

Importance of Geospatial Data for Monitoring and Managing Invasive Species for Sustainable Development: A Semantic Review

Marwa Waseem A. Halmy^{a*}

^aDepartment of Environmental Sciences, Faculty of Science, Alexandria University, Alexandria, Egypt

ORCID ID: <https://orcid.org/0000-0002-4183-973X>

Received: 09 August 2024; Accepted: 20 August 2024

Invasive species pose significant threats to ecosystems, economies, and human well-being worldwide. Effective monitoring and management of invasive species are essential for mitigating their impacts and promoting sustainable development. An analysis of 617 publications on invasive species using geospatial data and technologies revealed the critical role of geospatial analysis in understanding and managing invasive species. Based on the Latent Dirichlet Allocation analysis of the publications on invasive species six main categories of focus research areas were revealed, namely 1) Monitoring, Control and Invasion management; 2) Mapping, predictive modeling, and Climate Change Impact; 3) Risk assessment, and early detection; 4) Citizen Science and Community Engagement; 5) Impact Assessment and Ecological Interactions, and 6) Health and Disease Implications. The geographic concentration of research in the United States, China, Western Europe, and Australia underscores the need for broader global engagement. Predominant methods include remote sensing, aerial imagery, GIS, and spatial analysis, with a notable inclusion of citizen science indicating broader research participation. The focus on high-priority invasive species such as the Water Hyacinth, Zebra Mussel, and Emerald Ash Borer reveals a need for wider attention to other invasive species in scientific literature. The investigated research aligns with achieving several Sustainable Development Goals (SDGs), particularly SDG 15 (Life on Land) and SDG 13 (Climate Action), emphasizing the importance of terrestrial and climate-related studies. Geospatial data utilization offers substantial benefits, including enhanced detection, efficient resource allocation, and informed decision-making. Despite challenges, ongoing advancements in geospatial technologies and analytical methods promise to further improve capabilities in this field.

Keywords: Spatial Analysis, Satellite Images, SDGs, Machine Learning, Data Democratization, Alien Species

1. Introduction

Invasive alien species (IAS) pose significant threats to global biodiversity, ecosystem stability, human well-being and economies worldwide^{1,2}. The rapid globalization and increased movement of goods and people have accelerated the spread of invasive species, making their management a critical priority for conservation and public health efforts worldwide^{3, 4}. The Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) reported that over 37,000 alien species were introduced via various human activities to different territories and biomes worldwide. Around 3500 species play a substantial role in 60% of the global species extinctions⁵. These non-native species, when introduced to new environments, can outcompete, prey upon, or bring diseases to native species, leading to severe ecological and economic consequences^{6, 7, 8}.

The impact of invasive species extends beyond ecological degradation⁹. Economically, they impose substantial costs on agriculture, forestry, fisheries, and other sectors by reducing productivity and increasing control and mitigation expenses¹⁰. According to IPBES⁵ (2023), the annual global economic cost of IAS tops \$423 billion. Additionally, invasive species can affect human health by acting as vectors for diseases, exacerbating the burden on healthcare systems^{11, 12}. Addressing these multifaceted challenges requires innovative and effective strategies for monitoring and managing invasive species.

Thus, the effective monitoring and management of these species are crucial to mitigating their impacts^{3, 13, 14}. Geospatial approaches and tools, which encompass collecting and processing information about geographic locations and attributes of features of interest, has emerged as a powerful tool in the fight against invasive species¹⁵⁻¹⁷. With advancements in remote sensing, Geographic Information Systems (GIS), and spatial analysis techniques, researchers and

*Corresponding author
E-mail: marwa.w.halmy@alexu.edu.eg

practitioners can now collect, analyze, and visualize spatial data with unprecedented precision and detail¹⁸. These technologies enable the detection of invasive species at early stages, facilitate the mapping of their distribution, and support the development of targeted management interventions¹⁹⁻²³.

The integration of geospatial data in invasive species management offers several advantages²². Remote sensing technologies, such as satellite imagery and drones, provide extensive spatial coverage and high-resolution data, essential for large-scale monitoring efforts^{19-20, 24-26}. GIS allows for the integration of various data sources, enabling comprehensive spatial analysis and visualization²². Together, these tools support early detection and rapid response (EDRR) initiatives, long-term monitoring, and the assessment of management effectiveness.

Moreover, utilizing geospatial data for invasive species management contributes to the broader goals of sustainable development²⁷⁻²⁸. By protecting native biodiversity and ecosystem services, these efforts help maintain ecological balance and resilience. Economically, effective management reduces the financial burden on affected industries and enhances the sustainability of natural resources. In terms of public health, controlling invasive species that act as disease vectors mitigates health risks, contributing to the overall well-being of communities.

The following account draws inspiration from the #semanticClimate project (<https://semanticclimate.github.io/p/en/about/>) and insights gained from the Climate Knowledge Hunt Hackathon. These initiatives focus on developing tools to unlock climate change knowledge, democratization of data, and enable text and data mining on IPCC reports. These efforts highlight the critical role of integrating semantic web technologies to enhance text mining and data analysis capabilities. By synthesizing the existing literature, this review aims to explore the current state of knowledge on the use of geospatial data and techniques for monitoring and managing invasive species. It also, highlights diverse applications of remote sensing and GIS in detecting and controlling invasive species, discusses the challenges and limitations associated with these technologies, and examines the benefits, and future directions for the utilization of geospatial tools and techniques in monitoring and managing invasive species and their contribution to the achievement of the sustainable development goals. Insights into the

effectiveness of geospatial tools in addressing the invasive species crisis are provided along with recommendations for future research and policy development.

2. Methodology and approach used

The study sought to conduct a structured approach that ensures a comprehensive and unbiased review of the literature on the use of geospatial data for monitoring and managing invasive species. This section provides details on the search strategy and methodology used.

