP3 will advance current management recommendations by setting explicit recovery targets for each native species individually, avoiding the loss of species-specific information in aggregated indices (Smith et al. 2022). This allows for a better assessment of IAS risks to native species, reducing uncertainty in management recommendations.

The WP3 approach unfolds across four interrelated steps. First, we will pinpoint priority native protected species vulnerable to invasion and identify priority IAS affecting them. WP3 will harness AI-powered algorithms from WP1, establishing replicable workflows to streamline data extraction on native-invasive species interactions. This extraction process will utilize sources such as EASIN, IUCN, WRiMS, and GloBi (https://www.globalbioticinteractions.org/), building on the native-invasive interactions identified by the IUCN (Smith et al. 2022), addressing data gaps and potentially expanding the focus list to include additional native species of conservation concern identified under other international conventions.

Next, GuardIAS will use machine-learning models to predict areas susceptible to IAS under current and future scenarios. There is a mismatch between high-impact IAS distribution and the native species they affect (Gallardo et al. 2017), with IAS commonly found in degraded, lowland, coastal regions, ports and marinas (Gallardo et al. 2015), whereas conversely, threatened native species are usually in more pristine, highland areas (Gaston et al. 2008). As IAS expand their range due to factors like rising temperatures, this mismatch may change, emphasizing the need for adaptive management strategies. GuardIAS SDMs will help identify impact hotspots that combine high IAS exposure and high diversity of Red Listed species potentially affected. Through the four GuardIAS Scenarios, future models will integrate a range of climate (IPCC 2050 and 2100 scenarios), socioeconomic (shared socio-economic pathways, SSP), and technological variables. We aim to model ~250 aquatic inland IAS and RL species across major taxonomic groups. For marine species, GuardIAS will use ranges of thousands of species modelled by the Horizon project MPA Europe (coordinated by NORD) to assess the risk of marine IAS invading areas with native species and/or habitats of conservation concern. Coordination between freshwater and marine modelling teams will ensure methodological consistency across environments.

The next step involves integrating data on current and potential distribution, traits and impacts of IAS into Cumulative IMPacts of invasive ALien species (CIMPAL), a standardised tool developed in collaboration with the Joint Research Centre that quantifies the cumulative impacts of IAS on native ecosystems (Katsanevakis et al. 2016). In GuardIAS, CIMPAL will be adapted to assess cumulative IAS impacts on Red List threatened species. To support the development and implementation of this tool across aquatic environments, we will leverage the experience of GuardIAS partners in national and international scientific committees (i.e. IPBES, the IUCN's EICAT Authority and the EC Scientific Forum) that perform risk assessments and evaluate the impacts of invasive species, supporting the application of the EU Regulation on IAS.

To efficiently use limited resources, prioritizing which IAS to control and where to manage them is essential. We will begin by co-developing management objectives and targets, aligning with the EU Biodiversity Strategy, with inputs from the Advisory Board and policy stakeholders. We will use a Benefit-Cost Analysis (BCA), combining non-monetary assessment tools with the ecosystem service framework, to create an assessment in line with the welfare economic underpinnings of BCA. Using a simplified BCA prioritisation tool, a rapid and cheap appraisal of all IAS of Union Concern will be performed. We will harness data within published literature, existing databases such as WRiMS, AquaNIS, the Global Invasive Species Database (GISD), and previous WP3 tasks to assess the impacts of selected species. The analysis will include costs of eradication/control and societal costs of inaction, providing a framework for local prioritisation of IAS management. Additionally, we will use spatial prioritization tools like Zonation and PrioritizR, to identify priority areas for IAS management to meet recovery targets for native species under current and future conditions. These tools account for spatial connectivity, population benefits and recolonization probabilities (Strassburg et al. 2019), essential for assessing management effectiveness. The fine spatial resolution (1x1 km) and target-based approach of GuardIAS will compensate for the uncertainties of previous prioritization exercises (Smith et al. 2022), which were either too coarse or imprecise in determining specific species and IAS management benefits. The outcomes will include maps highlighting priority management sites and an optimized monitoring network for early IAS detection in critical areas. This approach will guide more effective strategies to reduce IAS impact on endangered species at a continental scale. The innovative aspects of WP3 methodology include the use of AI for data gathering, the integration of quantitative (CIMPAL) and spatial modelling tools (SDM), and the use of spatial prioritisation tools (e.g., Zonation, PrioritizR) to identify priorities for monitoring and managing IAS.

