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Monitoring aquatic invasive alien species based on
remote Earth observations: the water-hyacinth
(*Eichhornia Crassipes*) as test species in Portugal

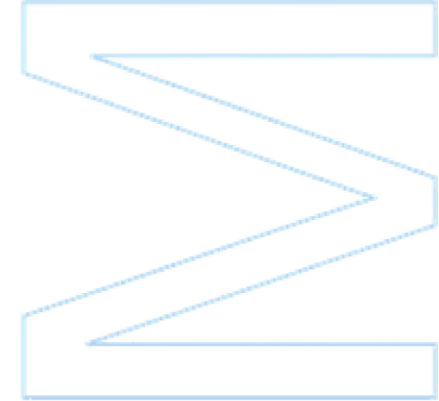
Daniel Moura Velho

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Monitoring aquatic invasive alien species based on remote Earth observations: the water-hyacinth (*Eichhornia crassipes*) as test species in Portugal

Daniel Moura Velho
Master's thesis presented to
Faculty of Sciences of the University of Porto in
Ecology and Environment
2022



Monitoring aquatic invasive alien species based on remote Earth observations: the water-hyacinth (*Eichhornia crassipes*) as test species in Portugal

Daniel Moura Velho

Master in Ecology and Environment

Department of Biology

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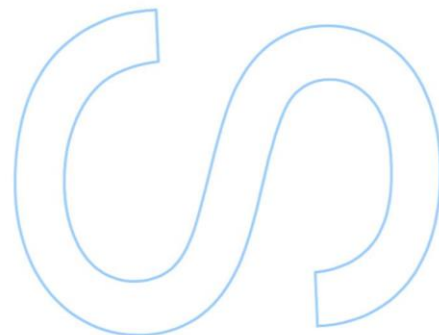
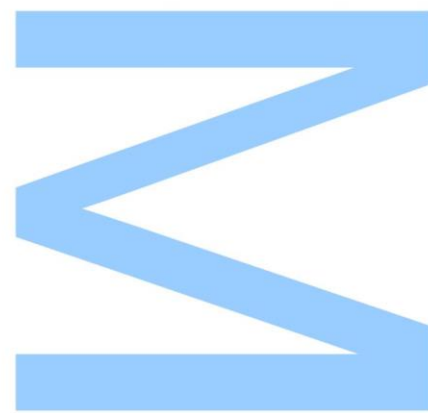
Supervisor

Joana Raquel Silva Vicente, Research Centre in Biodiversity and Genetics Resources & Faculty of Sciences of the Porto University.

Co-supervisors

Joaquim Mamede Alonso, Polytechnic Institute of Viana do Castelo, proMetheus - Research Unit in Materials, Energy and Environment for Sustainability.

João José Padrinho Honrado, Research Centre in Biodiversity and Genetic Resources & Faculty of Sciences of the Porto University.

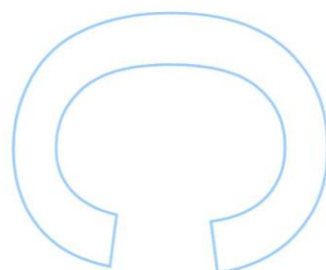
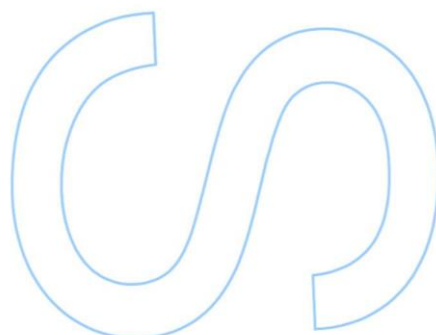
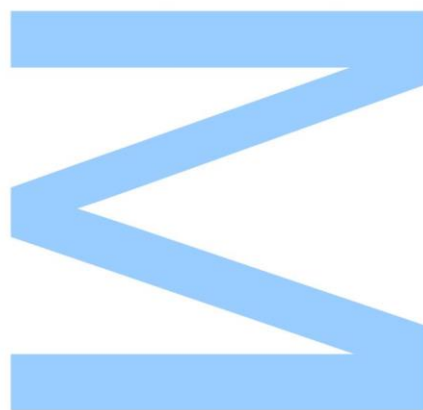




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Abstract

Aquatic invasive alien species (AIAS) are nowadays remarkable due to the social-ecological-economical impacts they cause to aquatic ecosystems, leading to profound changes in the ecosystems functions and services provided. There is an urgent need to reduce the impacts of AIAS, especially by preventing the introduction of new species and identifying priority species for control and management. Remote sensing (RS) techniques are becoming increasingly more used as a tool for mapping and predicting biological invasions. However, compared to terrestrial flora and ecology, there is a lack of a quantitative overview of the progress and extent of RS applications to the management of AIAS. In this study a systematic review of RS uses of AIAS is carried out with the objective to evaluate and discuss the progress and current state of how RS is being applied to manage aquatic invasions. The literature review indicates that the combination of both satellite image and unmanned aerial vehicle (UAV) to gather data for modelling aquatic invasive species distribution has been rarely explored, furthermore, the scientific research on this topic is majorly for large water bodies, due to the difficulties of mapping floating plants on dynamic water bodies like rivers. Considering this challenge, we developed a second study aiming the detection of water hyacinth, *Eichhornia crassipes* (Mart.) Solms, by combining multispectral images from UAVs and satellites to analyse and identify spectral zones with greater reflectance. Then spectral regions with higher ability to detect the target specie were used through ensemble modelling (biomod2) to map the distribution over time and space of the target species. The results demonstrate the ability of biomod2 to detect spectrally similar zones along all the riverbank, specially where the river slows down (at river bends) and in high density at small inlets, which is the expected. Future studies can adapt this methodology for monitoring water hyacinth to other locations or even for other AIAS. It is an innovative tool for policymakers and for environmental management, as it can be used to reduce the negative impacts, necessary resources, and costs by focusing and prioritizing the invaded regions.

Keywords: Biological invasions; systematic review; species distribution model; automatic classification; satellite; sentinel-2; UAV;

Resumo

As espécies exóticas invasoras aquáticas (EEIA) são atualmente notáveis devido aos impactos sócio-ecológicos-económicos que causam nos ecossistemas aquáticos, levando a grandes mudanças nas funções e serviços prestados aos ecossistemas. Existe uma necessidade reconhecida e urgente de reduzir os impactos dos EEIA, especialmente através da prevenção da introdução de novas espécies e da identificação de espécies prioritárias para controlo e gestão. As técnicas de deteção remota (DR) estão a tornar-se cada vez mais utilizadas como ferramentas de mapeamento e previsão de invasões biológicas. Contudo, em comparação com a flora/fauna terrestre, falta uma perspetiva quantitativa do progresso e da extensão das aplicações de DR para a gestão das EEIA. O estudo presente tem como objetivo avaliar e discutir o progresso e estado atual de como a DR está a ser aplicada para gerir as invasões aquáticas, a partir de uma revisão sistemática dos usos da DR nas EEIA. Com base na revisão de literatura, observamos que a combinação da classificação de imagens de satélite (para mapeamento/deteção de espécies invasoras aquáticas) e da modelização tem sido raramente explorada, além disso, a investigação científica sobre este tópico é maioritariamente para grandes corpos de água, devido às dificuldades de georreferenciar plantas flutuantes em corpos de água dinâmicos como rios. Considerando esta lacuna, desenvolvemos um segundo estudo com o objetivo de a deteção do jacinto-de-água, *Eichhornia crassipes* (Mart.) Solms, combinando veículos aéreos não tripulados (VANT) e imagens de satélite multiespectrais, permitindo uma melhor análise e identificação das zonas espectrais com maior resposta à presença da espécie e utilizando as variáveis espectrais com maior capacidade de deteção através do modelo “ensemble” (biomod2). Com os ortofotomapas dos VANT sincronizados com as imagens de satélite multiespectral, permite um conhecimento espacial preciso das zonas invadidas, mesmo num corpo de água dinâmico. No produto final os resultados demonstram a capacidade de detetar zonas espectralmente semelhantes ao longo de todas as margens do rio, especialmente onde o rio abranda e em alta densidade em pequenas entradas nas margens. Futuramente esta metodologia pode ser adaptada para a monitorização do jacinto-de-água em outros locais ou até mesmo para outras EEIA. Sendo uma ferramenta inovadora para a gestão ambiental, pois pode ser utilizada para reduzir impactos negativos, recursos necessários e outros custos, ao focar e ao dar prioridade às regiões invadidas.

Palavras-chave: Invasões biológicas; revisão sistemática; modelo de distribuição de espécies; classificação automática; satélite; sentinela-2; VANT

Table of Contents

Table Index	2
Figures Index	3
List of Abbreviations.....	5
1. Introduction.....	6
1.1 The challenge of managing biological invasions	6
1.2 Aquatic invasions and their impacts	7
1.3 Remote Sensing of aquatic environments	8
1.4 Species distribution models in invasion ecology.....	9
1.5 Objectives	10
2. Chapter I.....	12
2.1 Methods	12
2.1.1 Literature search	12
2.1.2 Literature review	12
2.2 Results and Discussion	14
2.2.1 Geographic location and spatial extent of research	14
2.2.2 Current Scientific Knowledge about remote sensing on IAS.....	16
3. Chapter II.....	25
3.1 Methods	26
3.1.1 Study Area	26
3.1.2 Target species - the water hyacinth (<i>Eichhornia crassipes</i>)	27
3.1.3 Field data collection	28
3.1.4 Image acquisition and processing	29
3.1.5 The mapping processes	30
3.1.6 Ensemble model.....	31
3.1.7 Model training and model validation.....	32
3.2 Results and Discussion	32
3.2.1 Water hyacinth spectral analysis	32
3.2.2 Ensemble Classification Performance	33
3.2.3 Water hyacinth Mapping	34
4. Gaps and Way Forward	36
5. Final Synthesis	37
6. References.....	38
Annex	46

Table Index

Main Tables

Table 2.1 - Features and categories used to characterise the compiled literature	13
Table 3.1 - Satellite imagery collection dates	29
Table 3.2 - Average scores of the three statistical classifiers for each classification algorithm.....	34
Table 3.3 - Performance evaluation for the final classifier combining biomod2 algorithms.	34

Supplementary tables

Table A1.1 – Number of records found By Countries.....	41
Table A1.2 – Number of records by species, type and taxa.	42
Table A2.1- Searches were performed considering a set of selected keywords. Search terms related to “invasive”, “aquatic environment” and “remote sensing” were compiled based on a list derived from a number of core references.....	44
Table A2.2 - The final set of keywords relating to “invasive”, “aquatic environment” and “remote sensing” were combined with the string “AND”, used to perform the literature search in the field ‘title+abstract+keywords’ of ISI Web of Science and Scopus. Afterwards a google scholar search was done with the final resulting on 29 new articles from 50 total that was not found in the previous list of records under consideration....	44
Table A2.3 - Search terms related to “invasive” and respective number of retrieved records.....	44
Table A2.4 - Search terms related to “Aquatic environment” and respective number of retrieved records.....	46
Table A2.5 - Search terms related to “remote sensing” and respective number of retrieved records.....	46
Table A2.6 – Selection of keywords used on the search engines SCOPUS, ISI WEB of Science and Google Scholar.....	50

Figures Index

Main figures

Figure 1.1 – Conceptual scheme of the study’s structure.....	5
Figure 2.1 - Framework considered for reviewing applications of remote sensing in the scope of aquatic invasive alien species.....	14
Figure 2.2 - Distribution of records across countries. The quantities are presented in different sizes of circles.....	15
Figure 2.3 - The number of records found for each of the spatial extents of the aquatic invasive alien species.	16
Figure 2.4 - A number of records per year of aquatic invasive alien species per remote sensing sources.....	17
Figure 2.5 - A Number of records found for each type of remote sensing source used in papers for the aquatic alien species.....	18
Figure 2.6 - A number of records across the different types of sources and sensors of remote sensing data.	20
Figure 2.7 - Quantity of records in percentage found for each of the species found at transitional spaces.	22
Figure 2.8 - Quantity of records, in percentage, found for each of species in the floating category.....	22
Figure 2.9 - Quantity of records, in percentage, found for each of the submerged species.	22
Figure 2.10 - Records in the percentage of type of analysis for each type of species..	23
Figure 3.1 - General workflow with the steps for mapping Water hyacinth.	25
Figure 3.2 - Study area’s location.....	26
Figure 3.3 - Target species the Water hyacinth (<i>Eichhornia crassipes</i>) found around the study area.....	28
Figure 3.4 – Hardware used for the field data collection.....	29
Figure 3.5 - Dsen2 Super resolution image by Lanaras, C. et al 2018.	30
Figure 3.6 - Spectral analysis of the spectral separability of the Water hyacinth from the main surrounding occupations, water and forest, for six different periods.	33
Figure 3.7 - Final product derived from the ensemble models.....	35
Figure 3.8 - Final ensemble projection derived from the ensemble models	35

Supplementary figures

Figure A1.1 - Distribution of records across countries. The quantities are presented in different sizes of squares.....41

List of Abbreviations

AIAP – Aquatic Invasive Alien Plants

AIAS – Aquatic Invasive Alien Species

ANN – Artificial neural network

cm – Centimeters

CTA – Classification Tree Analysis

E. crassipes – *Eichhornia crassipes*

EO – Earth Observation

EU – European Union

FDA – Flexible Discriminant Analysis

GAM – Generalized Additive Model

GBM – Gradient Boosting Machine

GIS – Geographic Information System

GLM – Generalized linear model

hm³ – Cubic hectometers

IAS – Invasive Alien Species

ISI WOS – Institute for Scientific Information Web Of Science

km – Kilometers

km² – Square kilometers

m – Meters

mm – Millimeters

RF – Random Forest

RGB – Red Green Blue

RS – Remote Sensing

SDM – Species Distribution Model

TSS – True skill statistic

UAV – Unmanned Aerial Vehicle

UN – United Nations

USA – United States of America

1. Introduction

1.1 The challenge of managing biological invasions

Through intentional or unintentional behavior by human activities, the geographical barriers to species distribution are being increasingly broken, causing the rate of introductions to increase over time promoting biological invasions (Su et al., 2016) (Havel et al., 2015). Biological invasions are among the most important drivers of the decline in biodiversity worldwide (Bellard et al., 2021). Introduced species capable to reproduce, naturalize and overcome local native species populations, are known as invasive alien species (IAS) threaten ecosystem values and services (Vicente et al., 2019), and often cause adverse ecological, social, and/or economic impacts (Blackburn et al., 2011) (Pyšek et al., 2020).