To conduct a review on the use of geospatial data for monitoring and managing invasive species the study focused on the Web of Science databases due to its comprehensive coverage of scientific literature and relevance to the fields of geospatial data and ecological studies. A comprehensive search strategy was developed using a combination of keywords and Boolean operators to capture relevant literature. The search terms were designed to encompass various aspects of geospatial data and invasive species management. The following keywords and phrases were used: geospatial data, geographic information systems (GIS), remote sensing, invasive species, alien species, biological invasion, monitoring, management, control, and ecology. The search queries were tailored to the specific syntax requirements of the Web of Science database as follows:

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(TS=("Geospatial Data" OR "Geographic Information Systems" OR "GIS" OR "Remote Sensing") AND TS=("Invasive Species" OR "Alien Species" OR "Biological Invasion") AND TS=("Monitoring" OR "Management" OR "Control" OR "Ecology")) NOT (DT= ("RETRACTED PUBLICATION" OR "EDITORIAL MATERIAL" OR "EDITORIAL MATERIAL" OR "RETRACTED PUBLICATION"))
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The outcome of the search on the Web of Science are included in the Supplementary Material, in a repository on Github (<https://github.com/marwawaseem/geospatial-data-for-monitoring-and-managing-invasive-species-for-sustainable-development>), and can be accessed through the following link:

<https://www.webofscience.com/wos/woscc/summary/bcf0e61f-803e-4921-8acf-7a3caa816259-f3c3a3e0/relevance/1>

To refine the search results, specific inclusion and exclusion criteria were followed. The inclusion

criteria involved considering peer-reviewed articles, reviews, and conference papers publications. Non-peer-reviewed articles, editorials, opinion pieces and retracted papers were excluded. Only studies focusing on the use of geospatial data for monitoring and managing invasive species and studies involving empirical data, case studies, or methodological developments published in English were considered.

The initial search results were exported into EndNote reference management software to organize and also as excel file to facilitate the screening process. The initial set of articles was screened by title and abstract to exclude clearly irrelevant studies. Key information from the selected articles was extracted, including study objectives, methods, geospatial technologies used, types of invasive species monitored, and main findings.

The extracted data were systematically analyzed and synthesized to identify common themes, methodological approaches, and gaps in the literature. The findings were organized into categories based on the use of geospatial data for different aspects of invasive species monitoring and management. For categorization of the main research topics addressed by the analyzed publications The Latent Dirichlet Allocation (LDA) approach was employed. The LDA is a generative statistical modelling approach used in natural language processing and machine learning to detect topics that occur in a collection of documents. The LDA topic modeling assumes each document is a mixture of a small number of topics, and each topic is a mixture of words²⁹. The goal of LDA is to identify the hidden topic structure within the text corpus, which can be useful for various applications like information retrieval, text classification, and summarization. The LDA approach was used for uncovering hidden topics within the titles of the publications that addressed the use of geospatial data and techniques in studying invasive between 2000 and 2024. For the bibliometric analysis, several tools were used to ensure a comprehensive examination of the literature. The primary tools and packages used included the ‘topicmodels’ version 0.2-16³⁰⁻³¹, ‘tm’ version 0.7-13³²⁻³³, ‘tidytext’ version³⁴, ‘tidyverse’ version 1.3.0³⁵, ‘wordcloud’ version 2.6³⁶, ‘igraph’ version 2.0.3³⁷⁻³⁸ and ‘ggplot2’ version 3.3.3³⁹ R packages were used for conducting the LDA analysis, text mining and bibliometric analysis, and to create word clouds, which can visually represent the frequency of terms in bibliometric data. All analysis was conducted within the framework of R version 4.3.3⁴⁰.

3. Geospatial approaches in invasive species research: Trends, methodologies, and focus areas

3.1. Trends and impact of geospatial data in invasive species research

A total of 617 publications on invasive species using geospatial data and techniques were included in this review. The analysis revealed a gradual increase in the number of publications utilizing geospatial data and techniques to study invasive species from 2000 to around 2010 (Figure 1). This suggests that the use of geospatial data and techniques in studying invasive species was gradually gaining attention and becoming more prevalent by the second millennium. From 2010 to 2015, the growth rate of publications increased more steadily. This indicates a growing recognition of the importance and utility of geospatial techniques in ecological and environmental research, particularly concerning invasive species. There is a notable and sharp increase in publications from 2015 onwards, peaking around 2020. This surge could be attributed to several factors, including advancements in geospatial technologies, increased availability of spatial data, particularly satellite data. Satellite data became freely available starting in the early 21st centuries, driven by policy changes and technological advancements. The Landsat Program was the pioneer in providing free access to satellite imagery. In 2008, the United States Geological Survey (USGS) made all Landsat data freely available to the public through its online repositories, GloVis (<https://glovis.usgs.gov/>) and EarthExplorer (<https://earthexplorer.usgs.gov/>). This policy changes considerably increased the accessibility of high-resolution, long-term Earth observation data.

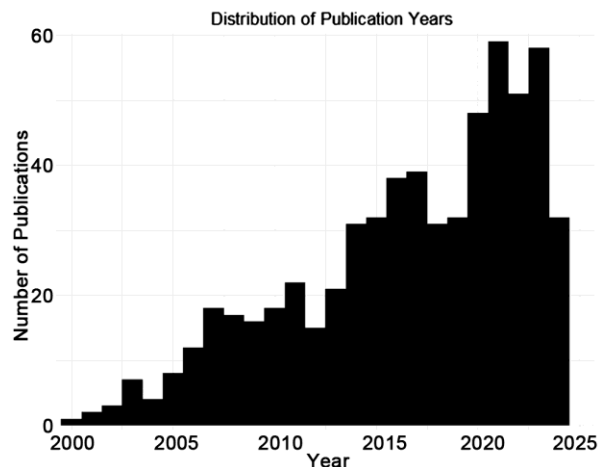


Figure 1 — Temporal trend of publications on invasive species using geospatial data and techniques between 2000 and 2024.

Following in the suit of Landsat program, the Sentinel Program that was launched by the European Space Agency (ESA) under the Copernicus initiative, provided free and open access to the satellite data. The program launched Sentinel-1 satellite in 2014, which offers radar imagery, followed by Sentinel-2 in 2015, which provides high-resolution optical imagery.

Other Sentinel satellites were then launched, and their data were made available for users free of charge. The Sentinel Program data can be accessed through the Copernicus Open Access Hub and the

Sentinel Data Hub (Table 1). More data sources and portals that offer access to a vast repository of satellite imagery and geospatial datasets from multiple sources were then established and made accessible to the public free of charge particularly for education and research purposes. The availability of these datasets facilitated studying global dynamics and processes on the land, in the oceans, and in the atmosphere.