Management options for eradication and control (WP4)

WP4 will develop and test data-driven and collaborative expert scoring methods to assess IAS management feasibility, using the modelling capacity in WP3. This will incorporate risk management considerations on top of risk assessment priorities based on IAS impacts on valuable conservation assets (WP3). To do this, we will draft a dataset of management interventions extracting information relevant for feasibility assessment, building on 11 species-centric case studies (Table 2), and working with organisations in the field (IUCN Resource Centre on IAS, Conservation Evidence reviews, Management synopsis of the EU Regulation). The selection of the IAS for the 11 case studies was based on their high impacts and relevance for management interventions. Most of these species have been listed either as IAS of EU Concern or of EU Member State Concern or are under consideration for inclusion. Hence, for these IAS there is already a mandate for management measures and elevated interest from stakeholders, increasing the likelihood of stakeholder engagement in co-developing management options. The dataset of management interventions will be published under FAIR principles, so that it can be used as a reference for future research. WP4 will also focus on essential reporting aspects of IAS management, aligning with the development of an IAS Management Standard. It will foster collaborative networks across Europe through the Community of Practice model and organize taxonomically focused workshops (invasive macrophytes, crayfish and fish) with scientists, stakeholders and practitioners. Social-ecological networks for the targeted species will be developed in collaboration with WP5. To assess conflicts with other aspects of the social-ecological system, WP4 will use the analysis of the ten-tenets for integrated successful and sustainable marine management (Elliott 2013). This includes cause, consequence and response pathway analysis, using the ISO standard Bow-tie analysis in which the conceptual models will be built with stakeholders and then parametrised using local information. Similarly, the adaptation assessment will determine any actual or predicted socio-economic opportunities from IAS. This takes a pragmatic approach to the acceptance of IAS in cases where eradication is not possible, which is especially relevant to open coastal and marine systems or in extensive freshwater systems where IAS populations have become well established before first detection.

Control efforts will adhere to the ten-tenets framework (Elliott 2013), ensuring solutions are ecologically sustainable, economically viable, technologically feasible, legally permissible, administratively achievable, socially desirable, politically expedient, culturally inclusive, morally and ethically defendable, and effectively communicable. This framework balances quantifiable data with qualitative narratives from stakeholders (e.g., policy makers, statutory authorities, industry and aquatic managers), ensuring integration with local, national and global laws / administrations (Cormier et al. 2022). The solutions can then be built into cause, consequence and response pathways within risk assessment and risk management strategies (Cormier et al. 2019), expanding into opportunity assessment and management, in line with project CERES (Climate change and European Aquatic RESources).

Citizen and stakeholder engagement (WP5)

WP5 will build on WP3 and WP4 to apply and evaluate a range of innovative methodological approaches and tools for engaging stakeholders (such as decision-makers, aquatic managers, practitioners, IAS researchers, marina users, aquaculture and fishing sectors) and the public, improving literacy and awareness about aquatic IAS, their impacts, and management options. WP5 rejects the outdated "deficit model" of one-way science communication, opting instead for a multi-way dialogue and engagement model (Courchamp et al. 2017), utilizing recent advances in CS. WP5 approaches are inter- and transdisciplinary in nature, as they will be developed and applied with researchers from the social, economic and political sciences and humanities as well as artists, designers and management practitioners. They can be described as STEAM approaches, as they integrate Arts into STEM (Science, Technology, Engineering, and Mathematics) disciplines.