Freshwater ecosystems like rivers, lakes, and wetlands are seen as some at the most risk (Angeler et al., 2014). These ecosystems account for only 0.8% of the land surface on earth but provide vital services such as providing habitats for 6% of global species, as well as providing many benefits to mankind (Dudgeon et al., 2006).

The effective management of this ever-expanding number of IAS has become a core socio-ecological challenge for the twenty-first century (Buchadas et al., 2017) (Cuthbert et al., 2021). Management of IAS can take many forms, roughly classified as prevention, rapid eradication, or long-term management (Robertson et al., 2020). Biological invasions are very hard to eradicate once they are introduced, so prevention is the cornerstone of many management strategies (Pimentel et al., 2005) (Vander Zanden & Olden, 2008). When prevention fails, swift action greatly increases the likelihood of successful eradication (Simberloff et al., 2013). Early detection and up-to-date information are paramount (Thamaga & Dube, 2018), especially in areas where the species form isolated populations. Traditionally assessments have been made by repeated field mapping/field surveys which require qualified people and over time and space, can become very expensive and often associated with low efficiency, especially in large and/or difficult to access areas (Vander Zanden & Olden, 2008).

In the last few decades, there has been an increase in the use of remote sensing as an alternative method for IAS detection and monitoring for both aquatic and land environments supported by the growing availability of imagery acquired by both, public and private satellites (e.g., Sentinel, Landsat, ASTER, Pleiades, WorldView, GeoEye, AVIRIS, CASI, HyMap, and others). However, there are still challenges in creating

efficient automated techniques for precise biological invasion monitoring to further mitigate their impacts (Marzioletti et al., 2021; Royimani et al., 2019).

1.2 Aquatic invasions and their impacts

The vast number of IAS has resulted in freshwater communities that are quite different in composition from those that existed before (Havel et al., 2015). As an example, among aquatic species introduced to six European countries, 69% have had detrimental ecological impacts, for this reason, biologic invasions are a huge threat to freshwater ecosystems. When evaluating the impact of IAS, aspects other than ecological ones, like economic and societal ones, must be taken into account (Simberloff et al., 2013). Aquatic invasive alien species (AIAS) come in a wide range of species from fauna to flora, for this reason, the impacts they cause can be varied and highly problematic. These species will try to out-compete native ones for resources like food or shelter (European Commission, 2014). Other impacts such as preying upon native species are a major issue since these are not evolved to deal with them, meaning that they are not used to interact with the invasive ones resulting in the invasive species having a higher success rate of preying on native species (Mooney & Cleland, 2001).

Inside the flora, one of the most problematic species types are the invasive macrophytes, plants that can strongly modify local aquatic conditions (Ribaudó et al., 2018). This aquatic invasive alien vegetation, including emergent, floating, or submersed forms, grows in water bodies. Generally, emergent macrophytes are found in shallow areas, with submersed plants in deeper water, and free-floating plants throughout the water surface (Merced et al., 2017). These biological invasions not only threaten biodiversity worldwide but also consequently, causes economic losses (Pimentel et al., 2000). According to Haubrock et al., 2021, the total costs in Europe summed to 116,61 billion euros between 1960 and 2020, being 60% damage-related and impacting multiple sectors.

The scale of the impacts is such that it cannot be ignored by the political community. As far as regulation goes, the United Nations Sustainable Development Goals (UN, 2015) underline the necessity of reducing the effects of IAS by preventing the introduction of new species and identifying priority species for eradication or control. The European Commission promulgated the Regulation on invasive alien species (EU 1143/2014 IAS Regulation) providing a normative frame to prevent, minimize and mitigate the negative impacts of IAS introduction and spread on biodiversity and related ecosystem services. In this context, Portugal's Decree-Law nº 92/2019 of 10 July ensures the implementation, in the national legal order, of this

regulation, establishing the legal regime applicable to the control, detention, introduction into nature, and repopulation of exotic species of flora and fauna (Ministério do Ambiente e Transição Energética 2019). Overall invasive species threaten the economy and biodiversity worldwide and the impacts caused by invasive species are more severe and more frequent than those caused by excessive growth of natives (Havel et al., 2015).

1.3 Remote Sensing of aquatic environments

Remote sensing (RS) is the process of detecting and monitoring the physical characteristics of an area by measuring the energy reflected or emitted by an object or surface, this is done without having any direct physical contact with the target (typically from satellite or manned/unmanned aircraft) (Read & Torrado, 2009). It is time-efficient and increasingly getting affordable for any researchers to work on a local, regional, or global scale (Rowan & Kalacska, 2021). This technique offers a useful approach to studying remote and complex environments providing spatial information that is otherwise difficult or impossible to obtain (Read & Torrado, 2009).

The data from RS is positional, the information obtained represents a discrete known location (Rowan & Kalacska, 2021). The precise and quantitative data acquired by RS can also be used to monitor the slow and progressive changes in various ecosystems and has become commonly used in ecological and environmental research (Jia et al., 2017). This provides a way to quickly monitor large areas with sensors that can provide high quality data in terms of positional, spatial and spectral resolution (Hestir et al., 2008; Shekede et al., 2008). Aquatic studies are increasingly using RS with the help of conventional techniques, as a tool to address some of the limitations of in situ methodologies (Duffy et al., 2019; Visser et al., 2013). Compared to terrestrial botany and ecology, aquatic studies have used RS less frequently (Rowan & Kalacska, 2020). This is due to the aquatic environment and species themselves as well as the lack of technologies designed specifically for use in water (Phinn, 2007; Visser et al., 2018) since the water column complicates analysis by weakening benthic reflectance signals (Nelson et al., 2006).

Although it has been less extensively applied in aquatic studies it is possible to apply it, as shown in Singh et al., 2020, for example, RS has permitted a timely and inventory assessment of aquatic weeds, environmental hazards, natural resources, and water quality monitoring by using the Landsat series of satellite-based sensors as satellite data.

1.4 Species distribution models in invasion ecology

Species distribution models (SDMs) have become powerful tools in a variety of fields including ecology, conservation biology and evolutionary biology. This modelling approach goes by several terms including "species distribution," "ecological niche," "environmental niche," "habitat suitability," and "bioclimate envelope" (Pearson, 2007). They correlate, based on statistical and machine-learning algorithms, species occurrence and absence records with environmental variables to predict suitable habitats where the species and subspecies are likely to occur (Chardon et al., 2020; Guisan & Zimmermann, 2000). Because species absence records are often less frequent than presence records, "pseudo-absence" data are commonly used to fit these models (Pearson, 2007). This type of modelling approach has numerous applications and has been used to model species from various biological groups in terrestrial, freshwater, and marine habitats (Elith & Leathwick, 2009). It may be used to forecast the species distribution in new areas or at a different time period, to test predictions of invasion potential using occurrence records from the invaded distribution or for planning and guiding fieldwork in areas where there is a higher probability of discovering new populations of a known species (Pearson, 2007).

SDMs are without a doubt valuable and helpful, however they often fall short to depict invaded areas and characterize several dimensions usually required by policymakers who need to swiftly and accurately detect invaded areas to plan actions. This is due to SDMs dependence on environmental factors (such as climate, geomorphology, soil, and land use), which frequently have coarse resolutions unsuitable for control or management efforts. Some SDMs can also be used to do pixel-based supervised classification through an ensemble approach, which is often referred to as "classifier fusion" or "stacking" methods in the field of RS image analysis and data mining science (Mouta et al., 2021).

By combining different supervised classification algorithms, these techniques enable the creation of a final consensus capable of discriminating the presence and absence of a species based on satellite spectral data (Mouta et al., 2021). As prove of that Ahmed et al., 2021, uses a combination of sentinel-2 radiometric indices and biophysical variables with machine learning and regression models to model the distribution of the invasive *Prosopis juliflora* successfully, with a ground sampling distance of 10 m.

1.5 Objectives

In this MsC thesis work a dual framework is applied (figure 1.1). Chapter 1 aims to evaluate and discuss the progress and current state of how RS is being applied to the management of aquatic invasions. Specifically, identify current and previous data sources and RS contributions. Chapter 2 applies RS techniques to detect water hyacinth through its spectral signature, using a combination of field datasets, free multispectral satellite imagery with a pixel-based classification modelling tool. To achieve both the objectives proposed in this study, a systematic literature search and review of RS applications to aquatic invasive alien species were made not only to evaluate and discuss the progress of RS applied to invasive species management but as well as a grounds for a succeeding case study, testing a new technique for detecting aquatic plant species. Accomplishing these objectives will improve the understanding of the scientific knowledge available on the use of RS in aquatic invasive species management, providing essential insight for future conservation actions concerning affected ecosystems. We have also enquired about the suitability of an original research article derived from the review made on chapter 1 "Monitoring aquatic invasive alien species based on remote Earth observations: A review (Velho et al., 2022)", for possible consideration in a remote sense science journal. Chapter 2 objectives may also provide an alternative way to early detect, map and monitor aquatic invasive alien species by using satellite image classification with ensemble modelling.

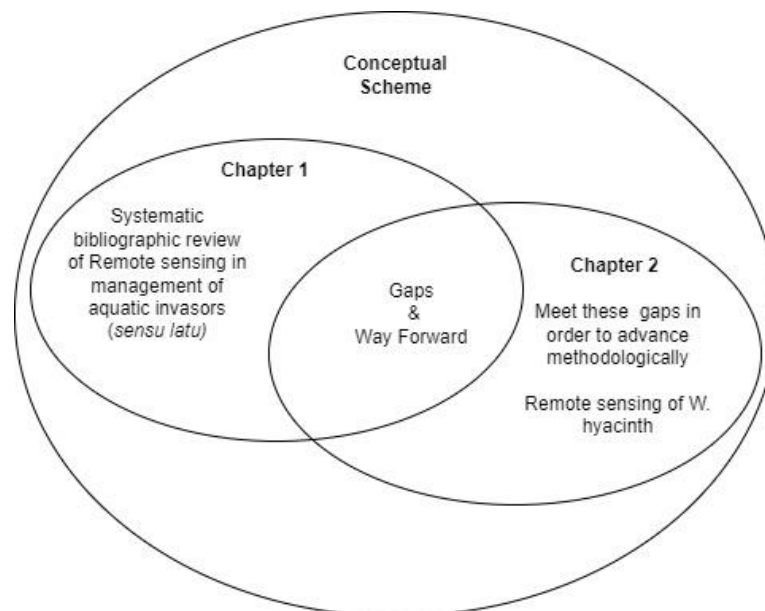


Figure 1.1 – Conceptual scheme of the study's structure.

Monitoring, and early detection of new introductions and/or expansion of the invaded area is a priority for researchers, environmental managers, and policy makers. In this sense, this study is supported by The SINVAQUA project emerged to meet this need, developing a remote monitoring system of invasive alien species, that gave rise to "A Best Practice Guide for the management of aquatic invasive alien species, the case of *Eichhornia crassipes* and *Elodea densa*" (IPVC & BIOPOLIS, 2022).

2. Chapter I

The study of biological invasion patterns, processes, and impacts has increasingly made RS a fundamental tool to monitorize its expansion. However, there is a lack of a quantitative overview of the progress and extent of RS applications to the management of aquatic invasive alien species (Vaz et al., 2018).

2.1 Methods

2.1.1 Literature search

In this study articles were selected and acquired from recognized search engines, more specifically, Scopus (at: <https://www.scopus.com/>), Institute for Scientific Information – Web Of Science (ISI WOS) (at: <http://webofknowledge.com/>), and Google Scholar as well as review articles and other references listed below used as supplementary literature.

The selection of keywords was achieved under both a bibliographic and an expert approaches (for detailed table see Annex 2, table A2.6), with a team of researchers experienced in remote sensing, biological invasions, and plant ecology, numerous keywords were used and this included "remote sensing", "Sentinel-1, Sentinel-2, and aquatic invasive alien species", "mapping", "assess", "monitoring", "detect", "vegetation indices", "satellite", "UAV", "aerial photography", "earth observation", the final list of keywords included the most common words to reach the most records published on the subject.