The free availability of satellite data has revolutionized numerous fields, including environmental monitoring, agriculture, urban planning, disaster

Table 1 — Main Sources of open source and free satellite imagery and geospatial data

| Source | Data provided | Data accessibility tool | Year tool available |
|--|---|---|---------------------|
| United States Geological Survey (USGS) | Publicly available data of Landsat Data collection (1-9), DEMs, land cover, digital maps, UAS imagery, aerial photos, radar, AVHRR, Sentinel satellite data, handful commercial satellite images, e.g. IKONOS, SPOT & OrbView3 | Earth Explorer (https://earthexplorer.usgs.gov/) | 2008 |
| | Publicly available data Landsat Data collection (1-9) | Global Visualization Viewer (GloVis) https://glovis.usgs.gov/ | 2001 |
| European Space Agency (ESA) | Sentinel Data (Radar, Optical, Atmospheric). Offers free and open access to Sentinel-1, Sentinel-2, Sentinel-3, and Sentinel-5P data, and other ESA operated satellites | Copernicus Open Access Hub (https://scihub.copernicus.eu/) | 2014 |
| | Another portal for accessing Sentinel data | Sentinel Data Hub (https://www.sentinel-hub.com/) | 2015 |
| The National Aeronautics and Space Administration (NASA) | Provides access to MODIS data from NASA's Terra and Aqua satellites which have been freely available since their launches, VIIRS data, other NASA various NASA missions | LAADS DAAC (Level-1 and Atmosphere Archive & Distribution System Distributed Active Archive Center) portal | 2000 |
| | MODIS Data (provide optical and thermal data), The Visible Infrared Imaging Radiometer Suite (VIIRS) satellite (provided free visible and Infrared data since its launch v/ in 2011), and other data from various NASA missions and satellites. | NASA Earthdata (https://www.earthdata.nasa.gov) | 2011 |
| | Global coverage, full resolution near real time satellite imagery | NASA Worldview application (https://worldview.earthdata.nasa.gov/) | 2012 |
| Google Earth Engine | A cloud-based platform providing access to a vast repository of satellite imagery and geospatial datasets from multiple sources, including Landsat, Sentinel, MODIS, and more. | Google Earth Engine Data Catalog (https://developers.google.com/earth-engine/datasets) | 2013 |
| OpenTopography (NSF-EAR-funded data facility) | High-resolution topographic data from LiDAR and other sources | OpenTopography data portal (https://portal.opentopography.org/datasets) | 2009 |
| Japan Aerospace Exploration Agency (JAXA) | Data from Japanese Earth observation missions, including ALOS, MOS-1, MOS-1b, JERS-1, ADEOS, Aqua, MODIS | JAXA G-Portal (https://gportal.jaxa.jp/gpr/information/tool) | 2015 |
| The National Oceanic and Atmospheric Administration (NOAA) | Data from NOAA satellites, including weather and environmental data. Various Satellite Imagery and Geospatial Datasets. | NOAA CLASS (Comprehensive Large Array-data Stewardship System) https://www.aev.class.noaa.gov/saa/products/ | 2003 |

management, and climate research. It has democratized access to critical information, enabling scientists, researchers, policymakers, and the public to monitor and understand Earth's systems more effectively⁴¹⁻⁴².

This trend may reflect ongoing research interest and continued development of methodologies in this field. The slight fluctuations could be due to various factors such as changes in funding, publication cycles, or shifting research priorities. Overall, there is an upward trend in the number of publications that leverage geospatial data and techniques to study invasive species over the past two decades. This trend highlights the increasing reliance on and recognition of geospatial tools in environmental research and management, which possibly driven by technological advancements in the field of remote sensing coupled with the growing awareness of the ecological impacts of invasive species on ecosystems.

A diverse range of journals totaling 253 covered the use of geospatial data and techniques in studying invasive species. The journals listed cover a broad spectrum of disciplines, including ecological applications emphasizing the application of ecological theories and methods; the management of rangelands, which are often affected by invasive species, the role of environmental management practices in controlling invasive species and the importance of photogrammetry, remote sensing techniques and earth observation data studies on the impact of invasive species on forest ecosystems. The top 10 journals that published studies on invasive species using geospatial data and techniques from 2000 to 2024 (Figure 2),

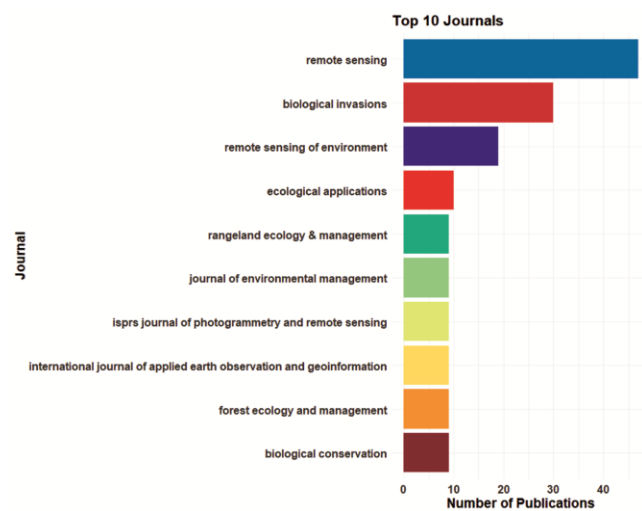


Figure 2 — Top 10 journals by number of publications addressing the use of geospatial data and techniques in studying invasive between 2000 and 2024.

was led by Remote Sensing which published the highest number of publications, indicating a strong emphasis on remote sensing techniques in the study of invasive species. Biological Invasions and Remote Sensing of Environment journals were also significant contributors, reflecting the integration of geospatial data in the field of biological invasions and environmental monitoring.

The word cloud (Figure 3) visualizes the keywords from publications that addressed the use of geospatial data and techniques in studying invasive species between 2000 and 2024. It suggests that the majority of the research focuses on invasive species and the use of remote sensing technologies, and that Geographic Information Systems and spatial analysis are significant components of the research. The main geospatial techniques employed in the investigated studies included "classification," "modeling," "lidar," "hyperspectral," and "spectroscopy" highlighting the use of advanced remote sensing technologies for data collection and analysis. The main research areas and applications focused on habitat assessment, landscape analysis, and conservation efforts, in addition to the practical applications of these studies in managing and mitigating the impacts of invasive species, the environmental and ecological aspects of the research with particular focus on the impact on the forest ecosystems in the context of invasive species studies.