Engagement of citizens will be achieved through art performances and practical activities that stimulate broadening of perceptions, behavioural changes, and desire to take action. "BioArtBlitz" events will combine art performances by commissioned artists and field activities to actively engage citizens in an emotional and imaginative way. These events, co-designed by biologists, humanities researchers, and artists, will address IAS impacts and management strategies, also touching on controversial aspects, such as eradication actions. Following the performances, participants will join field activities to assess IAS distribution, particularly in the case studies (Table 2). This activity will involve citizens in an effective way, providing a sensorial, immersive, individual but at the same time collective experience that will help participants to overcome the passive context of normal content consumption and make them active agents of change. Interactive interviews and focus groups during these activities will explore the potential and challenges of this approach for broader application.

GuardIAS will initiate a CS project targeting marina users to raise awareness of biofouling as a vector for IAS. Eye-catching multilingual roll-up banners detailing biofouling issues, proper removal methods and most common biofouling aliens will be displayed in at least 20 key marinas in Italy. Additionally, open-air laboratory activities in the high boating season and passive habitat collectors (fouling plates) will be used to raise awareness of biofouling in the wider public arena and aid recognition and identification of alien species. Boaters will be asked to "adopt" a plate at their private berth, periodically sending pictures that will be uploaded to the Zooniverse platform for visual identification of taxa, to involve people who despite being outside of the nautical environment, may be interested in the topic.

The CS platform for recording species, iNaturalist, will also be developed as a tool for collecting new observations, expert verification of records, and aiding border control detection in WP2. This process includes developing a community of practice as a project within iNaturalist that involves citizens and professionals, experts and learners. In addition, WP5 in collaboration with WP2 will engage citizens in collecting samples for eDNA analysis.

WP5 will build on recent research developing social-ecological systems (e.g., in the ongoing MarineSABRES project) and take a social-ecological network approach to identify and analyse social-ecological interactions (SEI) for selected freshwater and marine IAS. The construction and analysis of social-ecological networks is an emerging research approach (Bodin et al. 2019) with an array of promising applications in the field of invasion science. This approach combines ecological networks (e.g. food webs) with SEI (e.g. between stakeholders and species) and social-social interactions (e.g. between stakeholders). It can, for example, be used to assess and better understand IAS impacts in an integrative way, combining ecological, socio-cultural and economic impacts. Although social-ecological systems have had other applications in marine and freshwater systems analysis, their application to the field of IAS has been very limited. Fully articulated social-ecological networks hardly exist for biological invasions (but see MacNeil et al. 2024), hence their development and analysis are a novel approach in this project.

A profound understanding of the SEI of IAS, including feedback loops and causal-loop analysis, will also allow the development of applied games (also known as serious games) focusing on the management of at least four IAS. We will develop two types of applied games for two purposes: (1) games to be used with stakeholders (e.g. decision-makers, practitioners, aquaculture and fishing sectors, other interest groups) to co-design species-specific management strategies and (2) games to be played by the general public, thus raising public awareness about the impacts and management options of aquatic IAS. Applied games have huge potential in improving management, decision-making and raising public awareness (Garcia et al. 2022). The games will be developed for both physical and virtual playing and both for Europe as a whole and in specific regional contexts, depending on the focal IAS. Players will take the role of different stakeholders, travelling through time from the present to four potential futures, based on the GuardIAS Scenarios (developed in WP3). The players' overall goal in the games will be to successfully manage the focal IAS, with the challenge that they need to collaborate to achieve an effective management, yet at the same time having different stakeholder goals. The games can be played by real stakeholders (type 1) or members of the public (type 2). We will organise stakeholder workshops in the first project year together with WP4 to get initial input from the stakeholders for game development (co-design element), as well as a workshop in the final project year in which the type-1 games will be used to co-design management strategies that are specific for the focal IAS.