2.1.2 Literature review

To analyse the opportunities, and contributions from RS of invasive species in the aquatic environment, relevant features were selected from the records acquired, following the same methodology from bibliographic studies on IAS management (mostly Vaz et al., 2018) (table 2.1). Each record from the final spreadsheet was reviewed and categorized into four main categories, inside these four categories there are different types of features that either describe the content (e.g. spatial extent, species names, RS data sources, RS products, and RS, etc.) or describe formal aspects like the year and country from which the study was published. First, "study characterisation" was created to identify the article, the year, and the country that published the record as well as the spatial extent and habitat under invasion. Following that we focused on the category "target IAS", where was established the species characterisation, what is the species

name, taxa, and invasion stage. Then proceeds to “IAS Process and management”, here the focus is on the invasion stage and management action (e.g. expansion, mapping). Finally, within the “Remote sensing” category, there is the RS sources, that were obtained from the records, compiling information about used RS platform (e.g. satellite, aerial photography), spectral information, data features (e.g. resolution, sensing period of time), RS analysis and image classification (pixel or object-based).

Table 2.1 - Features and categories used to characterise the compiled literature

Categories	Description
A. STUDY CHARACTERISATION	
Country(ies) of assessment	The name of the country or countries
Spatial extent (scale of the study)	Global, national, local, regional
Habitat type	Marine, river, coastal, wetland
Year published	The year that the study/article/record was published
B. TARGET IAS	
Species	Name of the species
Species number	Multiple or single species
Taxa	Plant, algae, animal
Life/growth form	Species total submerged, at the water surface or transitional spaces
C. IAS PROCESS AND MANAGEMENT	
Species type	Alien or Alien invasive
Invasion stage	Introduction, establishment, expansion, dominance
Management contribution	Detection, mapping or prediction
D. REMOTE SENSING	
Data sources	Aerial Photography/videography, UAV, Field measurements, Satellite
RS sensor	Landsat, Sentinel-1, Sentinel-2, MODIS..
RS product	EVI; NIR; SAR;
Observation frequency	Frequency of the RS measures, e.g. daily measures, monthly measures, 1 measure, 2 measures
Collection interval	Duration of time of the RS measures, indicate the starting year/month and the end year/month
Spectral resolution	Indicate the spectral resolution of the RS observation data, as "optical multispectral", "optical hyperspectral" or "radar"
Spatial resolution/ grain size	Indicate the spatial resolution of the assessment: it should correspond to the size of the smallest object that can be resolved by the RS imagery, e.g. a pixel or minimum mapping unit. Indicate the measure as well, e.g. km ² , hectare, km x km
Type of classification	Pixel-based or Segmentation based
Model integration	RS data used directly, or as an input variable of a model

2.2 Results and Discussion

Initially a total of 50090 studies were identified for the word “invasive”, 117256 for the word “aquatic environment” and 2510869 studies for “remote sensing”. Then 3 set of keywords were used, combined with the string “AND” and perform the literature search in the field ‘title+abstract+keywords’ of ISI WOS and Scopus reducing to almost 1700 records. These were then evaluated following our selection criteria using titles, abstracts, and keywords and after elimination of duplicates, and discarded non-relevant records there were 727 records from the ISI WOS and 346 records from Scopus. Afterwards, a google scholar search was done at the end, resulting on 29 new articles from a total of 50 that was not found in the previous list of records under consideration (for detailed data see Annex 2, tables: A2.1; A2.2; A2.3; A2.4; A2.5). Of the remaining 1123 studies, 954 were excluded after evaluation of the full text of the paper, leaving a final total number of 187 records (figure 2.1). The first two search engines mainly focus on English language literature, largely scientific papers, whereas the references compiled within Google Scholar are more heterogeneous and less structured (Haddaway et al., 2015). For that reason, some of the records from Asian countries, more specifically Chinese, were sometimes either not available for reading or not in English.

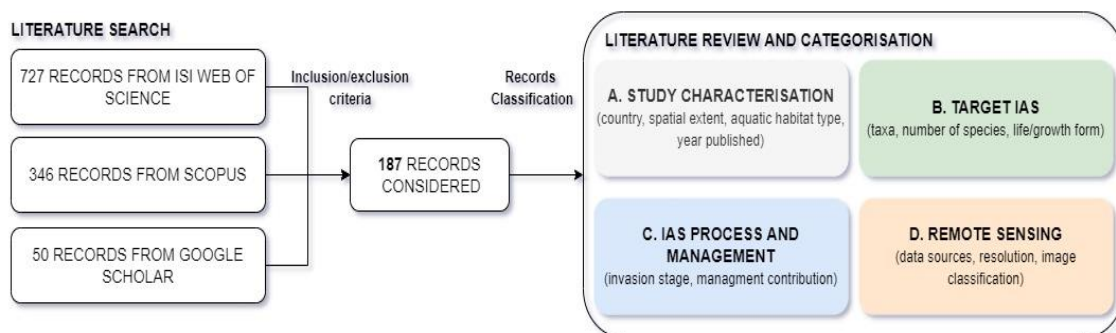


Figure 2.1 - Framework considered for reviewing applications of RS in the scope of aquatic invasive alien species. We began by searching for records focused on RS and AIAS in the ISI WOS and Scopus. We then applied criteria to exclude non-relevant records. Finally, records were reviewed for: (A) study characterisation; (B) target invasive alien species, (C) invasive alien species process and management; and (D) remote sensing (including main sources of RS data, types, and image classification) (see also Table 2.1).

2.2.1 Geographic location and spatial extent of research

Most of the records discussing RS of AIAS belongs to North America and Asia, accounting for 76,09% of the records, with 75 and 65 records, respectively (figure 2.2). Europe follows next with 22 records (11,96%) while Africa, Oceania, and South America together contributed with 11,96% of the records (see Annex 1, figure A1.1 and table A1.1

for more detailed information). This pattern is not unexpected, since there is a greater number of research and investigation institutions in these countries as well as a greater number of programs and volume of funds allocated to research.

Concerning the earliest records found from the 3 continents with the greatest number of records discussing the topic, North America has the earliest ones available, from 2000 till today, followed by Europe which started around 2013, Asia (especially China) has records only in the last 5 to 6 years and lastly all other continents. Although it appears that North America has the initiative on RS of AIAS the first record found was from South Africa in 1999, (Rowlinson et al.) where the authors identify and assess different RS data sources to map alien vegetation with the intent of clearing this riparian zones by removing them with the final objective of maximizing the water supply in South Africa due to the limits of usable freshwater.

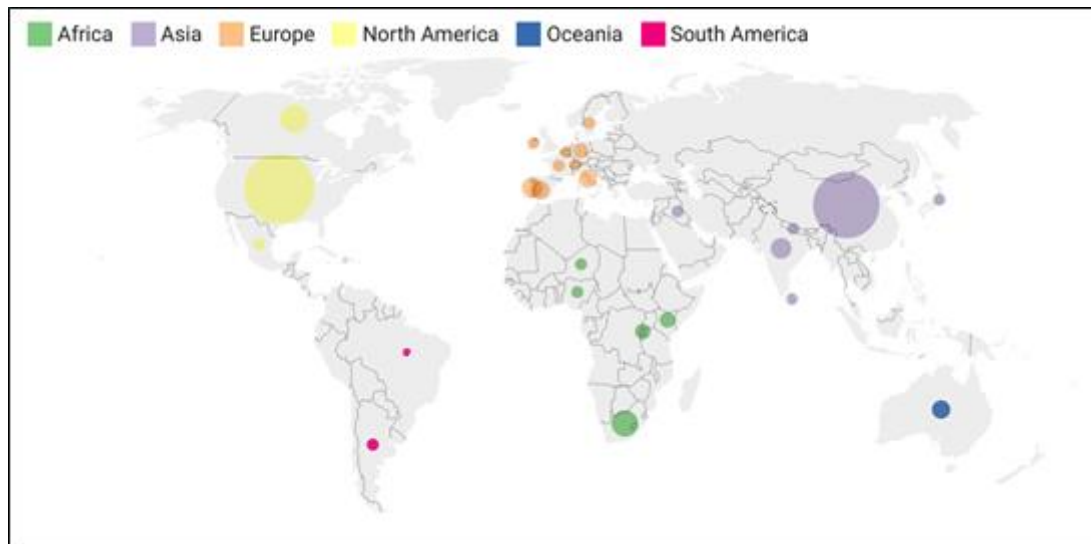


Figure 2.2 - Distribution of records across countries. The quantities are presented in different sizes of circles.

Concerning the spatial extent of the records, the majority of studies, 87%, focused on local and regional extent (49% and 38%), of the 187 studies included in the analyses, 12% focused on a national scale, and only 2% that explicitly took on a global scale (figure 2.3). Local and regional scales are by far the extents present in most records being used, with most records focusing on monitoring the expansion and mapping the invasions. Some examples are, records addressing monitoring, for instance, the *hydrilla verticillate*, an invasive aquatic plant that has rapidly spread through many water bodies in USA was targeted by, Kumar et al., 2019, who developed a tool for a rapid large-scale monitoring of *hydrilla verticillate* by integrating in-situ and Landsat satellite data. The results could support not only planning removal efforts but also evaluating current mitigation efforts since these invasions necessitate frequent and reliable monitoring across a broad extent

and over a long term. Singh et al., 2020, use RS to monitor invasive water hyacinth at a national scale, by using multispectral earth observation data and a modelling approach to discriminate Water hyacinth from other detected aquatic vegetation, creating a national scale EO-derived distribution map for the species. At a global scale Tyberghein et al., 2012, compiled global coverage data, like satellite-based and in situ measured data, representing various aspects of the marine environment relevant for species distributions to assemble a comprehensive, uniform, high-resolution, and readily usable package of global environmental raster that is user-friendly high-resolution, designed for species distribution modelling applications.

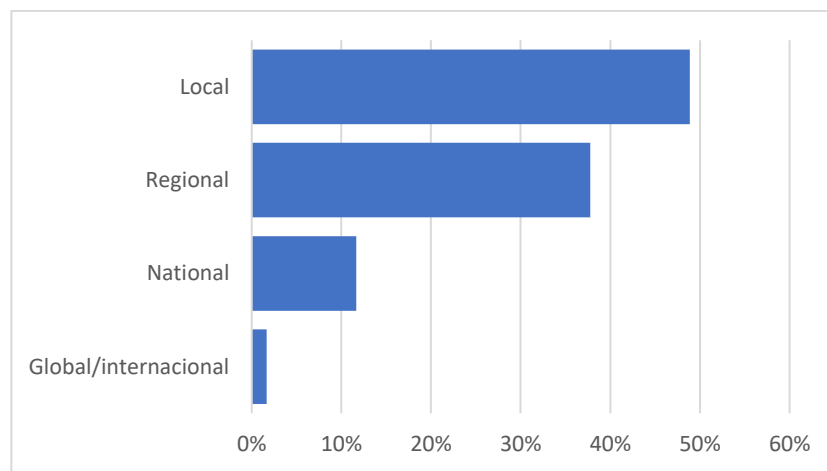


Figure 2.3 - The number of records found for each of the spatial extents of the aquatic invasive alien species.

2.2.2 Current Scientific Knowledge about remote sensing on IAS

The first study relevant included in the review was published in 1999. The literature review thus identified 187 relevant studies published between 1999 and December 31, 2021. These included studies concerning the use of RS on, detecting, predicting, management, control, and impacts of invasion of the aquatic environment by alien species. Only small numbers of papers matched our search criteria prior to 2010, with 0-2 studies per year from 1999 to 2006. Since 2010, there has been a progressive increase in the number of publications on the use of RS for alien invasive species on aquatic environments, it seems that the use of RS to help managing aquatic invasions has started emerging over the last decade. Publications continued to accelerate from 2016 to today, reaching 31 in 2021 resulting in a total of 187 publications, being the best year yet (the latest year for which there is complete count). The number of papers published may be low, but the acceleration is increasing greatly in recent years. The overall count of records discussing each RS source used in the study of aquatic invasive alien species is shown in figure 2.4.

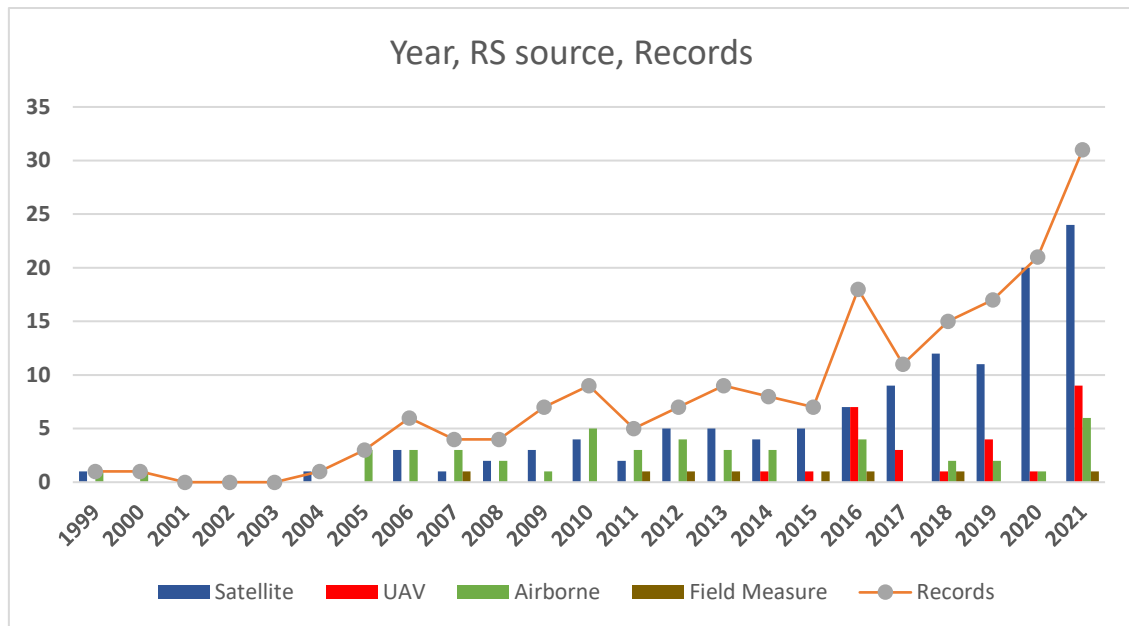


Figure 2.4 - A number of records per year of aquatic invasive alien species per remote sensing sources; N = 187 records.