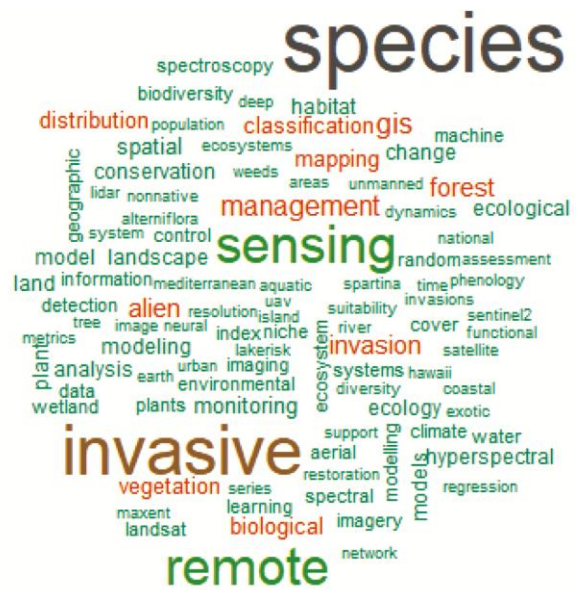


Figure 3 — Word Cloud of the keywords visualizing common research themes of the publications that addressed the use of geospatial data and techniques in studying invasive species between 2000 and 2024.

The word could reveal the use of emerging technologies and methods including "machine learning" and "artificial neural networks" indicating that emerging technologies such as machine learning and neural networks are becoming integral in analyzing geospatial data related to invasive species. Additionally, among the new technologies used for data collection in the investigated studies were the "UUV" (unmanned underwater vehicles), and "UAV" (Unmanned Aerial Vehicle) particularly the drones.

The use of geospatial data and methods for studying invasive species is widespread globally, as evidenced by the broad geographical distribution of the studies examined. The investigated studies covered 89 nations indicating a strong emphasis on studying invasive species utilizing geospatial techniques worldwide. The top geographical locations represented by publications on invasive species using geospatial data and techniques between 2000 and 2024 were led by the USA (Figure 4), with significant number of publications exceeding 200. The

geographical distribution of publications indicates that research on invasive species using geospatial data is a global effort, with particularly strong contributions from the USA, China, Italy, and Australia. This trend reflects the global nature of invasive species issues and the widespread application of geospatial techniques in addressing these challenges. The varying number of publications across different countries highlights both the global interest and the specific regional focuses in studying and managing invasive species. However, the geographic distribution of publications on invasive species revealed that the high publication regions included North America and Western Europe (Figure 5), while regions with sparse or no publications included central Asia, the Middle East and Sub-Saharan Africa. Except for China, India and South Africa, most of the publications were geographically from the global north, which indicate lesser research activity on invasive using geospatial approaches in the global south.

The investigated publication covered a wide range of species and addressed the most obnoxious invasive species globally. The most frequently discussed invasive species in the literature were "Water Hyacinth" and "Zebra Mussel" being the most frequently mentioned species (Figure 6), followed by "Asian Carp" and "Emerald Ash Borer". The focus of the publications helps identify which invasive species are of the highest concern in the current body of research, with considerable ratio of the studies covering some of the world's 100 worst invasive alien species, according to the Global Invasive Species Database. In addition to Water Hyacinth, Zebra Mussel and Emerald Ash Borer,

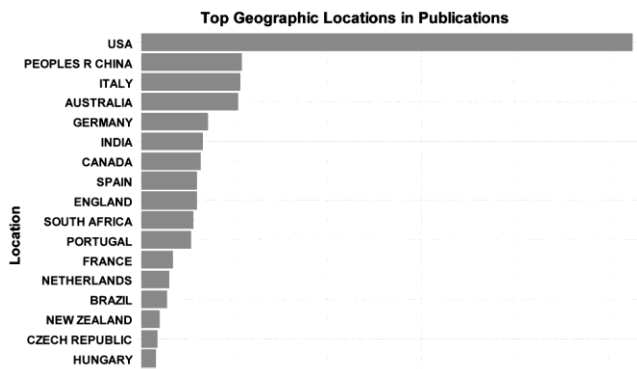


Figure 4 — The top geographical locations covered by the publications on invasive species using geospatial data and techniques between 2000 and 2024.

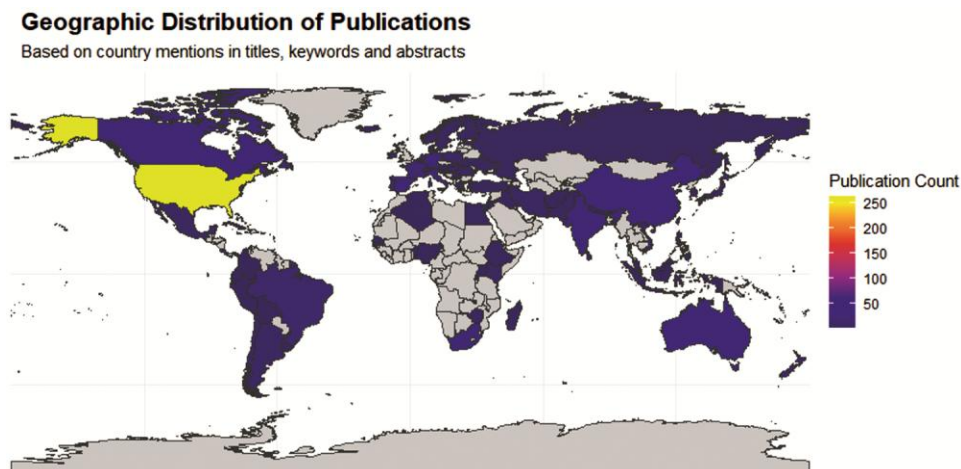


Figure 5 — Geographic distribution of publications on invasive species using geospatial data and techniques between 2000 and 2024.