Although public awareness IAS campaigns are common, e.g. Stop Aquatic Hitchhikers and Check, Clean, Dry (Seekamp et al. 2016; Shannon et al. 2020), we know very little about their effectiveness in changing public behaviour. There is a lack of research on this topic and previous studies suffer from inconsistencies in defined end points, unclear procedures and variability of campaigns, limiting the generality of conclusions (Haley et al. 2023). In GuardIAS, we will search the broader social sciences, psychology, and education literature for existing indicators for measuring learning, engagement and other relevant outcomes within a context of environmental education and nature conservation. For example, there is abundant research on the motivations of citizen scientists and learning outcomes of CS (Phillips et al. 2018) and on the effects of messaging on pro-environmental behaviour (Kidd et al. 2019). We will conduct a systematic review across disciplines and select suitable indicators within the context of IAS using a list of criteria co-created by the GuardIAS team during an internal workshop and thus ensuring a fit with the IAS context. We will design questionnaires and conduct surveys among participants in IAS monitoring via online CS platforms (e.g. iNaturalist, Zooniverse) and people involved in GuardIAS workshops and applied games. We will collect and analyse data using a pre-post control group design to measure the effects of the intervention in learning, engagement and behaviour. We take a "project-centric" approach (focusing on participants in a specific intervention) but, where relevant, will also consider volunteer-centric frameworks that explore how the accumulation of experiences can support broad learning objectives and inclusive CS (Allf et al. 2022). We will consider emotional, behavioural, cognitive and social experiences that are crucial to CS engagement (Phillips et al. 2018), specifically in an IAS context (Anđelković et al. 2022).

Also, we aim to engage researchers, practitioners, and citizen-science networks through collaborative open-access publications in official journals of the International Association for Open Knowledge on Invasive Alien Species (INVASIVESNET) – "Aquatic Invasions", "BioInvasions Records" and "Management of Biological Invasions" (Lucy et al. 2016). Specifically, we plan to publish special editions of the INVASIVESNET journals throughout the project duration, tailored to the WPs, incorporating findings from our three annual conferences. We will promote the submission of multi-author data papers, including CS data, to unearth and share previously unpublished IAS data, thereby enriching IAS datasets. Additionally, we will encourage and facilitate the publication of regular contributions with project-relevant knowledge and data in the INVASIVESNET journals. This approach is designed to broaden the scope of expertise and information shared within the project.

Dissemination, Exploitation, and Communication (DEC) (WP6)

WP6 aims to disseminate project outcomes, maximize the exploitation of results and enhance literacy, based on outcomes from WPs 1–5 and insights from the case studies. It focuses on societal engagement and comprehension through IAS literacy, guided by IOC-UNESCO principles. WP6 will educate and train a new generation of researchers in GuardIAS tools, enhancing their efficiency in IAS research. It includes a comprehensive DEC plan with various communication channels, educational resources, policy briefs, conferences and stakeholder training. WP6 plans international cooperation with initiatives such as KCBD, the Biodiversity partnership, the Mission on Ocean and Waters, EuroGOOS, UNEP GEMS Oceans Initiative, UN Decade of the Oceans, among others. To ensure coordination with the other sister project (terrestrial focus) funded under the same call but also other ongoing (e.g., GES4SEAS, ACTNOW, MarinePlan, MPA Europe, MARBEFES, BIOcean5D, DiverSea, OBAMA-NEXT, MARCO-BOLO) or upcoming Horizon projects under "Biodiversity protection and restoration" (e.g., CL6-2024-BIODIV-01-02, 01-04, 01-05), joint events will be organised, such as summer schools and scientific sessions at international conferences.

3. Impact

The project's impact extends to the broader objectives of Cluster 6 and EU Mission "Restore our Oceans and Waters" to halt and reverse the decline of biodiversity within inland waters and sea, better management of natural resources and reduce environmental degradation. GuardIAS places a strong emphasis on societal engagement in decision making and management processes, resonating with the transformative change agenda of Cluster 6.

GuardIAS will deliver prioritisation and impact assessment tools, aiding in achieving the EU Biodiversity Strategy and the KM-GBF objectives to manage established IAS and halve the number of Red List species they threaten. By improving impact assessments and developing management options, the project will enhance the quantification of IAS impacts on protected areas and support the BHD provisions (Art. 22), requiring member states to take measures to prevent alien species introductions and, if needed, to manage them effectively. GuardIAS directly supports key commitments of the upcoming EU Nature Restoration Law for coastal, marine and freshwater habitats and Article 20 of the IAS Regulation, by locating areas for restoration that maximize the recovery of protected species affected by IAS and providing management solutions for mitigating IAS impacts, a common necessity for effective restoration.