Concerning the type of RS source, satellite derived products are the most used (59,60%) followed by airborne (23,23%), and UAV products (13,13%) and lastly field measurements (e.g., through field spectrometers; 4,04%) (figure 2.5). From the data collected, the use of airborne (aerial photography and videography) dominated the field, specially from 1999 till mid-2000s, where it was then surpassed by the satellite imagery, the use of aerial photography also decreased in the last decade correlating with the emergence of readily available and improved satellite RS data and of high-resolution UAVs during the last decade (Manfreda et al., 2018). All the RS sources above mentioned have been used to successfully detect and map a variety of invasive alien species, and different sources can also be used to map the same species. For instances, Yang et al, 2007, uses airborne Hymap sensor, hyperspectral imagery, to distinguish and map the Water hyacinth from other plants in Texas, USA, whereas Dube et al., 2017, for freshwater ecosystems in a lake at Zimbabwe, uses satellite multispectral imagery from Landsat 8 with the same aim. Field measurements are used alongside or in a combination with airborne, satellite or UAV imagery (e.g., Yang et al., 2007 uses airborne and field measurements).

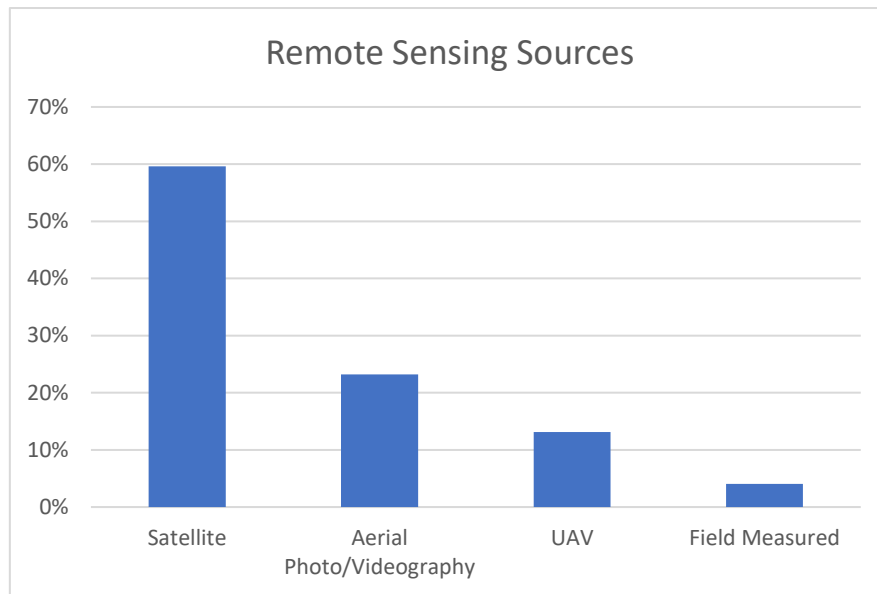


Figure 2.5 - A Number of records found for each type of remote sensing source used in papers for the aquatic alien species.

A large proportion of studies that include satellite sources rely on data derived from Landsat series (101 publications), followed by ESA Sentinel series (24 records), Gaofen series (10 records), SPOT series (10 records), MODIS, Quickbird and WorldView (8, 7 and 6 records respectively), the rest of the satellite products have under 5 records each (figure 2.6). The large use of Landsat 8 OLI sensor may correlate to it be very useful to water related studies, due to the sensor's improved spectral, spatial, temporal, and radiometric characteristics (Dube et al., 2017). Looking at figure 2.6, it is possible to see that these results are related to the longevity of the programs and the launch date of the satellites, the fact that the landsat and sentinel series has existed for a long time compared to other satellites listed makes it normal to find a greater number of studies carried out with this satellite. The cost and accessibility also matches the number of uses, when looking at the list we see that it is organized by cost with the most used source being the cheapest or free.

As for airborne studies, Hymap products are the most common used (12 records), followed by AISA products (7 records), CASI (3 records) and NAIP (2 records), being the rest of the studies evenly distributed with 1 publication each. Airborne studies usually use hyperspectral data although with a few exceptions, Civile C. et al, (2005) uses, 120 years old historical record of aerial photographs to reconstruct the spatial, temporal, and historical elements of the invasion of the *Spartina alterniflora* in Willapa Bay, USA. Another example is, Young et al, (2010) that uses 2 color infrared, high resolution airborne images, one from 1998 and another from 2007, for monitoring and mapping the expanding distribution of the alien *Zostera japonica* on the intertidal mudflats of estuaries

in the Pacific northwest, USA, the authors state that the relatively inexpensive color infrared aerial photography can reliably map the distribution of the nonnative seagrass outside the bathymetric zone of the native eelgrass, but higher spectral resolution techniques, like hyperspectral imaging, very probably will be required if needed to discriminate between the two species where both co-occur.

As for the use of UAV products, studies that use a UAV mounted with a Parrot Sequoia camera are the most used (5 records), followed by AggieAir and DJI products both with 4 records, followed by senseFly products (2 records) and the rest of the products with 1 records. These UAVs are useful for aerial surveys of areas and habitats that are challenging to access or navigate at ground levels, for instances, Chabot et al., (2017) uses the very high resolution images obtained from Canon Powershot S110 camera modified to capture NIR, mounted on a UAV (eBee sense Fly), to develop automate approaches for vegetation classification with the aim of evaluating the effectiveness of UAV-based monitoring the distribution of the *Stratiotes aloides* an aquatic invasive species in the Trent River on Canada. Some UAVs, like the referred DJI product series, mounted with only a visible light sensor, are used to assess situations, identifying areas of interest or to support the mapping when photo-interpretation is used. For example, Kellaris et al., (2019), uses imagery from DJI products to map heterogeneous seaweed habitats, the UAV was equipped with a visible light sensor (RGB) and the images were used to create photomosaics in three sites on São Miguel Island of Portugal, with the aim of being used as support in photo-interpretation for collecting modelling data in combination with ground-truth data to map an invasive algae species *Asparagopsis armata* by constructing predictive models of the seaweed coverage.

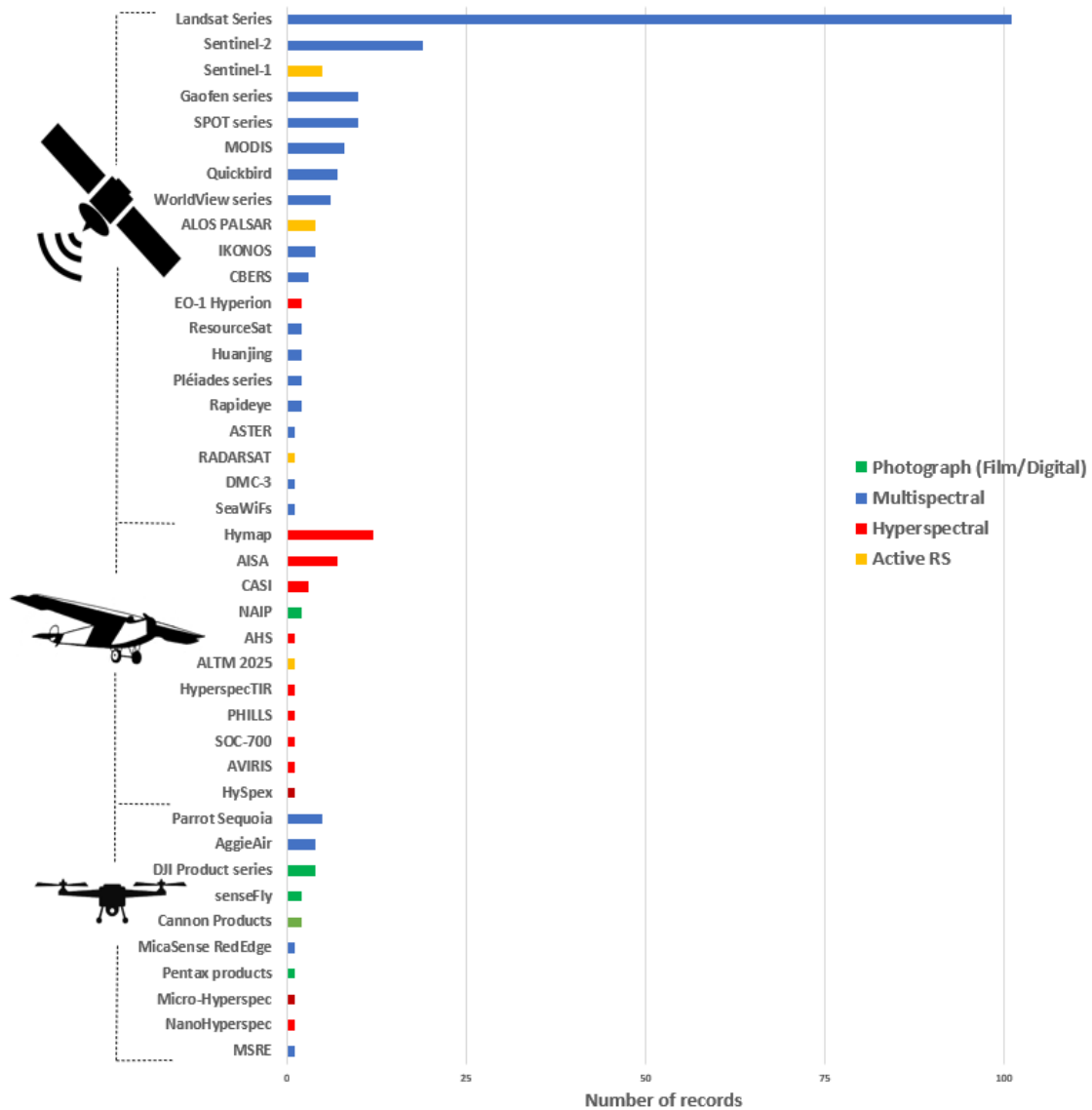


Figure 2.6 - A number of records across the different types of sources and sensors of remote sensing data.

Concerning species, the final count of studies involved 76 species (flora and fauna). The largest number dealt, being more than half of the total species, belongs to species at the transitional spaces (aquatic-influenced environments located within land boundaries) with 63%, followed by species at water surface environments 14% (mostly floating species that are visible for the use of RS), whereas submerged environment species (species totally underwater) were the least common with 23% records (for a more detailed table see Annex 1, table A1.2).

For transitional spaces, more than half of the studies found, are assigned to wetland grass family, being the cordgrass (*Spartina spp.*) 40,74% and common reed (*P. australis*) 21,60% the most frequent. Followed by the shrubs salt cedar (*Tamarisk spp.*) and wattles (*acacia spp.*) both with 4,32%, and the bulrush (*Scirpus mariqueter*) with

3,70%. The rest of the species in this category are found evenly distributed all under the 3% (figure 2.7). Most of the records listed for the cordgrass (*Spartina spp.*) comes from China, according to Chen et al., (2008), the biological invasion of this species is the most obvious ecological problem in China's eastern coastal wetland, and RS can be used to analyse and monitor vegetation at a large spatial and long-time scale, so it seems perfect for this type of studies. Wu et al., (2020), uses time series of four spectral indices calculated based on satellite imagery (MODIS and Landsat) to track the phenology and expansion of the (*Spartina alterniflora*). Zhu et al., (2016) also uses RS for the detection of this species by using medium resolution Landsat images and spectral features, the author results show an exponentially grow of the invasive over the past 10 years, the invasive species almost occupied all muddy beaches to become the most dominant coastal salt vegetation in the region.

Amongst water surface environment, most of the studies are for macrophytes especially the Water hyacinth (*Eichhornia crassipes*) 48,33% being almost half of the studies focused on this species alone, followed by the water-primrose (*Ludwigia spp.*) 8,33%, both the Lotus (*Nelumbo spp.*) and the waterchestnut (*Trapa natans*) with 6,67%, the giant salvinia (*Salvinia molesta*) and the water lettuce (*Stratiotes spp.*) with 5%, both the duckweed fern (*Azolla spp.*) and the water lily (*Nymphaeoides peltate*) with 3,33% and the rest of the species under 2% (figure 2.8).

Lastly for the submerged environment species the chart is more evenly distributed, where 16,67% is for the brazilian waterweed (*Egeria densa*), 11,11% for the pondweed (*Potamogeton spp.*) 8,33% for hornwort (*Ceratophyllum demersum*), 5,56% for the red algae (*Asparagopsis armata*), same for the waterthyme (*Hydrilla*), marine eelgrass (*Zostera spp.*), spiny water nymph (*Najas marina*), and for the green alga dead man's fingers (*Codium fragile*), all the rest species with 3,13% (figure 2.9).

