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DOI: https://doi.org/10.3897/arphapreprints.e160384

TRACKS: Six good practices for Non-Indigenous Species research and their SWOT evaluation

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Abstract

Addressing the challenges posed by Non Indigenous Species (NIS) demands coordinated efforts across terrestrial, freshwater, and marine ecosystems. In this study, we used the Italian research network as a case study to identify and evaluate measures designed to enhance NIS research through a structured, interactive, and expert-driven strategy.

The process began with a comprehensive evaluation of ongoing activities, research methodologies, and specific needs. This assessment informed the development of an initial set of proposals, which were collectively discussed and refined, leading to the identification of six good practices identified by the acronym TRACKS and described as: *i*) Tracking NIS in data collections; *ii*) Reference protocols for NIS data collection; *iii*) Active participation through citizen science and local ecological knowledge; *iv*) Collaboration in data sharing according to the FAIR principles; *v*) Knowledge Hub as centralized data repository for NIS data; *vi*) Strategic communication to raise public awareness and support public engagement.

A SWOT framework was then applied to analyze the internal and external factors influencing the Strengths, Weaknesses, Opportunities, and Threats associated with each practice. Consensus-building techniques were used throughout the evaluation process to ensure the robustness of outcomes. Finally, a quantitative assessment of the SWOT analysis was conducted with 90 NIS experts working in terrestrial, marine, and freshwater ecosystems. This approach provided valuable insights into differing perceptions and enabled a clear presentation of six good practices to be consistently applied across NIS research systems.

Keywords: Expert elicitation; Good practices; Invasive species; Structured evaluation; Italy

Introduction

Researchers worldwide continuously collect critical biodiversity data from terrestrial and aquatic ecosystems, underscoring the rising prevalence and significant impacts of Non-Indigenous Species (NIS), a crucial indicator of global environmental change (Seebens et al. 2017). Due to their potential to become invasive and extensively disrupt biodiversity and ecosystem dynamics (Simberloff 2013), NIS that transition to invasiveness, often termed Invasive Alien Species (IAS), have become a major global environmental concern (Vitousek et al. 1996; Diagne et al. 2021; IPBES 2023). IAS can indeed cause considerable biodiversity loss (Bellard et al. 2016), disrupt ecosystem services (Vilà and Hulme 2017), pose severe health risks to plants and animals (Hulme 2021), impose significant economic burdens (Diagne et al. 2021), and ultimately threaten human well-being (Shackleton et al. 2018). To address these impacts, integrative frameworks such as the One Health approach and the Biosecurity Continuum are increasingly utilized (Gozlan et al. 2024), along with enhanced prevention, early detection, and rapid response capacities at both national and international levels (IPBES 2023). Recent global estimates indicate that biological invasions impose economic costs of approximately 400 billion euros annually (IPBES 2023), comparable to other major natural hazards like earthquakes and wildfires (Turbelin et al. 2023).

The European Biodiversity Strategy for 2030, adopted in 2020 (European Commission 2020), explicitly identifies IAS as a major driver of biodiversity loss. The strategy underscores the importance of enforcing Regulation (EU) No. 1143/2014 (European Commission 2014), which was entered into force in Italy with the Legislative Decree 230/2017, along with related policies aimed at preventing and controlling IAS introductions. One of the strategy's key commitments is to reduce by 50% the number of species threatened by IAS, based on assessments from the IUCN Red List (https://www.iucnredlist.org).

Despite the European Union's comprehensive framework for addressing biological invasions, significant challenges remain in its effective implementation. Current initiatives tend to focus on a limited number of regulated IAS, notably the 88 species listed in the List of Invasive Alien Species

of Union Concern, which forms the core of Regulation (EU) No. 1143/2014 (Magliozzi et al. 2024; Ojaveer et al. 2025). Additionally, at the national level, Member States can adopt priority lists of IAS to guide their own management actions under this last Regulation. Moreover, the full regulatory landscape includes additional lists, such as the Priority list of quarantine pests, which covers insects, fungi, and bacteria relevant to plant health. Monitoring of these species is mandatory across all Member States under Regulation (EU) 2019/1702, which supplements Regulation (EU) 2016/2031 of the European Parliament and of the Council (Official Journal of the European Union, L 260/8–10). In marine ecosystems, Regulation (EU) No. 1143/2014 and EU legislation, in general, exhibit clear limitations in effectively managing the issue of biological invasions (Kleitou et al. 2021). Yet, NIS are specifically addressed under Descriptor 2 (D2) of the Marine Strategy Framework Directive (MSFD, 2008/56/EC), which mandates Member States to implement measures aimed at preventing new introductions. According to Commission Decision (EU) 2017/848, a Member State is considered to have achieved Good Environmental Status for D2 when the introduction of NIS as a result of human activity is minimized and, when feasible, reduced to zero.

Regarding the use of alien and locally absent species for commercial purposes, the Council of the European Union has established a regulatory framework for aquaculture, which is a significant pathway for NIS introduction. This includes Regulations (EC) No 708/2007, 506/2008, 535/2008, and Regulation (EU) No 304/2011, which aim to assess and minimize the potential impacts of NIS and associated non-target species on aquatic ecosystems, while supporting the sustainable development of the sector. In line with this legislation, European countries such as Italy have appointed institutional advisory committees of experts to assist in the evaluation process and conduct environmental risk assessments when introductions are requested. These committees are also responsible for maintaining a register of NIS introductions for aquaculture purposes, providing a historical record of all applications submitted

Guiding elements to protect biodiversity and ecosystems and minimize the impact of NIS from aquaculture have been further included in the Regional Plan on aquaculture management defined by the Contracting Parties of the Barcelona Convention (UNEP/MED, Decision IG 26/7.2023).

Noticeably, a significant obstacle to the effective implementation of these frameworks is the fragmented management of NIS, as terrestrial, freshwater, and marine ecosystems are often governed through sectoral policies and disconnected institutional responsibilities. This lack of integration hampers coordinated surveillance, data sharing, and response efforts, further complicating timely and effective action against biological invasions. To overcome these challenges, more effective cross-sectoral guidance and integrated case studies are essential for bridging knowledge gaps and fostering a cohesive, adaptive management framework, a need strongly emphasized by organizations such as IPBES (2023) and FAO (Azzurro et al. 2024a).

These intentions can be significantly hampered by the critical aspects of data management, including the centralization, standardization, harmonization, and sharing of data with third parties (Deriu et al. 2017; Groom et al. 2015, 2017; Seebens et al. 2020; Vilizzi et al. 2025). Additionally, effectively communicating information about NIS and their impacts on society is paramount, as societal awareness plays a crucial role in the sustainable management of biodiversity (Young et al. 2014; Rodríguez-Rey et al. 2022; Sosa et al. 2021; Golebie et al. 2022; Doley and Barman 2023). However, communication and public awareness efforts regarding NIS remain comparatively underdeveloped relative to those addressing other biodiversity threats, such as climate change (Courchamp et al. 2017).