As exemplified in the choice of case study species (Table 2), GuardIAS will contribute to the improved implementation of the IAS Regulation with the development of better dataflows, tools for surveillance, prioritisation, management and capacity building. Given the inherent challenges of managing aquatic invasions, GuardIAS places particular importance on preventative policies. In particular, GuardIAS will develop solutions for biofouling management to reduce IAS transfer and promote environmentally sound practices in accordance with the IMO guidelines. This will be achieved by developing superhydrophobic surfaces to reduce biofouling, lowering maintenance costs, air pollution and energy consumption. Biofouling-related drag can increase fuel use by 40%, with negative environmental effects, increasing CO_2 and SO_2 emissions from ships between 38% and 72% in 2020.

GuardIAS will set out a credible course of action aimed at bolstering several anticipated long-term outcomes outlined in the "Biodiversity and Ecosystem Services" Destination, including:

(i) Direct drivers of biodiversity decline will be understood and addressed—land and sea use change, natural resource use and exploitation, climate change, pollution, invasive alien species—as well as indirect drivers – demographic, socio-economic, technological, etc. GuardIAS aims to curb biodiversity loss from IAS by developing comprehensive tools for each invasion stage, from prevention to control, as outlined in Figure 1. GuardIAS will contribute to this outcome by: (1) forecasting future biosecurity risk patterns linked to shipping, global trade connections, energy and resource demands, (2) developing models and scenarios that quantify how aquatic invasions might unfold in Europe and how they are likely to affect biodiversity and (3) exploring socio-ecological networks and the link between IAS and socio-economic drivers, aligning with the call's overarching objective.

(ii) Protected areas and their networks will be planned, managed, and expanded, and the status of species and habitats will be improved based on up-to-date knowledge and solutions. GuardIAS aims to improve the management of endangered species and protected areas against IAS impacts by: (1) evaluating current and future risks, (2) identifying the most vulnerable areas and RL species, (3) prioritising monitoring efforts to enhance the capacity of IAS early detection, and (4) developing and testing stakeholder-collaborative management strategies for IAS eradication or control. These efforts align with the BS goal of enhancing the management of protected areas. GuardIAS will enhance information vital for management, such as IAS spatial distribution under current and future conditions and risk assessment, using innovative methods such as eDNA and remote sensing. It will also address knowledge gaps in IAS-native species interactions, disseminating findings via global platforms like GloBI. GuardIAS will transfer knowledge to aquatic managers, training them on ecological, socio-economic risks and best practices.

(iii) Biodiversity, ecosystem services and natural capital will be mainstreamed in the society and economy: e.g. they will be integrated into public and business decision-making; approaches for enabling transformative changes to tackle societal challenges will be built including by deploying nature-based solutions (NbS). Data and information from GuardIAS will feed KCBD and the Biodiversity Information System for Europe (BISE). KCBD will facilitate science-policy integration, enriching EU biodiversity policy making and implementation with research and innovation insights. Since IAS impacts can undermine NbS effectiveness, GuardIAS will offer essential mitigation strategies, bolstering the success rate of NbS in aquatic ecosystems.

(iv) Practices in agriculture, forestry, fisheries and aquaculture will be developed and improved to support and sustainable utilize biodiversity and ecosystems services. GuardIAS tackles the challenges IAS pose to fisheries and aquaculture, establishing EW systems with the involvement of fishers, citizens and NGOs to proactively mitigate IAS impacts on these sectors. Thematic workshops will focus on preventative strategies, equipping aquaculture practitioners and policymakers with measures to prevent IAS spread in aquatic environments, supporting the sustainability of aquaculture practices. The technological innovation of GuardIAS directly contributes to enhancing practices in fisheries and aquaculture by providing efficient tools for detecting and controlling IAS. The project's emphasis on risk assessment and management aligns with sustainable practices, aiming to mitigate IAS negative impacts on native species and ecosystems. GuardIAS collaborative approach, engaging scientists, stakeholders and organizations across Europe, enhances knowledge exchange and advocates best practices in IAS management, in line with the EU's goal of promoting sustainable natural resource use.