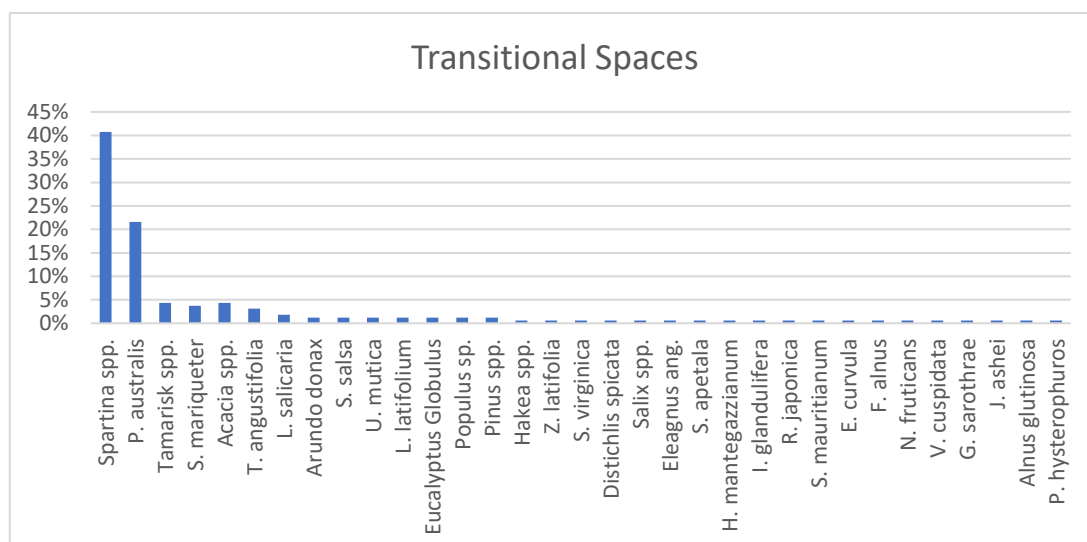


Figure 2.7 - Quantity of records in percentage found for each of the species found at transitional spaces.

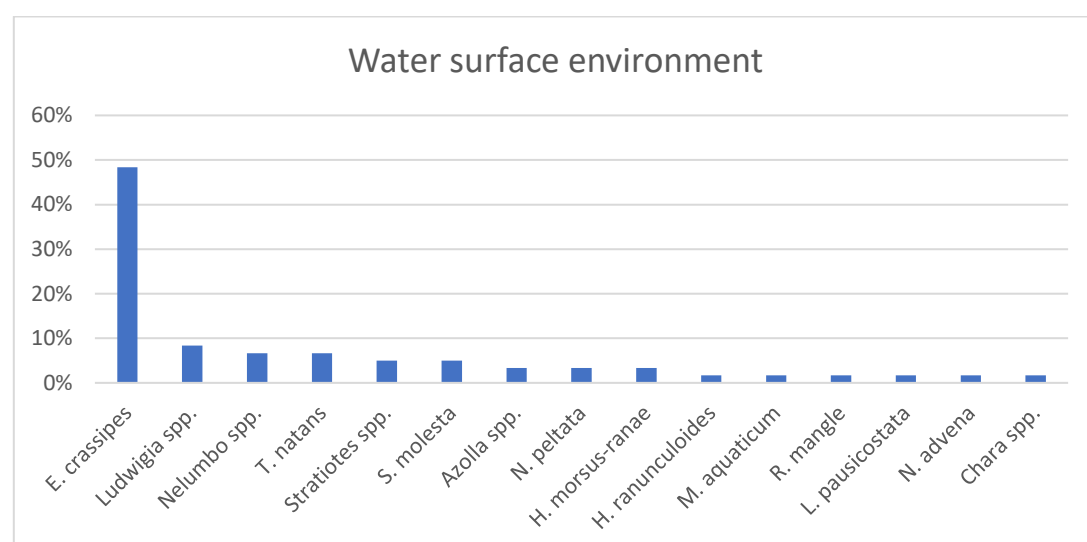


Figure 2.8 - Quantity of records, in percentage, found for each of species in the water surface environment category.

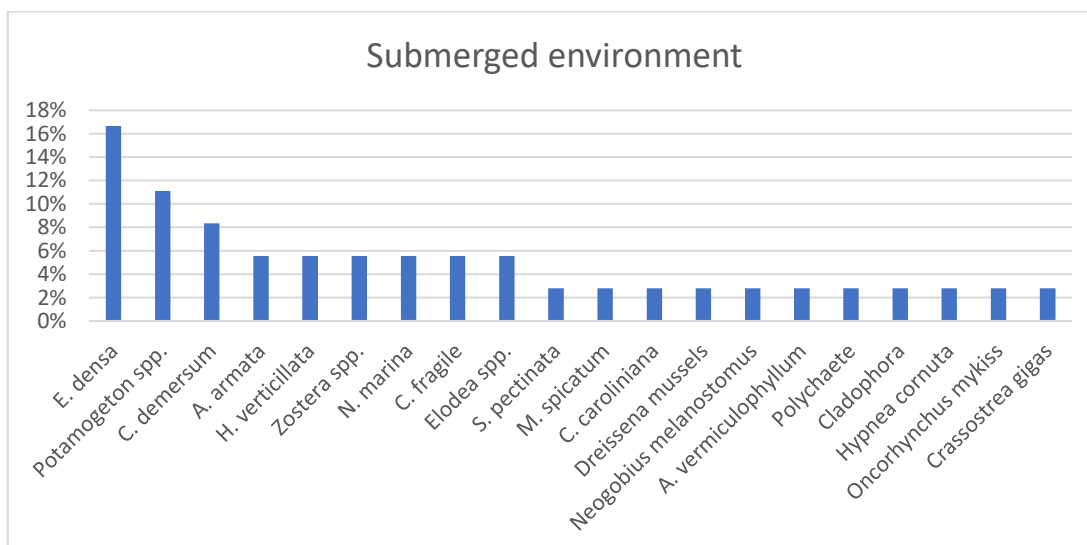


Figure 2.9 - Quantity of records, in percentage, found for each of the submerged environment species.

The properties and quality of the spectrum information, as well as the classification approach, might affect classification accuracy (Zerrouki & Bouchaffra, 2014).

Regarding the classification method, the data shows that most of the studies for AIAS mapping use a pixel-based approach instead of an object-based one on every occasion. For every type of aquatic environment, 76% of studies use pixel-base classification, either with multispectral or hyperspectral sensors, revealing that in this type of studies only 24% of the time use object-base. This results are found regardless the type of environment, for example, each time a study was done for the water surface environments, a pixel based approach was used 77,78% of the times as opposed to object-based with only 22,22%. (figure 2.10).

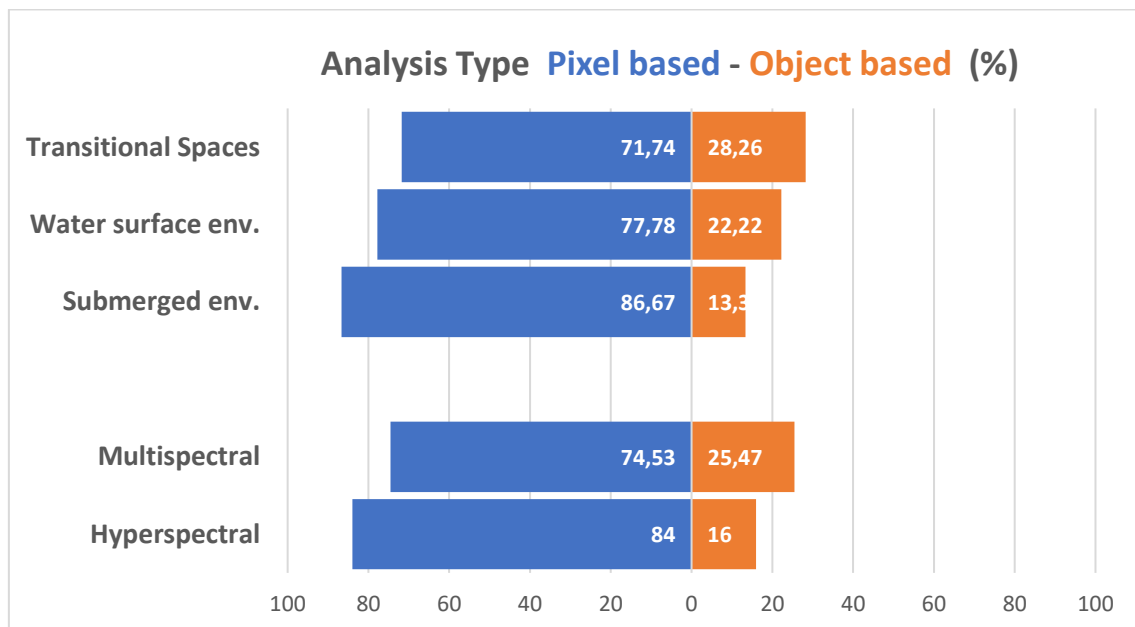


Figure 2.10 - Records in the percentage for each type of classification according with the spectral data for each group of species.

DerviSoglu et al., (2020), compare both classification methods in the determination of wetland coastline, it is seen that water surface areas determined by both methods using sentinel 2 satellite images with 10 m resolution have given close results, however, seems that in the accuracy analysis performed by random points some of the areas which are non-water stated as water in object-based classification and the non-water areas stated as water, according to the results the pixel-based maximum likelihood classification gave better results. Several studies have employed the use of multispectral RS with a pixel-based approach to identify invasive alien plant species. Some authors compared both classifiers for mapping invasive species, for example,

Abeyasinghe et al., (2019), uses UAV imagery to detect the invasive *Phragmites australis* in the Old Woman Creek estuary USA, and the image classification was performed using 3 pixel-based and 2 object-based classifiers, the author states that the findings suggest that the pixel-based classification had better results over the object-based to identify small patches of *Phragmites australis*. This doesn't mean that one methodology is better than the other, methodologies based on analysis per pixel are more continuous, aimed at detecting variations in intensity in the other hand object base are more discontinuous and potentially more general which for this type of studies might not be advised.

In terms of sensors used for this type of studies, the results indicate a greater use of multispectral sensors (81%) than of hyperspectral (19%). Both types of sensors use more often a pixel-based approach, whenever multispectral data was used, 74,53% of the time a pixel-based approach was used, the same was found for hyperspectral with 84%. The unpopular use of hyperspectral may be explained by the high cost and difficulty of acquiring and processing this data from satellite and airborne sources.

This analysis allows us to choose the best approach for the rs of AIAS, which are very problematic, since this promote short-term and long-term changes in ecosystems, jeopardizing their values and services. The literature review indicates that there is a growth in the scientific community's interest in biological invasions supported by the increased availability (quality and quantity) of data and RS sensors. However, there is a gap in knowledge to produce fine resolution mapping of invadade areas for complex hydrologisc systems like rivers, leaving policymakers and stakeholders without adequate scale (spatial and temporal) cartographic information.

This happens due to the difficulties inherent to the remote detection process in aquatic environments and to the fact that some species are in motion. New technical developments, which allow a combination of both medium resolution satellite data and UAV for identifying and modelling aquatic invasive species distribution, along with new super resolution algorithms make it possible to develop new methodologies that support the monitoring process.

Considering this challenge, In the following chapter 2, we developed a second study aiming the detection of Water hyacinth, *Eichhornia crassipes* (Mart.) Solms, by combining UAV and multispectral satellite imagery to analyse and identify spectral zones with greater reflectance. Then spectral regions with higher ability to detect the target specie was used through ensemble modelling (biomod2) to map the distribution over time and space of the target specie.

3. Chapter II

In this MsC thesis work it's proposed and developed a supervised image classification approach using RS and ensemble models to detect and map the extent of invasion by the Water hyacinth based on free Sentinel-2 data (figure 3.1) Specific steps of each stage are described in the flow diagram in the figure 3.1 and detailed in the subsections below (see Section 3.1.4, Section 3.1.5, Section 3.1.6, Section 3.1.7, Section 3.1.8 and Section 3.1.9). In the first step, the Sentinel-2 satellite imagery is obtained and treated with the "super resampling" Dsen2. Field surveys for Water hyacinth detection, allow the creation of an orthophotomap with UAV techniques for delimitation of the target species and main land cover present around the study area (water and forest). In the second step with georeferenced and vectorised areas, it is possible to (throughout imagery resampled and delimited) to perform a spectral analysis to choose the spectral regions with greater ability to distinguish the Water hyacinth from the water and the forest, this process allows the analyse and to choose spectral regions with greater ability to identify the target species. It is in the third step that it is added to the ensemble model, biomod2, training areas for the presence and absence of Water hyacinth in conjunction with the bands that were previously identified with greater importance. In biomod2, the ensemble model is built with classification algorithms and statistical indices to calibrated and validated, resulting in the final product of areas spectrally similar to those of the Water hyacinth.

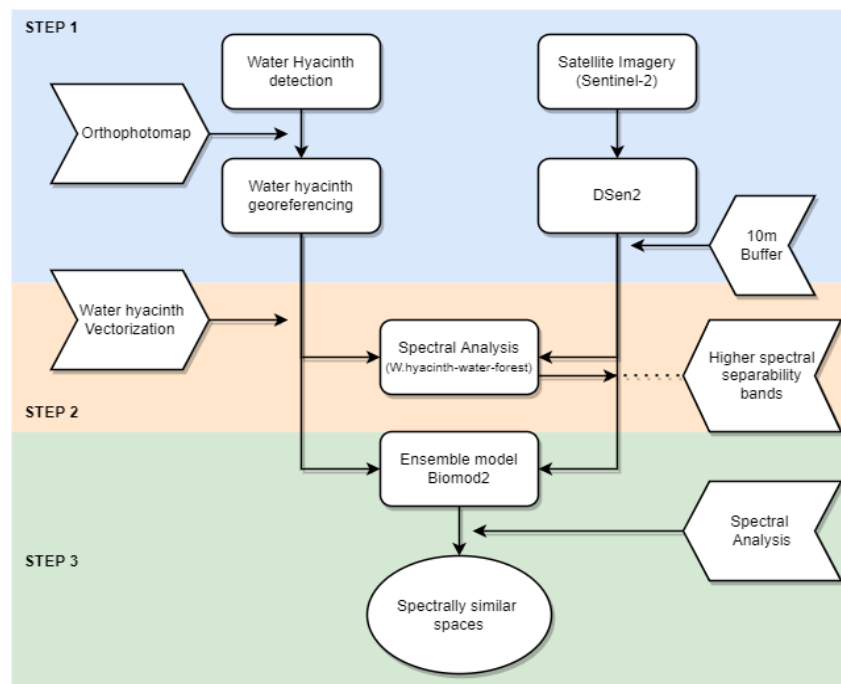


Figure 3.1 - General workflow with the steps for mapping Water hyacinth combining ground-truth samples with sentinel-2 satellite image classification into an ensemble model to achieve spectrally similar spaces of the species.