Building on these premises, this study aims to identify and evaluate a shared set of good practices suitable for adoption by various bioinvasion expert communities, using Italy as a national case study. Italy is one of the most biodiverse countries in Europe (Convention on Biological Diversity 2019) and represents a critical hotspot for biological invasions. Its wide range of ecosystems, from coastal zones to mountains, makes it particularly susceptible to the establishment of a broad variety of NIS, with significant impacts on both terrestrial and aquatic ecosystems (Gherardi et al. 2008; Colangelo

et al. 2017; Servello et al. 2019; Lazzaro et al. 2020; Occhipinti-Ambrogi et al. 2011; Domina 2021). According to data from the Italian Institute for Environmental Protection and Research (ISPRA; https://specieinvasive.isprambiente.it), nearly 3,800 NIS have been recorded in Italy, of which 3,659 are currently established. The economic cost of biological invasions in the country between 1990 and 2020 was estimated at approximately €23 million per year and it is expected to increase (Haubrock et al. 2021). This escalating situation negatively affects productive sectors such as agriculture, forestry, fisheries, and aquaculture (Haubrock et al. 2021; Campagnaro et al. 2022; Chiesa et al. 2025; Maistrello et al. 2024), endangers natural habitats (Lazzaro et al. 2020; Hulme et al. 2007; Pasta et al. 2017), and disrupts essential ecosystem services (Fedele et al. 2019). It also compromises human health in various ways, including through allergies (Cristofori et al. 2020; Pecoraro et al. 2024) and vector-borne diseases (Rossi et al. 2023; Cerri et al. 2024), while only a few cases of potentially new economic opportunities have been documented so far (Azzurro et al. 2024b). Effective management of these impacts relies on accurate, up-to-date data, which are often only partially available, fragmented across different research groups and infrastructures, difficult to access and re-use, and rarely communicated to the public. In compliance with the MSFD, Italy has a national monitoring programme for detection of marine NIS in hotspot areas since 2014 (Decree of the Ministry for Environment, Land and Sea Protection MATTM dated 11 February 2015 and Decree of the Ministry for Environment, Land and Sea Protection MATTM dated 2 February 2021). However, Italy notably lacks a national monitoring system for NIS, with the exception of List of IAS of Union concern, as mandated by EU Regulation 1143/2014 and the formally adopted monitoring guidelines with the Decree of the Ministry of Environment and Energy Security 12/2022.

In this study, in order to develop and evaluate a set of good practices aimed at enhancing research on NIS, we submitted an initial set of expert-based proposals to a quantitative SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis. The SWOT technique is a structured decision-making tool widely applied in various sectors (Gregory et al. 2012), including conservation (Mukherjee et al. 2015). Although rarely used in NIS research, it offers a flexible framework for

evaluating management strategies, particularly in contexts where data are incomplete, an issue commonly encountered in biodiversity monitoring (Patrício et al. 2016). The process was intentionally inclusive, involving NIS experts from terrestrial, marine, and freshwater domains, thereby facilitating the integration of diverse perspectives into shared proposals.

Methods

A structured four-steps approach (Fig. 1) was employed to identify and assess good practices for enhancing NIS research, using Italy as a case study. The workflow comprised: a survey of Italian experts on NIS and biological invasions to initially identify potential good practices (Step 1); a workshop utilizing the Delphi method to evaluate the feasibility of each practice, complemented by focus group discussions on their advantages and disadvantages (Step 2); a second workshop where the selected good practices were refined and SWOT indicators were developed (Step 3); and a final survey performing a quantitative SWOT analysis to assess these practices, considering their strengths, weaknesses, opportunities, and threats specifically within the Italian context (Step 4).

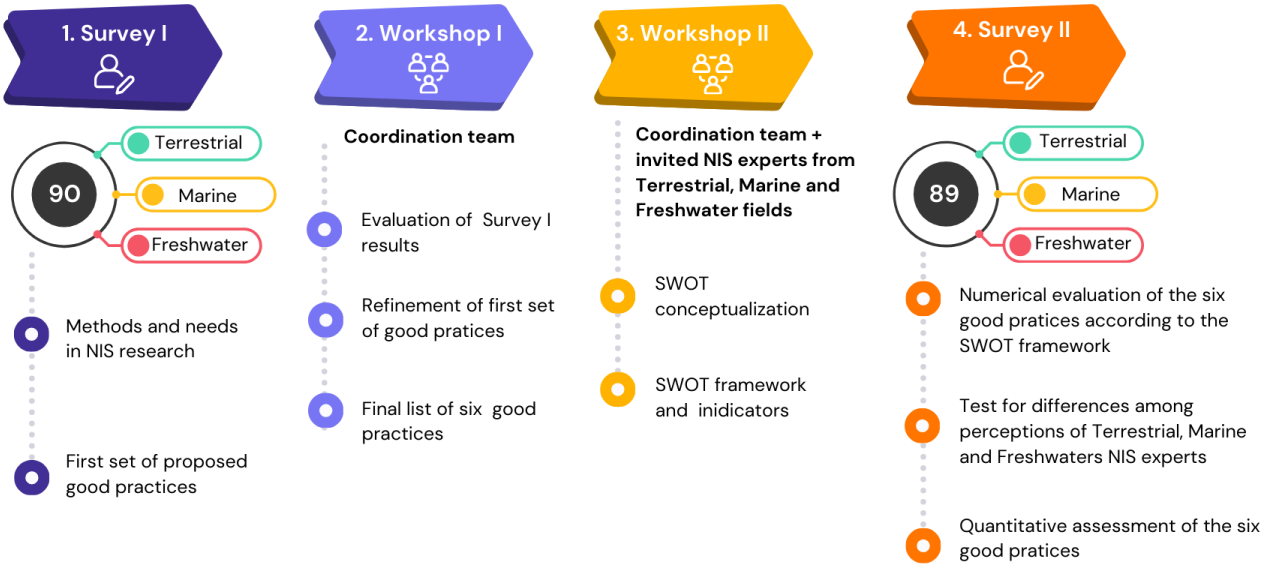


Figure 1. Overview of the four-steps approach. Workflow of the four-steps approach used to identify and qualitatively assess good practices for NIS research in Italy. A total of 90 experts in terrestrial, marine, and freshwater NIS were engaged throughout the process.

266

267 *Step 1 - Identification of experts and collection of recommendations for good practices*

268 Between July and November 2022, we engaged 90 experts specializing in the NIS taxonomy, biology,
269 ecology, monitoring, and management in Italy to gather insights into national research activities.
270 Experts were identified through three main strategies: (*i*) reviewing existing studies on NIS carried
271 out in Italy, (*ii*) identifying individuals involved in major conservation projects related to NIS, and
272 (*iii*) employing a snowball method, where experts were asked to recommend additional colleagues.
273 All participants completed an online questionnaire (Appendix 1), primarily composed of open-ended
274 questions. This survey aimed to map key research efforts, identify the most frequently studied NIS in
275 Italy, and compile ongoing research and monitoring activities, significant programs, methodologies,
276 and sampling schemes across diverse ecosystems. Additionally, it explored major gaps in current
277 research activities and assessed experts' willingness to participate in a harmonized approach for NIS
278 monitoring and data sharing. Based on the survey results, we identified an initial set of nine potential
279 good practices aimed at standardizing data collection, sharing, and communication about biological
280 invasions in Italy (Appendix 2).