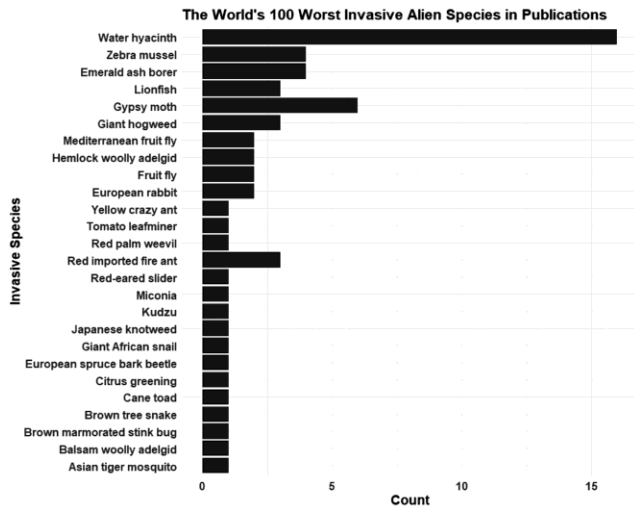


Figure 6 — Representation of the World's 100 Worst Invasive Alien Species list of the Global Invasive Species Database in the investigated publications.

which were the most frequently mentioned invasive species in the publications compared to other species; other species studied Lionfish, Gypsy Moth, Giant Hogweed, Mediterranean Fruit Fly and Hemlock Woolly Adelgid.

The analysis highlighted that certain invasive species, particularly the Water Hyacinth, Zebra Mussel, and Emerald Ash Borer, are the most frequently covered in scientific publications. These species are recognized as significant threats and have thus attracted considerable research attention. Other species like the Lionfish, Gypsy Moth, and Giant Hogweed also have substantial representation, reflecting their impact on ecosystems. The outcomes indicate a focused research effort on these high-priority invasive species using geospatial approaches, while a wide range of other invasive species received relatively less attention in the literature.

3.2. Geospatial tools and techniques in invasive species research

The analyzed corpus of publications encompasses diverse methods and techniques including remote sensing, unmanned aerial vehicles (UAVs), GIS, spatial analysis, predictive spatial modeling, citizen science applications and platforms, machine learning, artificial intelligence approaches and ecological assessments.

The main categories of geospatial tools, approaches, and techniques used in publications on invasive species, were the use of remotely sensed data whether multispectral⁴³⁻⁴⁵ or hyperspectral satellite images⁴⁶⁻⁴⁷, aerial imagery⁴⁸, LiDAR data^{46, 49-52}, and

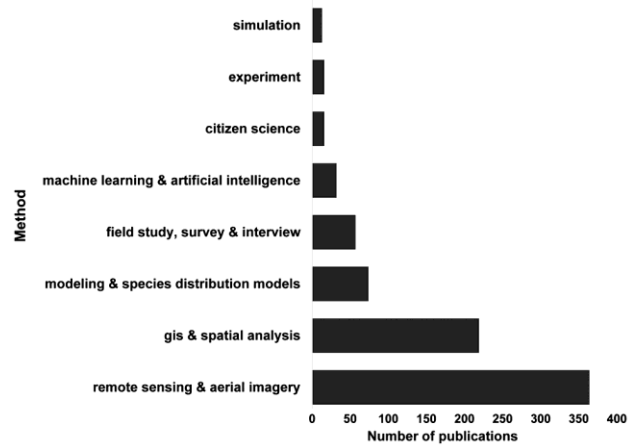


Figure 7 — The main categories of tools, approaches and techniques used in the investigated publications on invasive species using geospatial data and techniques between 2000 and 2024.

data captured by unmanned aerial vehicles such as drones⁵³⁻⁵⁴. Remote sensing and aerial imagery were used in the highest number of publications, with close to 350 (~57%) publications (Figure 7), which indicates the significant reliance on remote sensing and aerial imagery for studying invasive species. Remote sensing data from satellites can be used for large-scale ecological assessments, such as mapping forest damage from invasive insects and pathogens across different ecosystems⁵¹, which can be difficult to achieve using conventional methods. The use of UAV technologies has become prominent in monitoring terrestrial⁵⁴⁻⁶⁰ and aquatic⁶¹⁻⁶² invasive species particularly over the last five years across different ecosystems. Systematic reviews highlight their effectiveness in agricultural and natural landscapes for detecting invasive species whether as main source of geospatial data or integrated with other sources of remotely sensed data⁵⁶⁻⁵⁷.

Geographic Information Systems (GIS) and spatial analysis were the second most commonly used approaches in the investigated studies, with over 200 publications representing nearly 33% of studies. GIS and spatial analysis are crucial for mapping and analyzing the spatial distribution of invasive species. GIS platforms facilitate the integration and visualization of various data sources, creating detailed maps that highlight the distribution and spread of invasive species. Studies have used GIS to map the spread of harmful invasive species like the emerald ash borer⁶³⁻⁶⁴, Asian hornet⁶⁵, the Asian Longhorned beetle⁶⁶; and prioritizing areas for noxious invasive weeds control efforts such as Cogongrass⁶⁷⁻⁶⁸ and

Weeping Lovegrass⁶⁹. Tools like GIS and other spatial analysis methods are used to create risk maps for species like *Aedes koreicus*⁷⁰, *Aedes albopictus*⁷¹, and the Argentine ant, *Linepithema humile*⁷²; in addition to identifying areas susceptible to invasions under different environmental conditions and under different climate change scenarios⁷³⁻⁷⁴.

Distribution Models were featured in around 100 publications, highlighting the importance of predictive modeling in understanding and managing invasive species distributions⁷⁵⁻⁷⁷. Studies frequently used species distribution models (SDMs) to map the potential habitats of invasive species⁷⁸, such as ticks in Iran⁷⁹. Several studies used spatial predictive modelling techniques such as the Maxent model and other modelling techniques to project the change in the distribution of invasive species under current and future climate scenarios. Examples include predictions for the predator of honeybees⁸⁰ and the South American tomato pinworm⁷⁶; *Lantana camara*^{73, 81} and Cheatgrass⁸².

Machine learning (ML) tools and artificial intelligence (AI) applications including neural networks and artificial intelligence tools, are increasingly being employed to enhance geospatial data analysis and spatial modeling predictive accuracy⁸³. These emerging techniques and their supporting technologies were used in approximately 7.0% of the investigated publications, reflecting their growing but still limited application in the field. These approaches such as the neural networks enhance the capability of developing scalable prediction models and allow researchers to manage large geospatial datasets effectively⁸⁴. The ML and AI approaches were integrated in applications for mapping and predicting invasive species distribution^{56, 85} in addition to developing AI-based software to automatically identify invasive species and vectors of infectious disease particularly mosquitoes⁸⁶.