(v) Biodiversity research and support policies and processes will be interconnected at EU and global levels, making use of advanced digital technologies and societal engagement where appropriate. GuardIAS supports the goals of the EU Biodiversity Monitoring Coordination Centre and the European Open Science Cloud, facilitating interconnectivity at both EU and global levels. It will strengthen linkages between key IAS-related platforms, such as EASIN, AquaNIS (managed by KU-MRI), and WRiMS (managed by VLIZ), and upscale tools like Belgium's RIPARIAS EW system to the EU level for integration with EASIN. Leveraging AI and IT, GuardIAS will enhance IAS data integration, detection, and monitoring. Through social engagement (WP5) in the case studies (WP4) and with different sectors and international networks (WP6), GuardIAS will support interconnecting biodiversity research and EU policies. IAS-related governance and management will be integrated both horizontally (across sectors) and vertically (from the local to global) and interrogated using the management response-footprint pyramid approach (Cormier et al. 2022).

(vi) The biodiversity and health nexus will be understood, in particular at the level of ecosystems. This will be achieved by using the one-health approach, in the context of climate change and globalisation and by addressing contributions and trade-offs. GuardIAS, in its mission to combat IAS and their impacts, can significantly contribute to better understanding the biodiversity and health nexus at the ecosystem level. Through its research and mitigation efforts, GuardIAS will provide valuable insights into mitigating the negative effects of IAS on ecosystems and consequently, promote the health and sustainability of both natural and human systems.

GuardIAS will substantially contribute to the following UN Sustainable Development Goals:

- SDG14 (Life below Water). GuardIAS addresses multiple targets within SDG14, aiming to rectify hitherto deficiencies by quantifying the targets where possible (Cormier and Elliott 2017). It focuses on preventing and reducing marine biological pollution (Target 14.1), including novel tools for the prevention, early detection and control of marine IAS (WP1, WP2, and WP4). Developed models for prioritizing management of high-risk species and sites (WP3), taking into account global warming scenarios, will support the sustainable management of marine ecosystems (Target 14.2). GuardIAS also targets the control of invasive fish (see Table 2), promoting sustainable fishing and consumption to manage impacts on other marine resources (Target 14.4) and benefiting small-scale artisanal fishers and markets (Target 14.b). The project will enhance scientific knowledge, research capacity and marine technology transfer (Target 14.a), improving ocean health and marine biodiversity through effective actions against IAS (WP1, WP2, WP4).

- SDGs 6 (Clean Water and Sanitation) and 15 (Life on Land). GuardIAS activities (WP1, WP2, WP4) address SDG6 by improving freshwater ecosystem quality, aligned with the goal of protecting and restoring water-related ecosystems (Target 6.6). For SDG15, the project focuses on conserving and sustainably using inland freshwater ecosystems and their services (Targets 15.1, 15.5, 15.8), particularly Target 15.8, by implementing measures to control and reduce the impact of freshwater IAS.

- SDG5 (Gender Equality): GuardIAS is dedicated to promoting gender equality, diversity, and balance, particularly in leadership and stakeholder engagement, to ensure both sexes full and effective participation and equal opportunities in line with SDG Target 5.5. This is also reflected in the gender balance of the GuardIAS consortium.

Policy feedback measures

GuardIAS policy-relevant outcomes will contribute to meeting the requirements of multiple policies, strategies, and activities (Figure 5). WP1 will harmonize and integrate data and knowledge from multiple sources (see Figure 3), supporting environmental and risk assessments, action plans, and policy reports for the needs of the IAS Regulation, BS, RSCs, BHD, EEA, NRL, Marine Action Plan, the Ocean Decade, and the KM-GBF (Figure 5).