281

282 *Step 2 - Six good practices to be submitted to quantitative evaluation*

283 The nine potential good practices defined during Step 1 were discussed and refined, ultimately
284 consolidating them into a final list of six good practices for harmonizing data collection, sharing, and
285 communication about NIS through a consensus-based analysis (Appendix 2). These good practices,
286 detailed in Table 1, include: *i*) Tracking NIS in data collections; *ii*) Reference protocols for NIS data
287 collection; *iii*) Active participation through citizen science and local ecological knowledge; *iv*)
288 Collaboration in data sharing according to the FAIR principles; *v*) Knowledge Hub as centralized data
289 repositories for NIS Data; *vi*) Strategic communication to raise public awareness and support public
290 engagement.

291

292 *Step 3 - Conceptualization of SWOT indicators through a consensus-based approach*

293 The conceptualization of the SWOT analytical method involved developing a comprehensive set of
294 SWOT indicators categorized within each good practice across the four SWOT components.
295 Following general SWOT principles (Chang and Huang 2006), the analysis of opportunities and
296 threats focused on leveraging external factors beyond direct control, while the analysis of strengths
297 and weaknesses assessed internal factors, including management practices and operational efficiency.
298 This process was facilitated through collaborative focus-group discussions (Nyumba et al. 2018),
299 allowing integration of diverse perspectives and guiding the subsequent quantitative evaluation of
300 good practices in NIS research.

301

302 *Step 4 - Quantitative evaluation of the six good practices*

303 National experts were subsequently re-engaged to quantitatively evaluate the six selected good
304 practices using their corresponding SWOT indicators, which were presented under the 'TRACKS'
305 framework (Table I). A total of 90 researchers participated in this evaluation, categorized according
306 to their area of expertise: terrestrial (N = 33), marine (N = 28), and freshwater (N = 28) bioinvasions.
307 Participants assessed the strengths, weaknesses, opportunities, and threats of each practice using a
308 seven-point scale (1 to 7) in an online survey administered via Google Forms. Detailed information
309 about the survey structure is provided in Appendix 3.

310

311 *Data analysis*

312 We aggregated scores for the Strengths and Weaknesses, and for the Opportunities and Threats, of
313 each good practice of TRACKS, into two quantitative scores (hereinafter named "SW" for strengths
314 and weaknesses and "OT" for opportunities and threats), following the approach of Scolozzi et al.
315 (2014). Namely, for each good practice, we calculated SW final scores by subtracting the score
316 assigned to weaknesses from the score assigned to strengths. Similarly, we calculated OT final scores
317 by subtracting the score assigned to threats from those assigned to opportunities. This resulted in 6

SW and 6 OT final scores, two for each good practice, that ranged from -7 to +7. We divided our data analysis into three different steps. First, we employed cross-plots, to visually assess the level of agreement among experts on each of the six good practices. The plots, showing the mean as well as the first and third quartiles of SW and OT scores. Moreover, we used Partitioning Around Methods (PAM) cluster analysis to identify homogeneous groups of experts based on the SW and OT scores assigned to the six good practices. This method was chosen due to its robustness against non-normality in the data, compared to conventional k-means clustering. The optimal number of clusters was assigned by graphically exploring the average silhouette width, the gap statistics, and the within-cluster sum of squares (Kassambara 2017). Once we identified our groups of respondents, we tried to understand their nature, by comparing SW and OT scores and by checking their professional background.

Finally, we used the Kruskal-Wallis test to test for significant differences in the SW and OT scores assigned to each good practice, among experts working mostly on terrestrial, freshwater, or marine ecosystems. Statistical analysis was carried out through the software R version 4.4.2 (R Core Team 2025).

Results

TRACKS: Six good practices to improve NIS research under a SWOT framework

The consensus-driven process, outlined in Fig. 1, led to the identification of six good practices and 49 key indicators (Table 1), categorized within each practice and across the four SWOT components. These indicators of the TRACKS framework, which represent both the internal and external factors influencing the effectiveness of each measure, are illustrated in Table 1.

Table 1. Detailed description of the six good practices of the TRACKS protocol, submitted for quantitative evaluation, along with the corresponding indicators for each SWOT category

TRACKS	S - Strengths	W - Weaknesses	O - Opportunities	T - Threats
GP1. Tracking NIS in data collections: All research groups involved in collecting data on species abundance and/or distribution are encouraged to verify the presence of NIS (Non-Indigenous Species) among the species in their study, ensuring correct identification at the lowest taxonomic level for all species in a fully sampled community.	S1: Growing scientific interest in NIS S2: Existing data on species abundance and distribution S3: Existing taxonomic expertise in Italy	W1: Shortage of taxonomists in Italy W2: Inaccessible datasets. W3: Variability across data sources	O1: Increasing importance of NIS data for management and monitoring O2: Opportunities for research collaborations	T1: Risk of misidentification of NIS due to lack of expertise
GP2. Reference protocols for NIS data collection: For NIS data collection, it is recommended to adhere to established protocols when available. To facilitate this, it would be valuable to create a national list of reference protocols for NIS data collection.	S1: Available protocols for specific habitats and taxa	W1: Missing protocols for several NIS W2: Reluctance to adapt practices	O1: Positive sinergies with data collection O2: Enhanced use of NIS data for monitoring and research	T1: Risk of errors in protocol implementation
GP3. Active participation through citizen science & local ecological knowledge: When appropriate, the potential contribution of local communities to NIS data collection through participatory actions and citizen science (CS) should be evaluated. The Local Ecological Knowledge (LEK) method, which utilizes the knowledge and observations of local communities, is currently applied only in marine environments. It is suggested to expand and experiment with this approach in terrestrial and freshwater environments as well.	S1: Existing protocols and networks for CS and LEK S2: Active community groups (e.g., fishermen, nature associations) S3: Active social media platforms and networks	W1: Clear taxonomic limitations. W2: Limited ability to generate quantitative data W3: Need for data validation W4: Reluctance from some stakeholders	O1: CS and LEK expand spatial/temporal coverage of monitoring and improve early detection O2: Strengthening partnerships for monitoring	T1: Risk of misinformation due to conflicts of interest T2: Risk of inaccurate taxonomic identification if NIS data are not properly validated
GP4. Collaboration in data sharing according to the FAIR principles: The national scientific community should be encouraged to share and promote NIS data through best practices in Open and FAIR (Findable, Accessible, Interoperable, Reusable) Science. This can be achieved by highlighting the advantages of these practices and the associated tools in various research contexts through communication activities such as seminars, workshops, institutional training, and university courses.	S1: Scientific community increasingly recognize the value of NIS data S2: Alignment with international Open Science standards	W1: Lack of knowledge on how to produce shareable data W2: Reluctance due to competition and data ownership concerns W3: Lack of expertise in FAIR data management	O1: Shared databases enhance collaboration and the potential to access to international funds and projects	T1: Limited external threats
GP5. Knowledge Hub as centralized data repositories for NIS Data: Given the large volume of NIS data generated nationally, the development of an open-access reference repository to consolidate this information would be highly beneficial.	S1: Low initial cost using existing tools S2: National data could be consolidated in one location	W1: Need to align with international systems W2: Long-term funding and maintenance issues W3: Rapid obsolescence of the system	O1: Fosters collaboration and improves NIS data management O2: Contributes to international databases	T1: Risk of erroneous data being entered into the repository T2: Risk of increased competition could lead to conflicts among research groups
GP6. Strategic communication to raise public awareness and support public engagement: Data collected, along with accompanying video/photo documentation, can be leveraged in communication efforts on biological invasions at all levels. This would help raise awareness and increase the involvement of local communities in participatory research and monitoring activities.	S1: A general media's receptiveness to NIS issues S2: Visual content enhances public engagement via social media	W1: Many researchers lack communication skills and/or are not interested in communication W2: Limited potential of engagement with small, not conspicuous NIS species	O1: Increased public awareness should facilitate management actions on NIS O2: Synergies with CS and LEK for long-term engagement of local communities	T1: Overly alarmist communication could backfire T2: Misuse or politicization of scientific content, with manipulations of messages related to NIS