Citizen science tools and community engagement platforms, which allow public participation and engagement in geospatial data collection was utilized in about 5.0% publications, showing a trend towards inclusive research methods and development of next-generation surveillance frameworks for early detection and control of invasive species. Studies highlight the role of community-based monitoring and involvement in collection of invasive species occurrence data, in supporting timely detection and management⁸⁷⁻⁹⁰. The Mosquito Habitat Mapper toolkit of the Globe Observer Program, Mosquito

Alert, iNaturalist, GLOBE Land Cover app and other international citizen science platforms and apps are becoming integral in engaging non-experts in data collection, enhancing surveillance of invasive species like mosquitoes⁸⁶.

Despite the growing use of remotely sensed data particularly satellite images, still field studies, surveys, and interviews are conducted for studying invasive species studies (~13% of the analyzed publications). Field data are integrated with remotely sensed data and citizen science data indicating the value of ground-truthing and primary data collection in invasive species research⁸⁹⁻⁹¹.

Experimental methods were integrated into around 3.2% of the publications⁹², suggesting that controlled studies are less common but still relevant. Simulations were the least frequently used approach, with about 2.4% of the publications⁹³⁻⁹⁴, indicating that simulation is still not as commonly applied in this research area.

Overall, the analysis revealed that remotely sensed data, aerial imagery, and UAVs data along with GIS and spatial analysis, are the predominant approaches used in publications on invasive species using geospatial data and techniques. This trend underscores the importance of these technologies in mapping, monitoring, and managing invasive species. While traditional methods like field studies and emerging technologies like machine learning are also significant, their use is relatively less frequent. The inclusion of citizen science indicates a move towards broader participation in research, although it is not yet widespread. Overall, the chart highlights the diverse methodological approaches employed in the study of invasive species over the past two decades.

3.3. Research focus areas in geospatial studies of invasive species

The list of studies investigated showcases a variety of applications of geospatial analysis in understanding and managing invasive species across different ecosystems. Based on the LDA the 617 publications on invasive species using geospatial data and techniques were categorized into main six categories (Figure 8). The main research focus included:

(1) *Monitoring, Control and Invasion management*; this category was the dominant research category, which was addressed by has the highest number of publications, representing nearly more than 48% of the studies. It indicates a significant focus on tracking, managing, and controlling invasive species using geospatial data and techniques. The category includes

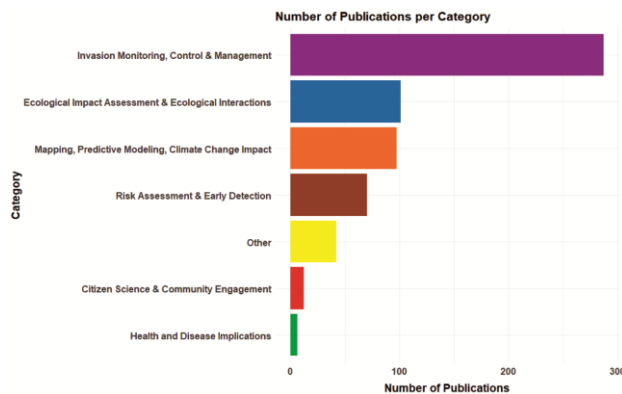


Figure 8 — The main topics covered by the publications on invasive species using geospatial data and techniques between 2000 and 2024.

many studies that focused on assessing the challenges of invasive species and the need for tailored management strategies^{27, 95-98}. Other studies explored the use of geospatial approaches in developing innovative frameworks for proactive management^{70, 99-100}.

(2) *Mapping, predictive modeling, and Climate Change Impact*; this category highlights the use of geospatial tools for mapping and predictive modeling of invasive species distribution, in addition to studying the changes in their distribution and the relationship with climate change. Mapping, predictive modeling, and climate change impact were covered by more than 24% of the publications. The category includes many studies spanning various geographic regions, including tropical islands, arid ecosystems, temperate regions, and urban areas^{43-45, 73, 75-77, 84, 101-106}.

3) *Risk assessment, and early detection*; this category included mostly studies that used remotely sensed data and spatial data for risk assessment and early detection' of invasive species. These studies represented approximately 16% of the publications, indicating efforts to assess risks and detect invasive species early using geospatial data. Remotely sensed data used included satellite imagery and aerial photography enable large-scale surveillance of landscapes, allowing for early detection of invasive^{21, 46, 48, 53, 65, 74, 95, 107-110}. Multispectral and hyperspectral imaging can identify invasive plant species based on their unique spectral signatures which can facilitate eradication efforts^{46, 48, 53, 70, 111}.

(4) *Citizen Science and Community Engagement*; the category includes studies that focused on assessing the use of geospatial data collected through citizen science initiatives and mobile apps to provide real-time information on invasive species

occurrences and enhancing monitoring^{86-90, 112-113}. This participatory approach leverages public engagement to gather extensive geospatial data related to invasive species and biodiversity conservation^{87, 113-114}.

(5) *Impact Assessment and Ecological Interactions*, a substantial number of publications, around 200, addressed the topic of 'ecological impact assessment and ecological interactions', emphasizing the importance of understanding the ecological consequences and interactions of invasive species. This category included studies that addressed the assessment of the ecological impacts of invasive species on native biodiversity, fire regimes, and ecosystem dynamics^{102, 15-119}. Studies also explored how invasive species interactions are influenced by patch size, fragmentation, and climate change^{73, 120-121}.

(6) *Health and Disease Implications*, this category included research studies that investigated the role of invasive species in spreading vector-borne diseases, and studies mapping the distribution of disease vectors like *Aedes albopictus* and *Aedes koreicus*^{71, 122} and assessing risks associated with invasive species like the New World screwworm¹²³. Thus, geospatial analysis can support public health by identifying high-risk areas for diseases like malaria and leptospirosis, informing targeted interventions.

Other topics addressed included studies that integrated genetic, spatial, and environmental data to enhance the understanding of invasive species spread and establishment^{99, 124-126} and studying the evolutionary dynamics of invasive species¹²⁷⁻¹²⁸.

The investigated publications demonstrated that the majority of the research publications on invasive species using geospatial data and techniques focused on invasion monitoring, control, and management. Other significant areas include ecological impact assessment, mapping and predictive modeling, and risk assessment. Lesser-studied areas involve citizen science, community engagement, and health implications, suggesting potential opportunities for further research and development in these fields.