3.1 Methods

3.1.1 Study Area

This analysis comprises an extension of approximately 60 km of the Cavado river (as well as its banks) from the mouth to the Caniçada Dam. The Cavado river rises in an area of accentuated relief in the north of mainland Portugal, at Fonte da Pipa, in Serra do Larouco (1536 meters). It is an elongated river with a transversal profile of narrow valleys (characteristic of a mountain river) at its source, progressing after the Caniçada dam, to open valleys that are flattening. The Cavado river basin comprises several municipalities of Minho (Amares, Barcelos, Braga, Cabeceiras de Basto, Esposende, Ponte da Barca, Ponte de Lima, Póvoa de Lanhoso, Póvoa de Varzim, Terras de Bouro, Vieira do Minho, Vila Verde) and in Trás-os-Montes (Boticas and Montalegre).

The Cavado river is 118 km long and its watershed has an area of 1600 km². The Cavado river basin is limited, in the north quadrant, by the Lima and Neiva river basins, in the south quadrant, by the hydrographic basin of the Douro and Ave rivers. It is estimated that, at the mouth, the annual flow of the Cavado River is approximately 2123 hm³ and the water storage capacity is of 1180 hm³. The annual accumulated precipitation in the Cavado watershed exceeds 3000 mm (at higher altitudes), decreasing progressively as we approach its mouth.

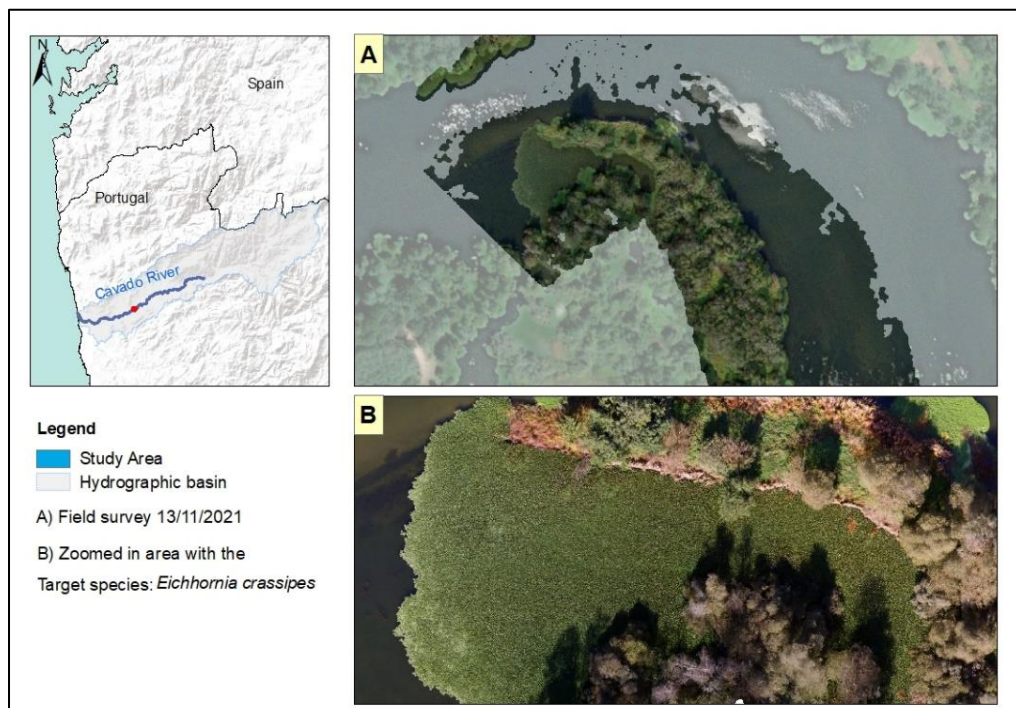


Figure 3.2 – Geographical definition of the study area, (A) orthophotomap of the Cavado river in Areias de Vila and (B) Zoomed in area of interest covered with the target species.

3.1.2 Target species - the water hyacinth (*Eichhornia crassipes*)

Biologic invasions are a huge threat to freshwater ecosystems, and aquatic invasive alien plants (AIAP) cause the most significant impact on them by changing their structure and function as well as disturbing key hydrological processes. *Eichhornia crassipes* (Mart.) Solms, is one of the most aggressive and lethal free-floating aquatic plants that degrade freshwater ecosystems (Thamaga & Dube, 2018). It's an erect, free-floating, stoloniferous, perennial herb. It grows to 1m in height with buoyant leaves, which vary in size according to growth conditions (Thakuri et al., 2019), and has a very rapid vegetative dissemination and a production of a high number of seeds giving, in invaded areas, a competitive advantage over other native macrophytes (Albano Pérez et al., 2011; Coetzee et al., 2017). It has attractive light blue to violet flowers, and for that reason, it was introduced as an ornamental plant (Ndimile et al., 2011; Téllez et al., 2008). Ecologically, it can modify the surface water clarity and cause hypoxia or a decrease in the concentration of related nutrients and contaminants, such as nitrogen, phosphorous and heavy metals (Thamaga & Dube, 2018). The plant fragments are carried away by either the wind or the water current, creating new spots of invasion far away from the original population (Téllez et al., 2008). The thick mats made by the *E. crassipes* were seen only as a practical problem for navigation, fisheries, irrigation systems, and electric power generation, however, recent research indicates that this species is a major threat to biodiversity, affecting aquatic fauna, plant diversity and other freshwater life as well as economic development activities (Otieno, 2014; Gichuki et al., 2012).

According to Moreira et al. (1989) in "Aquatic weed bioecology and controls in Portugal: a review", *E. crassipes* was first noticed in Portugal around 1939. In the past, this species problem was considered reduced in Portugal compared to other countries since the infestations were mostly in irrigation and drainage channels (Rebelo, 2012), but over the years it changed and became one of the most widely and rapidly spreading aquatic invasive species throughout Portuguese rivers causing several by clogging the river, impeding navigation, ending up reducing recreational and fish use and affecting aquatic fauna. It was first recorded on the Cavado river in 2003. A single study species *E. crassipes* (see figure 3.3) was selected as the target species because of this species being more widespread across the river resulting in larger training samples and being on the surface of the river (floating) most of its lifetime being easier to detect and map via satellite imagery. Once established *E. crassipes* is extremely difficult to eradicate

(Villamagna & Murphy, 2010). Early detection and up-to-date information regarding its distribution and whereabouts are, therefore, crucial (Thamaga & Dube, 2019).



Figure 3.3 - Target species the Water hyacinth (*Eichhornia crassipes*) found around the study area.

3.1.3 Field data collection

The field data were used for discrimination and classification using RS images and validation of satellite-derived Water hyacinth. The plant locality data for this study was collected on the month of July during fieldtrips. The section analysed is part of the river that crosses the most urban area of the municipality of Barcelos. To choose the sampling points, satellite images of the section of the river at dams and river bends, where the water is more stagnant allowing floating vegetation to get trapped and to accumulate, were analysed using the Google Earth software. With the use of these images, it was possible to have a general notion of land use and narrow the locations where Water hyacinth may be more likely to be making it easier to find, plan and travel to the sites of interest for the data collection. Once a location was found (figure 3.2.A), a Phantom 3 pro DJI UAV was deployed at 70 m high, to collect high resolution (< 5cm/pixel) RGB imagery (figure 3.4). A flight plan for the UAV was made with the software DJI Pilot, with an 85% side and 75% frontal superposition, this information collected was then used to create detailed orthophotomaps for the geographic delimitation of invaded areas using “Agisoft metashape” (figure 3.2).

It is important that there is a synchronisation between the capture of unmanned vehicle images with the satellite images, to ensure that we are marking good areas of Water hyacinth, for the correct extraction of “pure” spectral signatures which will allow identify where the species is for the past and for the future through an automatic classification with a good performance.



Figure 3.4 – Hardware used for the field data collection. From left to right, “Phantom 3 pro DJI” UAV used for the collection of high-resolution images; tripod with hardware for the automatic flight route of the UAV.

3.1.4 Image acquisition and processing

The Sentinel-2 satellite mission provided by the Copernicus Open Access Hub, delivers multispectral imagery with 13 spectral bands, acquired at three different ground sampling distance (10 m, 20 m and 60 m) with a swath of 290 km with an image acquisition frequency every 2 to 3 days. Here is tested the use of this moderately fine spatial-resolution multispectral imagery from a free and readily available source. By providing multispectral imagery, it allows analysing the behavior of the Water hyacinth in spectral regions normally neglected due to their low resolution. The use of quality, free and world-wide coverage satellite images is an asset to the decision process and a resource that should be used with great importance for current and future earth observation.

In this study, 17 images were selected, one per month, between May 2021 to February 2022 of Sentinel-2 level 2A, respecting a maximum selection criterion of 15% percentage of clouds per image and covering the entire study area at the final stage of bloom period (July–September), and post-flowering period (October–February) (table 3.1). The collection and processing of images before July is compromised by the occurrence of clouds along the study area during the months of June and May, with no images that meet the quality criteria except for one.

Table 3.1 - Satellite imagery collection dates

Collection Dates			
2021/05/04	2021/08/20	2021/10/19	2022/01/24
2021/07/08	2021/08/22	2021/11/10	2022/02/08
2021/08/12	2021/08/27	2021/11/13	-----
2021/08/15	2021/09/04	2021/11/30	-----
2021/08/17	2021/10/06	2021/12/18	-----

These images were then resampled using “DSen2”, a Super-Resolution algorithm capable to transform satellite imagery standardizing the spectral resolution of the various spectral bands through pre-trained deep learning neural networking (Lanaras et al., 2018). Methods like bilinear or bicubic interpolation can be used to upsample images but returns blurry images with little additional information content. Unlike this methods, the use of dsen2, attempts to do better and recovers as much as possible of the spatial detail while at the same time preserve the spectral information of the original bands through a “smarter” upsampling by using a (deep) machine learning approach, see an example in figure 3.5 (Lanaras et al., 2018). Through this method we can standardize the multispectral information at a resolution of 10 m allowing to analyse spectral regions with greater capacity to distinguish the Water hyacinth, thus allowing an optimisation of the use of the Sentinel 2 images. The final compiled information generated a spectral database with 204 gigabytes, which had to be properly catalogued and organized for later use.

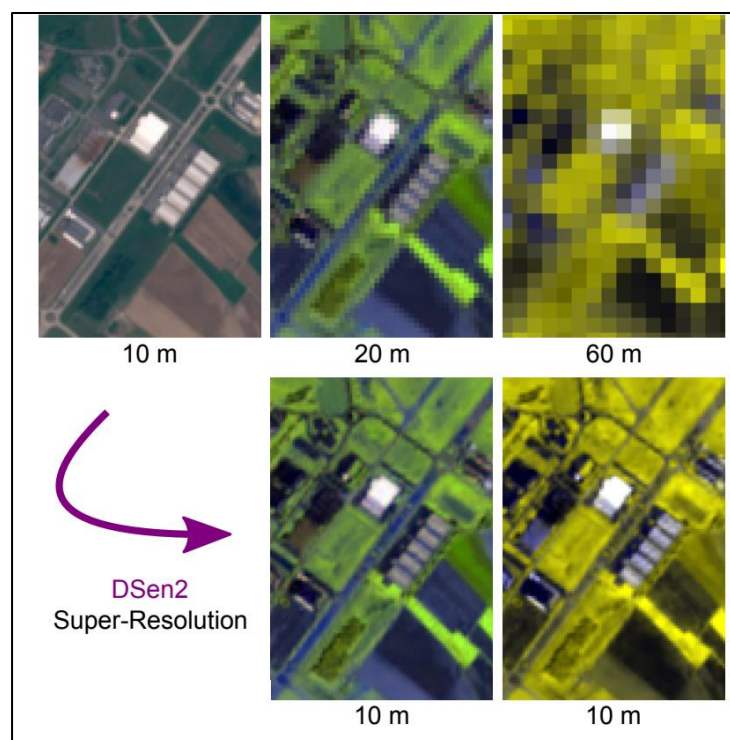


Figure 3.5 - Dsen2 Super resolution image by Lanaras, C. et al 2018, Top images: Input Sentinel-2 bands at 10 m, 20 m and 60 m GSD, Bottom: Super-Resolved bands to 10 m GSD, with the proposed method (DSen2).

3.1.5 The mapping processes

For the mapping process, to be able to develop and the calibration of pixel-based classifiers it is paramount obtaining the representative spectral signatures of the different phenological and physiological states of the Water hyacinth in the water body under

study and the various environmental conditions and ecological contexts (and seasonality). The study of the spectral separability of the plant allows the perception of the spectral bands where the plant has the greatest spectral difference in relation to the main surrounding occupations, water, and forest (figure 3.6). After having resampled all the bands with *dsen2*, the bands with the best ability to distinguish the target species are chosen. The selection of spectral regions with greater ability to distinguish Water hyacinth from, forest and water was made through the analysis of the spectral curves of each landscape component across 5 training areas for each component. Spectral curves were identified and analysed over time to our study areas (as seen in the figure 3.7).