343

344

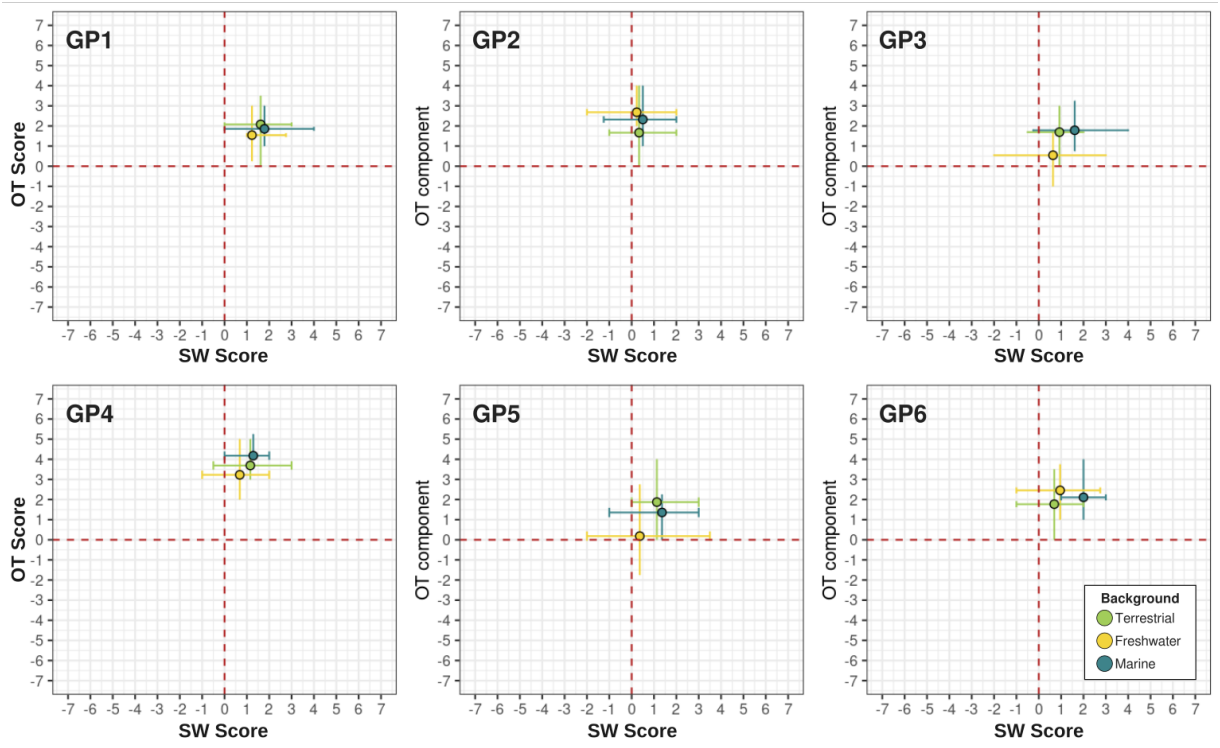
345 *Numerical evaluation of SWOT*

346 The analysis of crossplots indicated a good agreement about the six good practices among experts
347 working on terrestrial, freshwater, and marine NIS (Fig. 2). All three groups of experts evaluated the
348 six good practices positively, in terms of their strengths and opportunities. However, evaluations of
349 the SW component were more uncertain than those of the OT component (Fig. 2). Experts working

on freshwater NIS were slightly more uncertain in their evaluation of SW and OT scores. This uncertainty is mainly due to the use of Citizen Science (CS) and Local Ecological Knowledge (LEK) for monitoring NIS (as in good practice n. 3, GP3 in Fig. 2), as well as for the development of a centralized repository for NIS data (GP5 in Fig. 2).

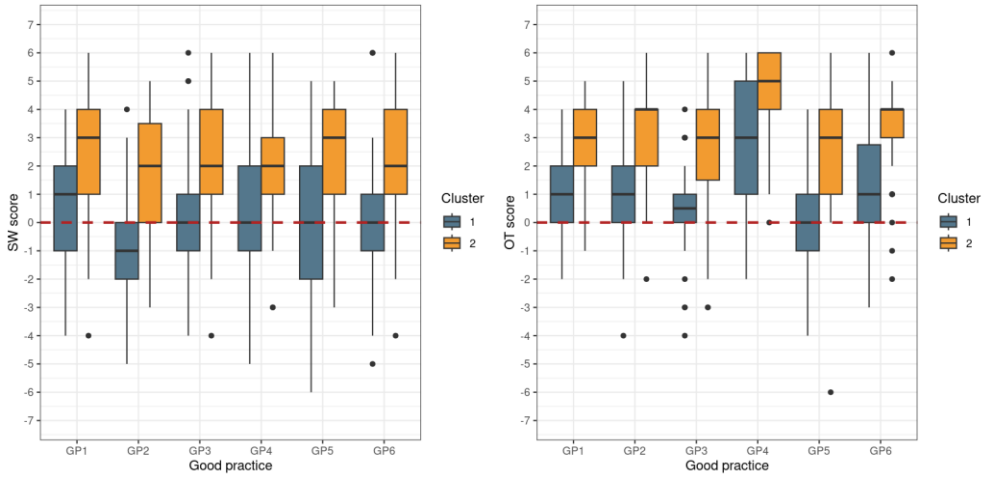
The cluster analysis identified two groups of experts (Figs. S1, S2). These two groups were rather homogeneous in their composition, in terms of experts working with terrestrial NIS (43.4% vs. 44.1%), with most of their differences being limited to SW and OT scores (Fig. 3) and in the proportion of experts working on freshwater (32.6% vs. 16.2%) and marine (23.9% vs. 39.5%) NIS. Namely, one group of experts assigned higher SW and OT scores to the development of a centralized repository for NIS data (GP5, Fig. 2) and to the communication about NIS risk to people (GP2, Fig. 2).