The temporal trends in the different topics related to invasive species using geospatial data and techniques fluctuated between 2000 and 2024 (Figure 9). Invasion Monitoring, Control & Management consistently has a high number of publications over the years, with noticeable peaks around 2005, 2010, 2015, and 2020, indicating periodic increases in research focus on monitoring, controlling, and managing invasive species. Ecological Impact Assessment & Ecological

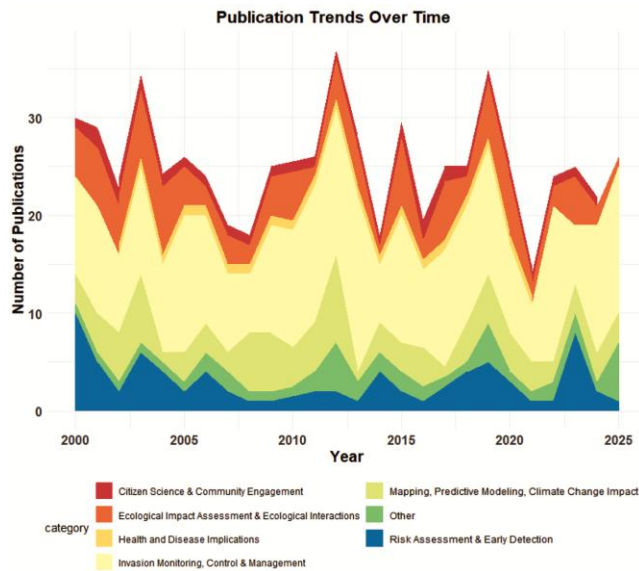


Figure 9 — The temporal trend of the main topics covered by the publications on invasive species using geospatial data and techniques between 2000 and 2024.

Interactions category also showed a consistent presence throughout the years. Although not as prominent as the monitoring and management category, which indicates steady interest in understanding the ecological impacts and interactions of invasive species. The ‘Mapping, Predictive Modeling, and Climate Change Impact’ category demonstrated a steady trend with noticeable peaks similar to those in the main category. This trend suggests a significant ongoing interest in using geospatial data for mapping and modeling the impact of climate change on invasive species. The ‘Risk Assessment & Early Detection’ category showed also a steady presence but with fewer publications compared to the top categories. The other categories showed a minor but consistent presence throughout the period, indicating diverse but less frequent research topics including the Citizen Science & Community Engagement and Health and Disease Implications. The analysis revealed that the majority of publications on invasive species using geospatial data and techniques have focused on monitoring, control, and management, followed by ecological impact assessment and modeling. There are periodic peaks in research output, suggesting times of heightened research activity. Lesser-studied areas include citizen science, community engagement, and health implications, highlighting potential areas for further research and development. main topics of the publications addressing

4. Case studies

The following case studies illustrate the diverse applications and significant impact of geospatial data and technologies in addressing the challenges posed by invasive species:

4.1. Zebra Mussel (*Dreissena polymorpha*) in the Great Lakes, North America

The Zebra Mussel, native to freshwater lakes in Southeast Russia, has become a significant invasive species in North American water bodies, particularly the Great Lakes, causing ecological and economic harm. In a study published in *Ecological Applications* by Bossenbroek et al. (2001)¹²⁹, they used satellite imagery and aerial photography to monitor water quality and detect zebra mussel colonies. They used also GIS-based models to predict the potential spread of Zebra Mussel using environmental suitability indices such as water temperature, pH levels, and calcium concentrations. The outcomes of the study helped in the early detection and rapid response efforts, and improved understanding of high-risk areas for future infestations, guiding management practices and policy decisions.

4.2. Red Imported Fire Ant (*Solenopsis invicta*) in China

Solenopsis invicta is an invasive species causing economic losses and ecological damage in several areas in China. Wang et (2023)¹³⁰ used satellite images for habitat suitability modeling and monitoring *S. invicta* mound distribution. GIS tools were utilized to analyze environmental factors contributing to the ant spread and to develop predictive models. Using Maxent models and wide-ranging surveillance data along with environmental factors, the change in the distribution of the fire ant due to climate change was predicted. The model predicted the spread Fire Ant to 23 territories in China due to climate change. A pioneer integrated strategy for controlling the invasive species was initiated in China based on the outcomes of this study. This comprehensive approach involved disrupting transmission pathways, enhancing surveillance efforts, reporting pest distributions, and implementing preventative and control campaigns. These measures enhanced the efficiency of eradication programs by targeting high-risk areas and reduced the impact on public health and agriculture by informing stakeholders about high-risk zones and management practices.

5. Prospects and challenges

5.1. Benefits of geospatial approaches and the contribution to SDGs

Geospatial technologies enable monitoring of large and remote areas that are difficult to survey through conventional and ground-based methods, thus improving the efficiency of detection and management efforts^{68, 131}. Remote sensing can cover vast landscapes, while drones can focus on specific areas with high precision¹³². Geospatial data systems integrate diverse datasets, including environmental, biological, and socio-economic data, allowing for comprehensive analysis and informed decision-making. This integration is crucial for understanding complex invasion dynamics and developing effective management strategies¹³³. Additionally, remote sensing and GIS technologies reduce the need for extensive field surveys, lowering the costs associated with monitoring and managing invasive species. Remotely sensed data can provide up-to-date information over large areas at a fraction of the cost of ground surveys¹³⁴. Moreover, efficient management and control of invasive species and infectious diseases using geospatial data and techniques align with achieving the SDGs.

The majority of research publications on invasive species using geospatial data and techniques were aligned with achieving the SDGs. The distribution of publications that address various Sustainable Development Goals (SDGs) in the investigated studies of invasive species using geospatial data and techniques from 2000 to 2024 (Figure 10) revealed that the main SDG addressed was SDG 15 (Life on Land), which was addressed with over 500 studies.