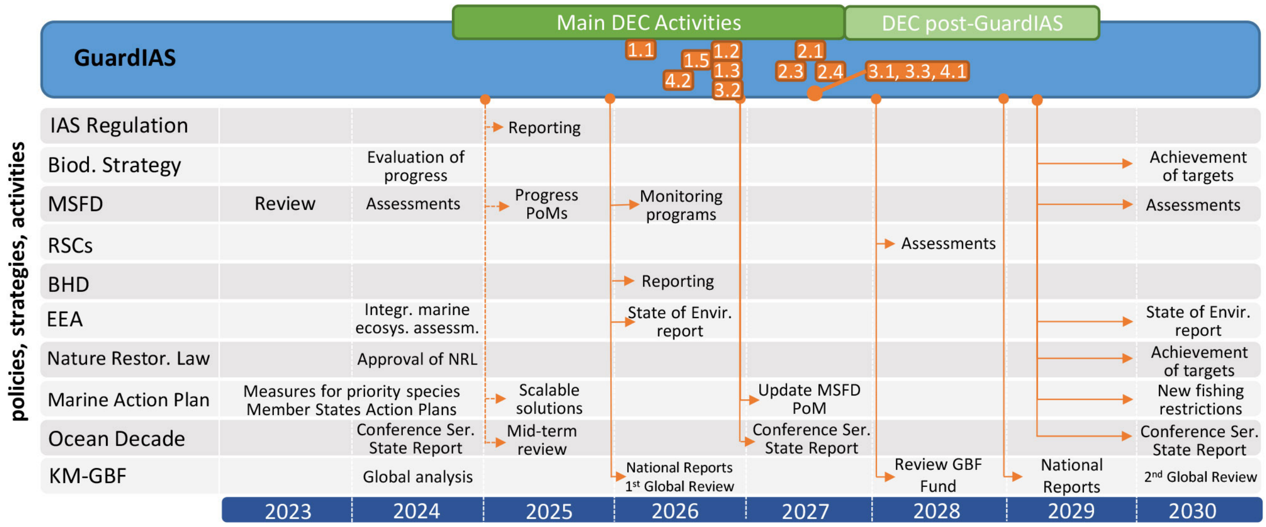


Figure 5. Timeline illustrating the integration of GuardIAS outputs into various policies, strategies, and activities, influencing them during (2024-2027) and post-project. PoM: programme of measures; NRL: Nature Restoration Law: MSFD: Marine Strategy Framework Directive; RSCs: Regional Seas Conventions; BHD: Birds and Habitats Directives; EEA: European Environment Agency; Orange numbers denote GuardIAS deliverables.

WP2 will develop novel tools, methodologies and field protocols for monitoring aquatic IAS, aiding the implementation of WFD, MSFD and BHD. GuardIAS will optimise outputs for policymakers (e.g., through Tasks 4.3, 5.5, 6.3, 6.5, 6.8, 6.9, 6.10) by ensuring data interoperability and that the developed methods and tools are fit-for-purpose and efficient to address policy needs. GuardIAS will achieve this through collaboration with national policymakers and leveraging National Contact Points. The Community of Practice (T4.3) will facilitate knowledge transfer and involve policy stakeholders in creating KER. Policy end users will engage in workshops for feedback and co-design the data flow among different systems (Figure 3), the GuardIAS EW tool to be integrated in EASIN (T2.6), and management strategies for focal IAS (T4.3, T5.3, T6.4). GuardIAS will establish strong links with EASIN, the official EU information system for IAS Regulation, ensuring accessibility of GuardIAS datasets and tools to member states. GuardIAS aims to provide robust evidence for informed decision-making on IAS management and engage with European and international regulatory bodies, networks and advisory groups, leveraging the consortium's strong ties with international and national research and innovation activities. The outcomes of co-design workshops and targeted policymaker engagement will be distilled into various impactful resources, including videos, policy briefs, infographics, guides, training material, and recommendations (WP6). The project's DEC plan is dynamically aligned with policy milestones (Figure 5), involving key stakeholders in the AB to optimize project impacts.