The Kruskall-Wallis test did not highlight any significant difference in SW and OT scores for the six good practices, between experts working on terrestrial, freshwater, or marine NIS (Fig. 4, Fig. 5).



365 **Figure 2. Distribution of Strengths and Weaknesses (SW) and Opportunities and Threats (OT)**
366 **scores.** Scores were calculated for NIS experts with three different backgrounds (Terrestrial,
367 Freshwater, Marine) across the six good practices. Horizontal bars represent the SW component,
368 ranging from negative values (weaknesses) to positive values (strengths), whereas vertical bars
369 represent the OT score, ranging from negative values (threats) to positive values (opportunities).
370 Points represent each group in terms of its arithmetic mean for the SW and OT scores, while bars
371 represent the first and third quartile of SW and OT scores.

372



373

374 **Figure 3. Distribution of Strengths and Weaknesses (SW, left) and Opportunities and Threats**
375 **(OT, right) scores.** Between the two groups of experts (blue and orange) identified through cluster
376 analysis, for the six good practices.

377

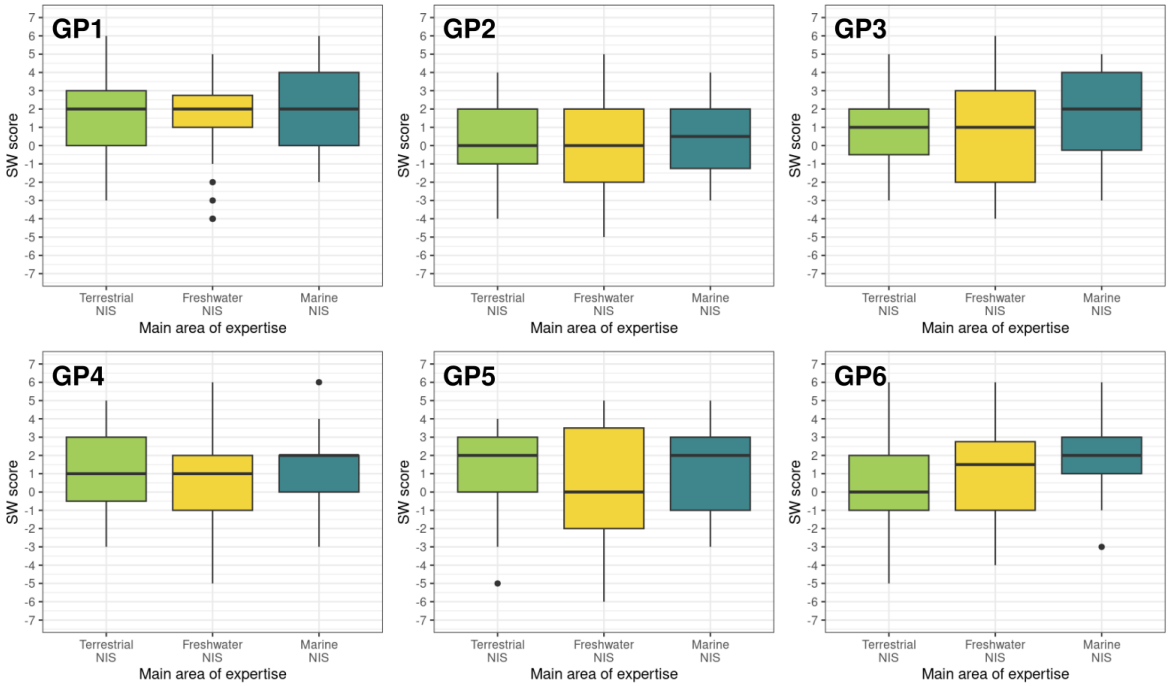


Figure 4. Distribution of Strengths and Weaknesses (SW) scores. Comparison between experts working on terrestrial, freshwater, and marine NIS, for each of the six good practices.

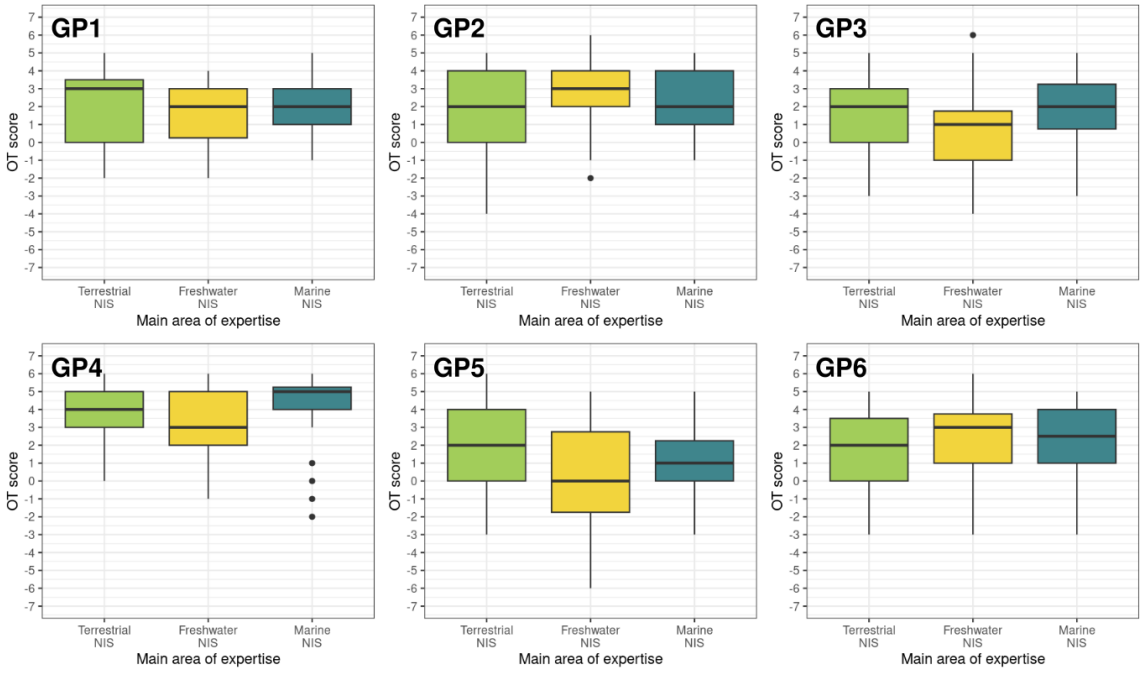


Figure 5. Distribution of Opportunities and Threats (OT) scores. Comparison between experts working on terrestrial, freshwater, and marine NIS, for each of the six good practices.

Discussion

As in other fields of ecological science, NIS research depends heavily on key aspects that form a common foundation, and efforts to identify and establish a shared set of good practices are increasingly promoted by the scientific community (e.g., Groom et al. 2017). Current challenges often stem from existing heterogeneous data collection methods and workflows, as well as from different scientific practices of bioinvasion researchers (Tedersoo et al. 2021). Identifying a focused set of well-defined good practices can help guide targeted interventions to improve workflows and practices.