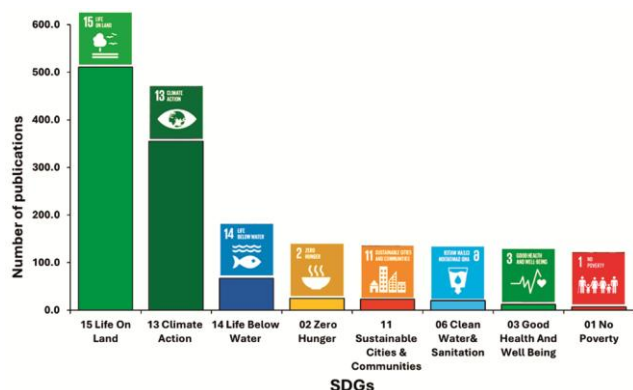


Figure 10 — The Sustainable Development Goals (SDGs) addressed in the investigated publications of studies on invasive species using geospatial data and techniques between 2000 and 2024. Each bar represents the number of publications addressing an SDG.

This indicates that a significant amount of research focuses on terrestrial ecosystems, land management, and biodiversity conservation. The other main SDG addressed was SDG 13 (Climate Action), which was addressed with around 350 publications. Climate action is another major focus area, highlighting the impact of invasive species on climate change and vice versa. Other focus areas included SDG 14 (Life Below Water): which was addressed by around 150 publications, reflecting the importance of studying invasive species in aquatic ecosystems. SDG 2 (Zero Hunger) and SDG 11 (Sustainable Cities & Communities) both were addressed by a modest number of publications, indicating research on how invasive species affect food security and urban environments. The SDG 6 (Clean Water & Sanitation), SDG 3 (Good Health and Well-being), and SDG 1 (No Poverty), which represent niche areas where the impact of invasive species intersects with water quality, public health, and poverty alleviation were addressed with relatively fewer publications.

The SDGs that were addressed by the majority of investigated research publications on invasive species using geospatial data and techniques highlighted the critical importance of terrestrial and climate-related studies in the context of invasive species and reflected the multifaceted impact of invasive species on various aspects of sustainability and human well-being.

5.2. Challenges and Limitations

The accuracy of geospatial analyses depends on the quality and resolution of available data. Inconsistent or sparse data can lead to unreliable predictions and assessments. Additionally, high-resolution data can be costly and difficult to obtain for all regions¹³⁵. The effective use of geospatial technologies requires specialized skills and knowledge, which may be lacking in some organizations or regions. This explains the disparity revealed through the analysis of the geographical distribution of the investigated publications between the global north and the global south. Therefore, training and capacity building are necessary to fully utilize these tools¹³⁶. Integration of multisource geospatial data can be challenging in certain cases. Combining data from different sources (e.g., satellite imagery, ground surveys, citizen science) poses challenges in terms of standardization and interoperability. Ensuring data consistency and compatibility is crucial for accurate analyses¹³⁷. Integrating diverse data sources including genetic, environmental, and citizen science; and improving model accuracy remains a challenge. That explains

the paucity of studies that involve the use of diverse data sources. Advances in machine learning and AI offer promising solutions but require continuous refinement.

5.3. Future Directions

Advancements in remote sensing technologies and machine learning hold promise for enhancing geospatial data applications in invasive species management. The emerging technologies such as UAVs, LiDAR (Light Detection and Ranging) and synthetic aperture radar (SAR) offer new possibilities for detailed vegetation and topographic mapping, enhancing invasive species detection capabilities¹³⁴. Integrating machine learning algorithms with geospatial data can improve predictive modeling and automate the detection of invasive species in large datasets. AI can help identify patterns and make predictions that are beyond traditional analytical methods¹³⁸. Collaborative platforms and data-sharing agreements can enhance data accessibility and utilization¹³⁶, and improve the development of emerging technologies to better suit the needs of societies. Effective management of invasive species requires cross-disciplinary collaboration, combining insights from ecology, technology, public health, and social sciences. Therefore, strengthening collaborations between researchers, governments, and local communities can facilitate the sharing of geospatial data and resources, promote participatory approaches and improving the overall effectiveness of invasive species management efforts.

Proactive management and early intervention of invasive species requires continuous development of scalable and real-time monitoring systems capable of using advanced geospatial technologies and big data analytics, while considering the uncertainty of the changing climate. Therefore, future studies need to consider the dynamic models that account for rapid environmental changes and the possible shifting species ranges.

6. Conclusion

The studies investigated underscore the pivotal role of geospatial data and approaches in understanding and managing invasive species. Advanced technologies and methodologies provide valuable insights into the distribution, impact, and control of invasive species across ecosystems. Continuous innovation and integration of new data sources will enhance the effectiveness of these efforts,

contributing to better ecosystem management and public health outcomes. Predominant methods in publications include remote sensing, aerial imagery, GIS, and spatial analysis, underscoring their importance in mapping, monitoring, and managing invasive species. Remote sensing, GIS, and advanced analytical techniques like machine learning and drones are crucial for monitoring, mapping, and managing invasive species and their impacts on ecosystems. Traditional field studies and emerging technologies like machine learning are also significant, though less frequent. The inclusion of citizen science indicates a move towards broader research participation.

The interdisciplinary nature of research on invasive species highlights the prominence of remote sensing, as indicated by the leading position of the journal "Remote Sensing." The variety of top journals underscores the broad application of geospatial methods across ecological and environmental disciplines, emphasizing the crucial role of these techniques in managing invasive species.

A geographic concentration of research in the United States, China, Western Europe, and Australia, with moderate activity in Canada, India, and parts of South America and Europe, highlights the need for broader global engagement in research addressing invasive species using geospatial approaches. Certain invasive species, particularly the Water Hyacinth, Zebra Mussel, and Emerald Ash Borer, are frequently covered in scientific publications due to their significant threat. Other species like the Lionfish, Gypsy Moth, and Giant Hogweed also receive substantial attention, reflecting their impact on ecosystems. The focused research effort on high-priority invasive species using geospatial approaches indicates a need for broader attention to other invasive species in the literature.

Utilizing geospatial data offers substantial benefits, including enhanced detection, efficient resource allocation, and informed decision-making. Despite challenges, ongoing advancements in geospatial technologies and analytical methods promise to further improve capabilities in this field. Continued research and collaboration are essential to fully harness the potential of geospatial data in combating invasive species and protecting global biodiversity.

Research on invasive species using geospatial data aligns with achieving SDGs, particularly SDG 15 (Life on Land) and SDG 13 (Climate Action), highlighting the critical importance of terrestrial and

climate-related studies. Other addressed SDGs include SDG 14 (Life Below Water), SDG 2 (Zero Hunger), and SDG 11 (Sustainable Cities & Communities), reflecting the multifaceted impact of invasive species on sustainability and human well-being.

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