A total of 139 areas were then generated using manual photointerpretation on the ArcGIS 10.0 software, where 42 areas were classified as presence of Water hyacinth and 97 the absence of it. For presence the only selected areas were where it was clear that it contained nothing but Water hyacinth. In contrast, to form the non-target or absence areas, many cover types were selected and marked, ranging from pixels of river water to other floating species. This training areas were then used in the ensemble model to classify the water hyacinth.

3.1.6 Ensemble model

In this study we chose to use the R package “biomod2: Ensemble Platform for Species Distribution Modelling”. This package is designated an ensemble modelling platform implemented in the statistical software R, it allows for predicting the habitat suitability of a species across a geographic space by combining different modelling/classification techniques based on statistical and machine learning algorithms (Thuiller et al., 2009).

The package permits to run consistently up to 10 single models on a presence/absences (resp presences/pseudo-absences) dataset and combining them by either a mean, weighted mean, median, or by committee averaging in ensemble models and ensemble projections (Thuiller et al., 2009). Allowing the exclusion of algorithms with poor performance and including only the best performing individual models in an ensemble forming a more accurate prediction with better transferability, outperforming single classifiers (Hao et al., 2019).

Using the latest version of the *biomod2* package (version 3.4.6) within the software R version 4.0 with the standard configuration and 30 modelling rounds. Eight modelling algorithms were used in this study to build and ensemble, which are Generalized Linear Model (GLM), Flexible Discriminant Analysis (FDA), Gradient

Boosting Machine (GBM), Random Forest (RF), Classification Tree Analysis (CTA), Generalized Additive Model (GAM), Artificial Neural Network (ANN), and MAXENT, Phillips (MAXENT.Phillips).

3.1.7 Model training and model validation

The calibration of image classifiers and the models to be constructed for the validation of the respective outputs, requires the aggregation of existing information on the distribution of the target species as well as the spatially explicit collection of information on the ground (Mouta et al., 2021). For the input dataset, occurrence records of Water hyacinth were split into 80% of the dataset for training and the respective 20% used to assess classification accuracies across all imagery (evaluation purposes), 30 model replications were performed using the default options of biomod2. To balance the training data and avoid biasing, the number of pseudo-absences was set equal to the number of presences with both the same weight in the calibration process (0.5 prevalence). To evaluate the overall model performance, the area under the Receiver Operative Characteristic Curve (ROC), True Skill Statistic (TSS) and Cohen's Kappa (KAPPA) were used, the first measures vary from [0 to 1] while both the latter between [-1 and 1]. Only individual models with an AUC, TSS and Kappa, score above 0.7 were included in ensemble models, since values closer to one represent better-performing classifiers and higher discrimination ability. Weighted mean was used to combine individual models into an ensemble.

3.2 Results and Discussion

3.2.1 Water hyacinth spectral analysis

Spectral analysis over time shows that the Water hyacinth has a large spectral range, and its reflectance values vary greatly throughout its life cycle, with this in mind the analysis of the evolution of its spectral curves allows finding the spectral and temporal regions where it is easier to detect it. Spectral curves were identified and analysed over time to our study areas (as seen in the figure 3.7). By analysing the spectral reflectance based on multispectral data, results shows that, it is in line with vegetation with some green leaf density like Water hyacinth, with a absorption in the red wavelength of 660 nm and a high reflectance peak in the NIR light wavelengths around the 850 nm.

It was through this study that we realized that there is a greater difference in-between bands 6 and 11, using only this range of bands to calibrate the models in the biomod2 package. By using only spectral regions with a high ability to discriminate

between invasive plants and their surroundings, the computational process can be sped up (by reducing the number of spectral variables employed) and the final model's ability to distinguish invaded from non-invaded areas can be increased, in this regard, spectral bands between 6 to 11 for the month of November presented the highest ability to discriminate between water hyacinth from water and forest. A reason for this is the fact that the forest is in senescence making the water hyacinth leaves stands out more.

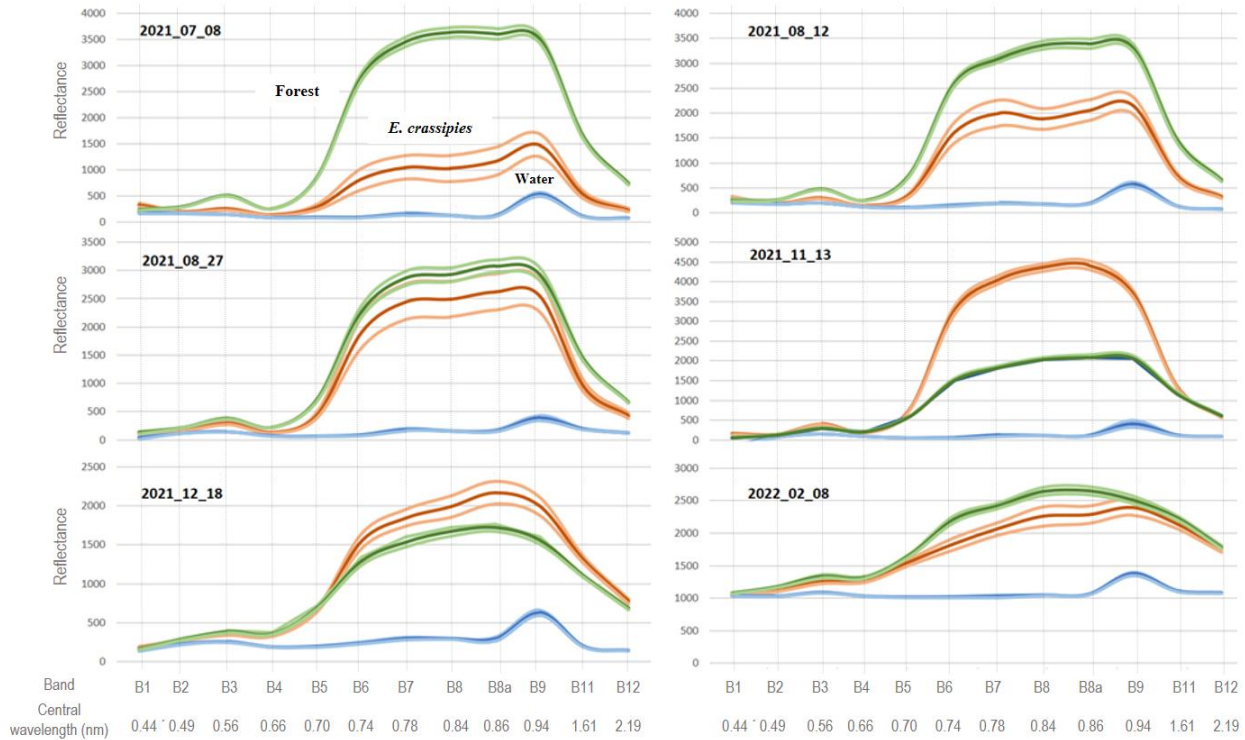


Figure 3.6 - Spectral analysis of the spectral separability of the Water hyacinth (orange) from the main surrounding occupations, water (blue) and forest (green), for six different periods.

3.2.2 Ensemble Classification Performance

The results demonstrate the ability of the final model to detect spectrally similar areas with overall positive evaluation by the three statistical classifiers as well as sensitivity and specificity (table 3.2). On average, high-performance scores with 0.94 for TSS, 0.99 for ROC, and 0.78 for KAPPA. The supervised classification technique that produced the best results for all evaluation parameters were the generalized linear model, followed by flexible discriminant analysis and the random forest algorithms, on the other hand, Maxent had the lowest scores of all the classifiers, being that it must be used when working with pseudo-absences and not with absences (Table 3.3).

Table 3.2 - Average scores of the three statistical classifiers for each classification algorithm

Classification Algorithm	TSS		KAPPA		ROC	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
RF	0,759	0,133	0,685	0,132	0,890	0,076
GLM	0,860	0,061	0,690	0,092	0,962	0,021
MAXENT.Phillips	0,484	0,170	0,582	0,154	0,742	0,085
FDA	0,645	0,176	0,648	0,120	0,913	0,082
ANN	0,724	0,132	0,643	0,118	0,898	0,067

Table 3.3 - Performance evaluation for the final classifier combining biomod2 algorithms.

Evaluators	Evaluation	Cutoff	Sensitivity	Specificity
KAPPA	0.779	599	68.421	99.749
TSS	0.945	198	100	94.472
ROC	0.993	202.5	100	94.598

3.2.3 Water hyacinth Mapping

The result, through the spectral signature (from band 6 to band 11) and different supervised machine learning algorithms, corresponded to the mapping areas spectrally similar to those of the Water hyacinth for all images collected. The month with the largest area invaded was September, as the temperature drops, the areas start to decline. The ensemble classifier based on biomod2's ensemble technique was able to distinguish invaded areas by the Water hyacinth from training areas, in terms of spectral similarity (see figure 3.7 and 3.8).

The results demonstrate the ability to detect spectrally similar areas along all the riverbank, specially where the river slows down (at river bends) but, the areas with the higher density of the species occurs in small inlets which is the expected, due to the accumulation of the plant. In Figure 3.7 it is possible to see the changes in the density of the species as time goes by, revealing the expected changes in the spaces with spectral similarity to the Water hyacinth, with an increase during mild to high temperature months, July to September (peak of the expansion), followed by a decrease with the arrival of colder months, November and December.

The validation of the results could have been done throughout field trips to confirm the presence of the water hyacinth in the places designated by the projection, to see if it matches. However, due to the deadline for the delivery of this thesis work it was not possible to accomplish this final step.

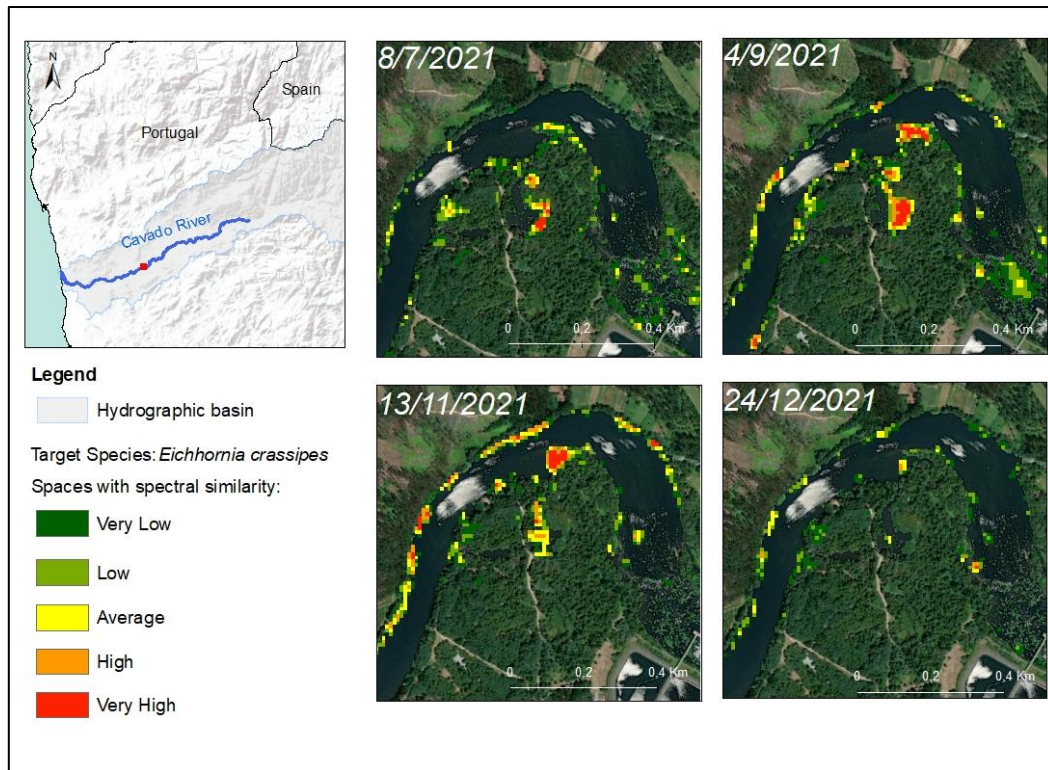


Figure 3.7 – Final results derived from the ensemble models, for one part of the river Cavado with different dates revealing the changes in the spaces with similar spectral to the Water hyacinth.