While not exhaustive, our findings provide an evaluation of six distinct good practices aimed at enhancing NIS research through a collaborative and transparent approach. The SWOT analysis and its quantitative assessment indicate that the TRACKS approach is applicable across terrestrial, marine, and freshwater ecosystems, with strong consensus among bioinvasion experts.

The analysis of Strengths captured existing assets and capabilities, while Weaknesses highlighted critical limitations potentially hindering implementation or requiring improvement. Opportunities identified external trends and potential synergies favoring adoption, whereas Threats recognized possible challenges necessitating mitigation actions.

In the following sections, we provide a comprehensive discussion of each of the six identified good practices, exploring their potential development using Italy as a case study. Finally, we briefly discuss how future research could be employed to evaluate their effectiveness.

GP1 - Tracking NIS in data collections

Good Practice 1 encourages research groups already collecting data on native biological communities to also verify and report NIS occurrence. This approach would imply the need of an accurate identification of NIS at the lowest taxonomic level, contributing to a more comprehensive understanding of sampled communities.

411 According to our panel of bioinvasion experts, GP1 is characterized by significant strengths and
412 opportunities that could facilitate its adoption by the scientific community, with only minor
413 differences across terrestrial, marine, and freshwater ecosystems. This likely reflects the growing
414 interest in NIS ecology and evolution (Campbell et al. 2022; Gozlan et al. 2024), as well as the
415 increasing recognition of NIS monitoring in national and international policy frameworks (Genovesi
416 et al. 2015; Essl et al. 2020; but see also Lenzner et al. 2024).

417 However, the broader loss of direct interactions with nature among ecologists (Soga et al. 2025), and
418 more specifically the shortage of trained taxonomists, remains a critical barrier to the accurate
419 identification of NIS. This shortfall increases the risk of misidentification, particularly for certain
420 taxonomic groups (Golo et al. 2023), and it is shared across countries in all fields of conservation
421 science (Agnarsson and Kuntner 2007; Engel et al. 2021; Löbl et al. 2023). In Italy, this shortage may
422 be further exacerbated by long-standing cuts in public research funding and its disproportionate
423 impact on the scientific sector compared to other European countries (Viesti 2018).

424 Addressing the challenge of a correct NIS identification will require stronger collaboration among
425 research institutions to train a new generation of taxonomists. This could be achieved through
426 dedicated courses, workshops, and summer schools, co-organized with environmental agencies and
427 supported by diverse funding sources. These efforts should also extend to the emerging field of DNA
428 barcoding, which holds great promise for improving species identification (Antil et al. 2023)

429 Another major challenge to the implementation of GP1 is the fragmentation of data and the limited
430 knowledge on NIS distribution. Although recent efforts have been made to produce and share large-
431 scale distribution maps for NIS in Italy and surrounding regions (Azzurro et al. 2022; Magliozzi et
432 al. 2023; Petrosyan et al. 2023), detailed and up-to-date information remains unavailable for most
433 species. Addressing this gap will require stronger collaboration between specialized research groups
434 and bioinvasion experts with robust taxonomic expertise, ideally coordinated through a structured
435 national program.

436

437 *GP2 - Reference Protocols for NIS Data Collection*

438 For NIS data collection, Good Practice 2 recommends following established protocols whenever
439 available. To support this effort, building a national repository of reference protocols for NIS
440 monitoring would be highly valuable. Data collection is a fundamental component of any
441 management strategy for NIS and IAS (Blossey 1999; Mehta et al. 2007) and its standardization is a
442 prerequisite for large-scale data-collection initiatives in ecology and the environmental sciences
443 (Kissling et al. 2018). The use of standardized protocols for data collection paves the way for the
444 creation of synergies between biodiversity researchers and experts in data warehousing and data
445 science (Farley et al. 2018) and will increase the use of NIS data in research, for example in studies
446 about global change or biogeography, due to their inclusion in large and freely accessible global
447 biodiversity datasets, such as GBIF (https://www.gbif.org/).

448 For many animal and plant species covered by the Habitats Directive (92/43/EEC), the Water
449 Framework Directive (WFD), and the Marine Strategy Framework Directive (MSFD), monitoring
450 protocols already exist. In Italy, significant efforts have been made in this direction: collaboration
451 among leading scientific societies and national experts has led to the development of protocols for
452 more than 300 taxa, including 117 plant and 215 animal species (Ercole et al. 2016; Stoch and
453 Genovesi 2016). Although primarily developed for native species, many of these protocols can be
454 adapted for NIS that are taxonomically or ecologically similar to native taxa. However, they do not
455 cover the full spectrum of NIS, and the development of comprehensive monitoring programs,
456 especially for the early detection of NIS, remains an open issue. Based on these premises, our expert
457 discussion led identified three main challenges to the fulfillment of GP2. The first one is related to
458 the need of updating existing protocols, most of which were published over a decade ago (Ercole et
459 al. 2016; Stoch and Genovesi 2016), to include NIS reported in Italy in the last ten years, as well as
460 species with a high probability of future introduction (e.g., Mammals: Bertolino et al. 2020; marine
461 NIS; Tsiamis et al. 2020). Secondly it will be important to standardize reference protocols across
462 taxa, to ensure that NIS records are collected according to consistent quality standards. This is crucial

463 because different taxonomic groups are often monitored by experts with diverse approaches to species
464 identification, and to the collection of data and metadata. Finally, efforts should be made to refine
465 and promote reference protocols to ensure that they are accessible, clear, and usable by a wide range
466 of stakeholders with different levels of expertise and digital literacy. If protocols are ambiguous, user-
467 unfriendly, or unintuitive, their adoption by bioinvasion experts and practitioners will remain limited.

468 Particular attention should also be given to monitoring potential NIS introduction gateways, such as
469 ports, airports, nurseries, garden centers, aquaculture facilities, and bivalve shellfish purification and
470 expedition centers, to promptly detect new introductions (Pace et al. 2022). The Marine Strategy
471 Framework Directive 2008/56/EC has already adopted this approach carrying out monitoring for
472 Descriptor 2 (NIS) in areas with a higher risk of introduction such as ports of international economic
473 importance and mussel farms (ISPRA 2020). Moreover, according to the Regulation 708/2007/EC,
474 following an introduction of NIS or non-routine translocation for aquaculture purposes, a monitoring
475 plan is defined by the competent authority, in order to assess whether the impacts were accurately
476 predicted or if there are additional or different impacts on susceptible habitats. The plan lasts two
477 years or a full generation cycle, whichever is longer. It is carried out by the applicant and can involve
478 other stakeholders such as environmental agencies, fishermen and angling associations. This need
479 calls for training initiatives aimed at diffusing protocols for data collection outside the research
480 community, by involving technicians working in aquaculture facilities, plant nurseries or garden
481 centers.