4. Work plan

GuardIAS is an intricately designed, multidisciplinary initiative, comprising 7 interconnected WPs (Figures 1, 2; Supplementary material Table S1). The Gantt chart for the project (Figure S1) provides a comprehensive overview of the scheduling of tasks, milestones, and deliverables. The PERT chart (Figure S2) outlines the critical paths linking essential tasks required to achieve GuardIAS objectives, as detailed in the project methodology. The comprehensive work plan provided in Table S1 reflects GuardIAS commitment to robust coordination, efficient communication and the pursuit of its ambitious objectives in tackling IAS.

Grant title

GuardIAS – Guarding European Waters from IAS.

Authors' contribution

All authors contributed to writing, reviewing & editing the proposal and manuscript and in research conceptualization; SK: coordination, research conceptualization; AZ, SO, MC, BG, ET, TA, JMJ, MS, NB: Work Package leaders, coordination of WP and Task preparation, research conceptualization; KE, SR, DP, AM, RB, JR, NN, VH, RB, FEL, LV: Task leaders, coordinating/drafting specific tasks, research conceptualization.

Authors' ORCIDs

Stelios Katsanevakis: 0000-0002-5137-7540; Anastasija Zaiko: 0000-0003-4037-1861; Sergej Olenin: 0000-0002-0773-1442; Mark John Costello: 0000-0003-2362-0328; Belinda Gallardo: 0000-0002-1552-8233; Elena Tricarico: 0000-0002-7392-0794; Tim Adriaens: 0000-0001-7268-4200; Jonathan M. Jeschke: 0000-0003-3328-4217; Maria Sini: 0000-0002-9608-3503; Nóirín Burke: 0009-0000-9009-5549; Kosmas Ellinas: 0000-0002-5682-2121; Stephan Rutten: 0009-0003-0311-2622; Dimitris Poursanidis: 0000-0003-3228-280X; Agnese Marchini: 0000-0003-4580-0522; Rein Brys: 0000-0002-0688-3268; Joost A. M. Raeymaekers: 0000-0003-2732-7495; Nicolas Noé: 0000-0002-9503-4750; Virgilio Hermoso: 0000-0003-3205-5033; Rakel Blaalid: 0000-0002-3883-8189; Frances E. Lucy: 0000-0002-4785-2724; Laura N.H.Verbrugge: 0000-0003-2888-9027; Peter A.U. Staehr: 0000-0002-1580-4875; Leen Vandepitte: 0000-0002-8160-7941; Daan de Groot 0009-0002-8820-0797; Michael Elliott 0000-0002-2519-4871; Julian Maclaren: 0000-0001-7073-2926; Mengyu Li: 0000-0002-6791-1170; Damiano Oldoni: 0000-0003-3445-7562; Antonios Mazaris: 0000-0002-4961-5490; Vasilis Trygonis: 0000-0001-9590-0391; Pascal I. Hablützel: 0000-0002-6739-4994; Teun Everts: 0000-0001-7862-4209; Jennifer C.A. Pistevos: 0000-0001-8081-7069; Stefanie Dekeyzer: 0000-0001-9525-2742; Sophia E. Kimmig: 0000-0002-4140-6002; Fiona S. Rickowski: 0009-0003-2320-0275; Vadim E. Panov: 0009-0003-0738-0800

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Ethics and permits

The GuardIAS project aims to enhance aquatic conservation efforts through innovative ecological monitoring. Its goals are ethically grounded in contributing positively to aquatic ecosystems and biodiversity preservation. The methodologies employed in GuardIAS are designed to be environmentally friendly, minimizing impact on aquatic habitats. Techniques for IAS management are chosen to ensure the humane treatment of aquatic species, adhering to ethical research practices. GuardIAS is anticipated to have a significant positive impact on aquatic conservation, aiding in the protection of endangered species and habitats. The project complies with all relevant national and international laws and regulations related to aquatic conservation and IAS management, ethical research practices, and biodiversity protection, ensuring legal and ethical integrity in its execution. All partners will ensure early compliance of the proposed research with EU and national legislation on ethics in research.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Work package description [KPI: Key Performance Indicator]

Figure S1. Gantt chart indicating the duration of WPs and Tasks, milestones, and deliverables.

Figure S2. PERT Chart indicating the main connections between critical tasks necessary to achieve the main GuardIAS objectives and outcomes of the call.

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