482

483 *GP3 - Active participation through citizen science and local ecological knowledge*

484 Bioinvasion experts from our panel emphasized that data from Citizen Science (CS) initiatives and
485 Local Ecological Knowledge (LEK) offer significant strengths and opportunities that could support
486 their broader adoption in bioinvasion research, not only in Italy. First, both CS and LEK have proven
487 to be valuable sources of information due to their ability to increase spatial coverage and improve
488 early detection of NIS (Pocock et al. 2024). Several studies have shown that integrating official

records with CS data can help create more accurate representations of the invaded range of NIS (e.g., for plants, Crall et al. 2015; Gervazoni et al. 2023; e.g., for insects, Maistrello et al. 2018), predict the environmental suitability of invaded habitats (Di Febbraro et al. 2023), and support management and eradication efforts (Malek et al. 2018; Leza et al. 2020).

At the European level, González-Moreno et al. (2025) compared official databases with CS platforms in their ability to report first records of NIS and found that CS platforms reported earlier than official sources in 20% of cases, and within the same year in another 30%. Furthermore, CS initiatives and the involvement of local communities can help strengthen relationships between the scientific community and stakeholders (Encarnação et al. 2020; Roy et al. 2023; Pocock et al. 2024, Azzurro et al. 2024c). Nowadays, the use of data from CS is facilitated and promoted by the existence of established practices, active communities, and dedicated platforms (e.g., iNaturalist). Finally, the use of smartphones and specific Apps has significantly enhanced citizen engagement and increased both the volume and spatiotemporal coverage of data on IAS occurrences (Howard et al. 2022). This phenomenon is amplified by the widespread use of social media platforms such as Facebook, and Instagram and TikTok, which have also proven to be valuable tools for collecting records of animal species, including NIS (Chowdhury et al. 2024).

A step toward standardizing these procedures in Italy is represented by the National Guidelines for the Collection, Validation and Transmission of Data on IAS of EU Relevance under EU Regulation 1143/14, which has been enacted in Italy through Legislative Decree No. 12/2022. Similar actions are also emerging at the regional level (Bonacito et al. 2024).

Regarding the weaknesses of CS and LEK data, both approaches are more easily applied to taxa that are easier to observe and identify (Callaghan et al. 2021; Knape et al. 2022). As a result, they tend to under-represent important but less conspicuous NIS, such as small or unattractive species. For instance, Price-Jones et al. (2022) noted a significant rise in CS projects related to NIS in Europe and found that most of these focused on plants and insects, likely due to their accessibility and prevalence in urban areas, while birds and other groups remained underrepresented. Similar imbalances can be

observed in the marine environment, where most actions primarily NIS megafauna, particularly fish species (Azzurro et al. 2019a). Another weakness is the relatively low potential of CS and LEK data to collect quantitative information, such as species abundance.

However, occurrence data from CS and LEK (Price-Jones et al. 2022), can reflect site occupancy whose relationship with species abundance has been long acknowledged (Gaston et al. 2000; Steenweg et al. 2018). Recent studies have additionally demonstrated the potential of well-structured protocols to collect LEK to estimate the relative abundances of NIS, for example on ordered scales, model its spatiotemporal trend and assess consensus among experts (Azzurro et al. 2019b; Azzurro and Cerri 2021). We suggest future research should explore these elicitation methods beyond marine and coastal ecosystems and consider their integration into CS initiatives. Additionally, protocols like IDEA (Hemming et al. 2018) could be adapted to involve citizen scientists and local communities in probabilistic assessments of NIS occurrence.

The main threats characterizing the use of CS and LEK are related to the absence of rigorous validation, particularly when not supported by collaboration with taxonomists, as recommended by GP1 and GP2. Misidentified records may compromise the reliability of scientific conclusions, as well as the performance of algorithms used for image classification and the automated integration of new data (Koch et al. 2023). For this reason, robust validation systems in CS and LEK projects are increasingly adopted (Price-Jones et al. 2022).

GP4 - Collaboration in data sharing according to the FAIR principles

Experts emphasized the importance of sharing NIS data within the scientific community, through the adoption of best practices for Open and FAIR (Findable, Accessible, Interoperable, Reusable) science, recognizing the benefits of these practices and tools in various research contexts. Aligning with FAIR principles (Wilkinson et al. 2016) and Open Science practices (Groom et al. 2017) goes well beyond academic interest, being essential for informing evidence-based decisions by environmental managers and policymakers (Groom et al. 2015; Reyserhove et al. 2020). Good

Practice 4 received the highest Opportunities and Threats (OT) score among the evaluated practices (Figs. 2, 5), demonstrating the considerable opportunities deriving from data sharing and the growing awareness among conservationists and researchers working on bioinvasions about this topic. Data sharing enhances the visibility of results within the scientific community, increases citation rates (Leimu and Koricheva 2005; Tahamtan et al. 2016), and promotes the reuse of data beyond the scope of the original collection and publication (Wallace et al. 2020; Wallace et al. 2021; Bertram et al. 2023). On the contrary, NIS data that are not shared tend to have a short life cycle, which ends once a certain study is published.

A key strength of this good practice lies in the availability of well-established quality standards about the creation of biodiversity datasets (Sequeira et al. 2021), which increasingly serve as a foundation for harmonized data management in conservation science. Scholars and data managers working on NIS are actively engaged in the development and adoption of community-agreed standards (Wallace et al. 2020). These include shared terminologies (Groom et al. 2019a; Soto et al. 2024; Vilizzi et al. 2025), data and metadata schemas (Groom et al. 2017), workflows (Reyserhove et al. 2020; Seebens et al. 2020; Seebens and Kaplan 2022), and long-term storage in canonical repositories (Pagad et al. 2022). Among these, Darwin Core stands out as a widely adopted standard for publishing and integrating biodiversity information (Wieczorek et al. 2012). The adoption of such standards in European Commission-funded projects (Open Research Europe 2022) underscores their pivotal role in promoting collaborative research, data interoperability, and long-term stewardship.

The most significant potential weaknesses of data sharing include researchers' reluctance to share data, due to competition between groups. In the case of NIS, it is crucial to emphasize any newly recorded species or newly colonized area should be reported immediately upon detection, without waiting for the formal publication process, particularly for species of Union concern. Delayed reporting not only reduces the likelihood of a successful eradication but also significantly increases its cost (Genovesi et al. 2024) and can result in infringement proceedings at the EU level. Researchers

must recognize the urgency of sharing NIS data promptly, as part of their contribution to biodiversity conservation (Groom et al. 2015).

GP5 - Knowledge Hub as centralized data repository for NIS Data

As revealed by the results of Survey I, a substantial volume of NIS data is generated at the national level but remains fragmented across various databases and repositories. This issue is common across multiple disciplines, including ecology, forestry, microbiology, humanities, and social sciences (Hampton et al. 2013; Tedersoo et al. 2021). In light of these findings, the expert panel proposed the development of an open-access reference repository to consolidate this information, a measure considered highly beneficial. The proposal received high scores in both the Strengths and Weaknesses (SW) and Opportunities and Threats (OT) assessments, particularly among one of the two identified clusters of bioinvasion experts (Fig. 3). This outcome underscores the widespread need for a centralized system to store, preserve, access and disseminate up-to-date NIS information, a need already expressed or attempted by other authors (e.g., Haubrock et al. 2023; Onley et al. 2025).

Despite existing challenges, the development of a centralized, open-access repository presents numerous strengths and opportunities, making it both feasible and attractive to the bioinvasion research community. Its implementation could be anchored to international platforms such as the Global Invasive Species Database (https://www.iucngisd.org/gisd/), or built upon existing national databases. In the case of Italy, this can be the national database on invasive alien species developed by ISPRA (https://www.specieinvasive.isprambiente.it/ricerca-db-italia), or the Register of Alien Species in Aquaculture (https://www.registro-asa.it/), coordinated by ISPRA in accordance with EC Regulation No. 708/2007 under the Ministry of Agriculture, Food Sovereignty and Forests (Masaf). Regardless of the country, the implementation of a national database to be used as a reference repository requires close collaboration among all research institutions working on NIS and bioinvasions with the support of national digital research infrastructures (Colangelo et al. 2017; Di Muri et al. 2023).

An alternative, bottom-up approach, is to aggregate georeferenced records of NIS occurrences, like in the case of the geo-platform ORMEF (www.ormef.eu, see Azzurro et al. 2024c). The aggregation of georeferenced records from different research groups would be particularly advantageous to centralize NIS data in countries of the Global South, where the digitalization of biodiversity data is still limited (García-Roselló et al. 2023). Nevertheless, reference repositories should be designed to ensure their interoperability with major international databases such as GBIF (https://www.gbif.org/), an aspect that would minimize conflicts of interest among research groups by providing a neutral, third-party-managed platform.

The weaknesses and threats associated with Good Practice 5 require to be carefully addressed. Meeting international data quality standards (Wieczorek et al. 2012; Chapman et al. 2020) and ensuring the long-term sustainability of a central database in terms of funding and maintenance remain major challenges. Establishing a pipeline for data centralization and validation will require the formation and continuous support of a network of expert taxonomists, who must also be trained to use the system effectively. Maintaining this network is essential to prevent the inclusion of erroneous records and will depend on stable, long-term funding.

Furthermore, it is crucial that the national repository be designed to support the rapid communication of new NIS records, encouraging researchers to report data promptly rather than waiting for formal publication (Genovesi et al. 2024). Timely reporting is especially critical for Invasive Alien Species (IAS) of Union Concern under EU Regulation 1143/2014, which mandates eradication or management measures upon detection. The scientific community must ensure that all new records of IAS of Union Concern are promptly reported to the relevant authorities—namely, the Ministry of the Environment, Masaf, ISPRA, and Regional Administrations—to enable rapid response and effective containment.

GP6 - Strategic communication to raise public awareness and support public engagement

Communication activities and awareness campaigns are commonly linked to NIS research (Haley et al. 2023), serving as vital tools to prevent new introductions (Garcia-Llorente et al. 2008), mitigate the negative effects of invasions (Roy et al. 2024), and address potential conflicts that may arise (Novoa et al. 2017; Biasetti et al. 2021). The media are highly receptive towards biological invasions, a topic frequently covered by newspapers and television news, particularly for certain taxonomic groups(e.g., terrestrial vertebrates, Lioy et al. 2019), although sometimes with some distorsions (Woodworth et al. 2023; Wong 2024). Therefore, our panel of experts highly ranked the idea of promoting communication on NIS.

To maximize effectiveness, communication messages should be positive yet realistic, aiming at informing rather than at persuading them (Blastland et al. 2020), emphasizing the active role citizens can play.

Among the strengths of this good practice, experts highlighted that existing voluntary codes of conduct, targeted at diverse stakeholders and activities potentially linked to NIS introductions (e.g., angling, boating, horticulture, pets, aquariology), are particularly valuable tools to facilitate proactive citizen engagement. Today, several EU-funded projects (e.g., https://www.csmon-life.eu/; https://lifeasap.eu/index.php/it/; https://www.ceh.ac.uk/our-science/projects/alien-csi-about-action) successfully employ the 'bioblitz' method participatory activities involving both citizens and researchers in identifying species within a defined area and timeframe, typically 24 hours (Schofield 2020). Such initiatives effectively raise public awareness about biological invasions and have successfully led to the detection of new NIS occurrences (Meeus et al. 2023). The main weaknesses of this proposal are related to the fact that invasion biologists may lack communication skills or interest in public outreach. Therefore, collaboration with communication professionals, many of whom already work within scientific institutions across Italy, is essential. Communication experts can strategically enhance outreach campaigns in two critical ways: first, by raising awareness about the importance of reporting and monitoring smaller, less charismatic NIS, which typically receive limited public attention and are under-reported; second, by employing communication skills to

643 prevent overly alarmist messaging that can discourage public engagement and potentially result in
644 unintended negative consequences.
645 Risks associated with this activity were also discussed. If messages are not effectively delivered or
646 reach the wrong audience, they can become counterproductive, wasting resources or even leading to
647 behavioral changes that exacerbate the problem or elicit backlash (revised by Haley et al. 2023).
648 Expert-guided communication strategies can also help prevent the politicization of NIS and related
649 monitoring efforts, which are sometimes deliberately framed misleadingly or instrumentally
650 (Ernwein and Fall 2015; Chinn et al. 2024; Reeb and Heberling 2024) and the decision to perform a
651 public awareness campaign should be made after a process of thoughtful consideration.
652

653 **Conclusions**

654 In this study, we identified six good practices that could improve both the processes and outcomes of
655 NIS research by enhancing how researchers collect, manage, and share data, as well as how they
656 communicate relevant information to the public. These practices emerged and were quantitatively
657 evaluated from the contributions of a large and diverse group of experts in bioinvasions, working
658 across terrestrial, freshwater, and marine ecosystems. Given the highly diversified contexts in which
659 these experts operate, the wide variety of methodological approaches and range of taxa and habitats
660 investigated, these good practices are intended as general guidelines, which share principles that can
661 be broadly applied across various settings. Importantly, these proposals are not intended to overlap
662 with or replace existing taxonomic-specific or ecosystem-specific guidelines focused on monitoring
663 standardization, such as those developed for IAS of Union concern under EU Regulation 1143/2014.
664 Instead, they are meant to support all research groups collecting NIS data, including those without a
665 dedicated focus on NIS, which may nonetheless contribute significantly to NIS research by providing
666 relevant information on species' occurrence, abundance and distribution. We hope that the outcomes
667 of this synthesis will foster collaboration among the variety of stakeholders involved in NIS research
668 and monitoring, including scientific institutions, citizen scientists, NGOs, and environmental

669 agencies. It may also foster methodological harmonization and integration among research groups
670 with diverse expertise, including taxonomists, fisheries and aquaculture biologists, veterinarians, and
671 agricultural and public health entomologists, all of whom play crucial roles in NIS research. Such
672 integration would help bridge the current cultural and operational divide between terrestrial and
673 aquatic systems, reduce fragmentation among researchers, and build new capacities to effectively
674 investigate NIS and address rapidly changing ecosystems in Italy and beyond.

675

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Supplementary information and Appendix

The Supplementary Materials, which include Appendixes (Appendix 1, Appendix2, Appendix3), supplementary Figures (Fig. S1, Fig.S2), as well as reproducible data and software code, are available at: https://osf.io/sf3ag/