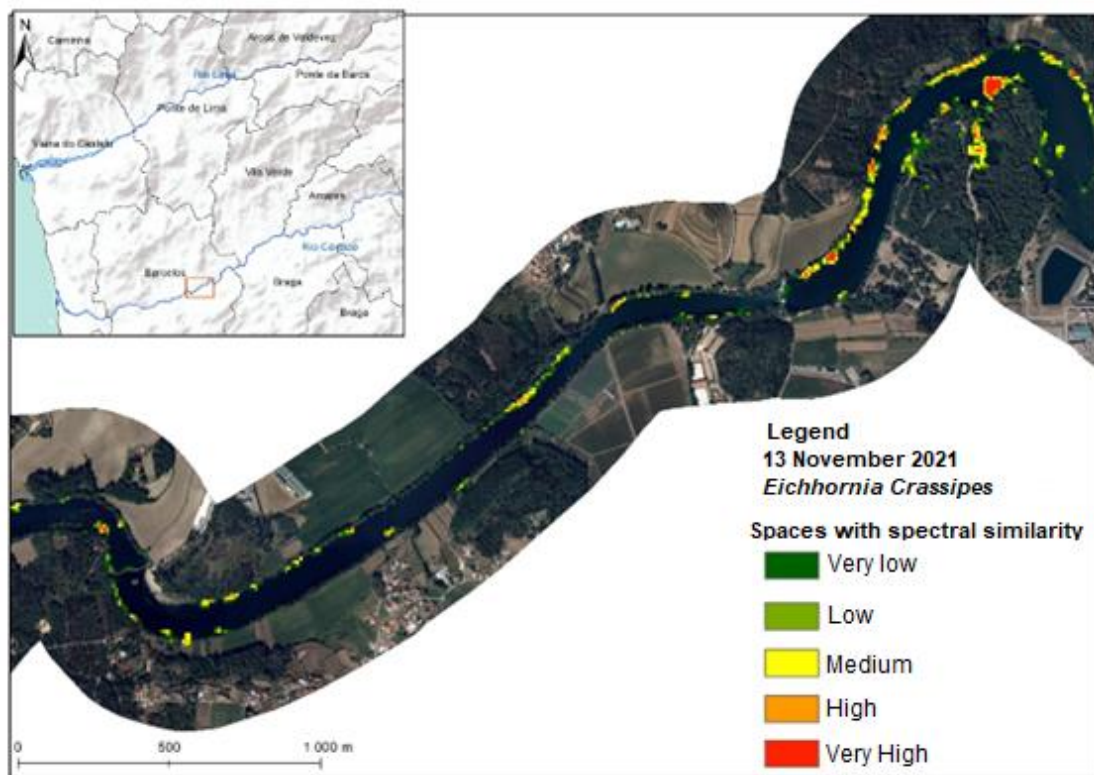


Figure 3.8 – Spatially explicit mapping of spaces with similar spectral reflectance to the Water hyacinth

4. Gaps and Way Forward

Mapping the distribution of Water hyacinth is possible due to the distinct spectral signals of the aquatic vegetation compared to the surrounding water and forest. The distinction between water hyacinth and other vegetation can prove challenging.

It can be said that in classifying water hyacinth from other landcover types, NIR and SWIR regions were selected as optimal bands. The same was found by the author (Dube et al., 2017), but using Landsat spectral information instead of sentinel, for distinguishing Water hyacinth from other land cover types.

Sentinel-2 images have a greater ground sampling distance (10 m) than Landsat 8 images (30m), which creates excellent opportunities for monitoring the expansion of this invasive species into rivers and narrower channels. Studies that use Sentinel data focus mainly on original bands at 10 m (Bands 2, 3, 4 and 8a) not exploiting the full potential of multispectral data. The applied methodology was able to represent the invasion patterns of the Water hyacinth in the study area revealing the potential to support regional to global policy initiatives focused on prevention, early detection, and monitoring of invasions.

Improvements in the results obtained can be achieved by resorting to non-free but very-high spatial resolution images such as RapidEye or WorldView-2/3. Something else that could improve our results would be to take a greater number of UAV flights to locate more areas with Water hyacinth, enabling us to collect more spectral curves overtime covering the full life cycle of the plant, which we may then use to better distinguish the species from its surroundings. Future studies can adapt this methodology for monitoring Water hyacinth to other locations or even for other AIAS. Being able to produce reliable, rapid, and accurate information without extensive user input would allow the proliferation of RS (Rowan & Kalacska, 2020) and when used appropriately, it is an innovative tool for policymakers and for environmental management, as it can be used to reduce the negative impacts, necessary resources, and costs by focusing and prioritizing the invaded regions.

5. Final Synthesis

The introduction of exotic species and their naturalization is considered one of the greatest threats to the structure and functioning of ecosystems, being a complex problem that needs answers at a multi-scalar level for decision making.

In the first study we tried to identify challenges and gaps and use the data as grounds for the second chapter. Based on the literature review, we examined the extent to which RS has been used to address the management of AIAS worldwide and despite the tremendous advances made in monitoring IAS using RS, this has yet to focused primarily on aquatic species.

Complementarily to advances in RS, new statistical and machine-learning algorithms allow to better exploit and profit from this data. Chapter 1 shows that the combination of both satellite image classification (for aquatic invasive species mapping/detection) and modelling has been rarely explored, furthermore, the scientific research on this topic is majorly for large water bodies like lakes and reservoirs due to the difficulties of mapping floating plants on moving and dynamic water bodies like rivers.

Considering this challenge and the results found previously, in chapter 2 was adopted a novel methodology, by combining unmanned aerial vehicle (UAV) and multispectral satellite imagery through biomod2 modelling, to create a combined supervised image classification of areas with similar spectral signatures to the macrophyte Water hyacinth. The methodology applied, overcomes the challenges of mapping floating aquatic species (over space and time) on a river allowing a better understanding of invasiveness patterns and ultimately safeguards ecological and economic values promoted by water resources.

The results show the ability to map in a resolution suitable for local decision-making processes invaded spaces. This demonstrates the potential of this methodology for the development of monitoring tools capable of contributing to increasingly accurate and efficient plans over time.

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Annex

A1. Additional information about the records found by Countries and Species

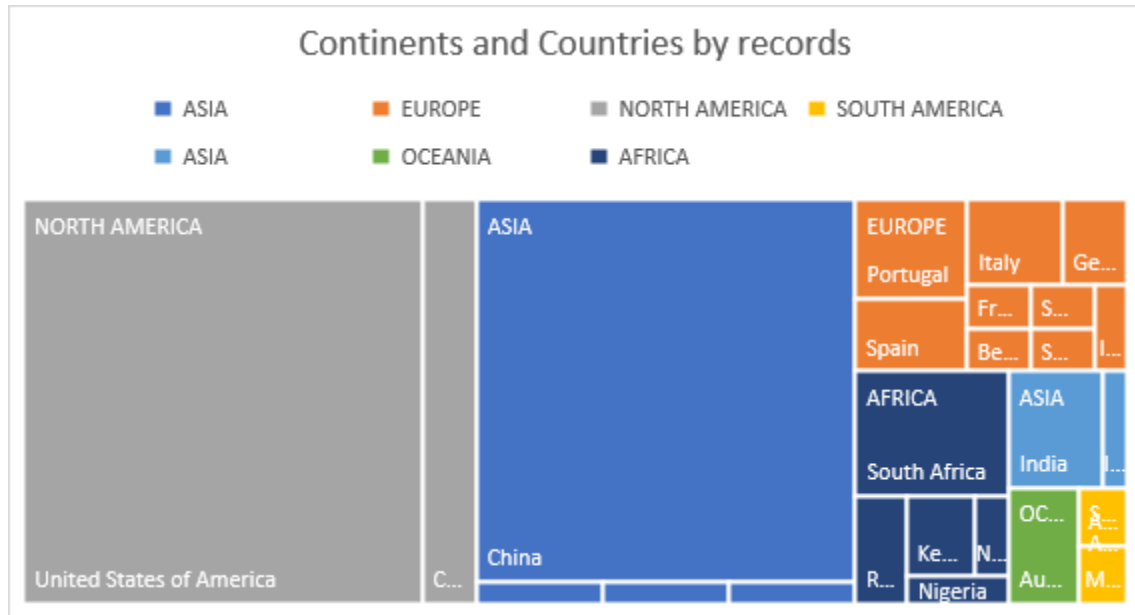


Figure A1.1 - Distribution of records across countries. The quantities are presented in different sizes of circles.

Table A1.1 – Number of records found, by Countries

Continent	Country	Records
NORTH AMERICA	United States of America	65
ASIA	China	57
NORTH AMERICA	Canada	10
AFRICA	South Africa	10
EUROPE	Portugal	5
EUROPE	Italy	5
EUROPE	Spain	4
ASIA	India	4
OCEANIA	Australia	3
EUROPE	Germany	2
EUROPE	France	2
AFRICA	Rwanda	2
AFRICA	Kenya	2
ASIA	Japan	1
ASIA	Nepal	1
ASIA	Sri-lanka	1
EUROPE	Belgium	1
EUROPE	Switzerland	1
EUROPE	Sweden	1
EUROPE	Ireland	1
SOUTH AMERICA	Argentina	1

SOUTH AMERICA	Mexico	1
SOUTH AMERICA	Brazil	1
ASIA	Iraq	1
AFRICA	Niger	1

Table A1.2 – Number of records by species, type and taxa.

Species	Number of Studies	Type	Taxa
<i>Spartina alterniflora</i>	63	Transitional S.	Plant
<i>Phragmites australis</i>	35	Transitional S.	Plant
<i>Eichhornia crassipes</i>	29	Water surface	Plant
<i>Egeria densa</i>	6	Submerged	Plant
<i>Scirpus mariqueter</i>	6	Transitional S.	Plant
<i>Typha angustifolia</i>	5	Transitional S.	Plant
<i>Tamarix ramosissima</i>	4	Transitional S.	Plant
<i>Trapa natans</i>	4	Water surface	Plant
<i>Ceratophyllum demersum</i>	3	Submerged	Plant
<i>Lepidium latifolium</i>	3	Transitional S.	Plant
<i>Lythrum salicaria</i>	3	Transitional S.	Plant
<i>Nelumbo nucifera</i>	3	Water surface	Plant
<i>Salvinia molesta</i>	3	Water surface	Plant
<i>Stratiotes</i> spp.	3	Water surface	Plant
<i>Tamarisk</i> spp.	3	Transitional S.	Plant
<i>Acacia Saligna</i>	2	Transitional S.	Plant
<i>Arundo donax</i>	2	Transitional S.	Plant
<i>Asparagopsis armata</i>	2	Submerged	Algae
<i>Codium fragile</i>	2	Submerged	Algae
<i>Dreissena</i> mussels	2	Submerged	Animal
<i>Elodea canadensis</i>	2	Submerged	Plant
<i>Eucalyptus globulus</i>	2	Transitional S.	Plant
<i>Hydrilla verticillata</i>	2	Submerged	Plant
<i>Hydrocharis morsus-ranae</i>	2	Water surface	Plant
<i>Ludwigia hexapetala</i>	2	Water surface	Plant
<i>Ludwigia</i> spp.	2	Water surface	Plant
<i>Najas marina</i>	2	Submerged	Plant
<i>Nymphoides peltata</i>	2	Water surface	Plant
<i>Pinus pinaster</i>	2	Transitional S.	Plant
<i>Populus</i> sp.	2	Transitional S.	Plant
<i>Potamogeton crispus</i>	2	Submerged	Plant
<i>Spartina anglica</i>	2	Transitional S.	Plant
<i>Suaeda salsa</i>	2	Transitional S.	Plant
<i>Tamarix chinensis</i>	2	Transitional S.	Plant
<i>Urochloa mutica</i>	2	Transitional S.	Plant
<i>Acacia Cyclops</i>	1	Transitional S.	Plant
<i>Acacia longifolia</i>	1	Transitional S.	Plant
<i>Acacia melanoxylon</i>	1	Transitional S.	Plant
<i>Acacia dealbata</i>	1	Transitional S.	Plant
<i>Agarophyton vermiculophyllum</i>	1	Submerged	Plant
<i>Alnus glutinosa</i>	1	Transitional S.	Plant
<i>Azolla africana</i>	1	Water surface	Plant
<i>Azolla filiculoides</i>	1	Water surface	Plant
<i>Cabomba caroliniana</i>	1	Submerged	Plant
<i>Chara</i> spp.	1	Submerged	Algae
<i>Cladophora</i>	1	Submerged	Algae
<i>Crassostrea gigas</i>	1	Submerged	animal
<i>Distichlis spicata</i>	1	Transitional S.	Plant
<i>Eleagnus ang.</i>	1	Transitional S.	Plant
<i>Elodea nuttallii</i>	1	Submerged	Plant

Eragrostis curvula	1	Transitional S.	Plant
Frangula alnus	1	Transitional S.	Plant
Gutierrezia sarothrae	1	Transitional S.	Plant
H. mantegazzianum	1	Transitional S.	Plant
Hakea	1	Transitional S.	Plant
Hydrocotyle ranunculoides	1	Water surface	Plant
Hypnea cornuta	1	Submerged	algae
I. glandulifera	1	Transitional S.	Plant
Juniperus ashei	1	Transitional S.	Plant
Lemna paucicostata	1	Water surface	Plant
Ludwigia peploides	1	Water surface	Plant
Myriophyllum aquaticum	1	Water surface	Plant
Myriophyllum spicatum	1	Submerged	Plant
Nelumbo lutea	1	Water surface	Plant
Neogobius melanostomus	1	Submerged	Animal
Nuphar advena	1	Water surface	Plant
Nypa fruticans	1	Transitional S.	Plant
Oncorhynchus mykiss	1	submerged	animal
Parthenium hysterophuros	1	Transitional S.	Plant
Polychaete	1	Submerged	Animal
Potamogeton nodosus	1	Submerged	Plant
Potamogeton spp.	1	Submerged	Plant
Reynoutria japonica	1	Transitional S.	Plant
Rhizophora mangle	1	Water surface	Plant
Salicornia virginica	1	Transitional S.	Plant
Salix spp.	1	Transitional S.	Plant

A2. Details on keyword selection and literature search procedure.

Table A2.1- Searches were performed considering a set of selected keywords. Search terms related to “invasive”, “aquatic environment” and “remote sensing” were compiled based on a list derived from a number of core references.

Search terms (set of keywords)	Number records
"Ecolog* invasion*" or "Invasion* biology*" or "Invasion* ecology*" or "Invasive species*" or "alien species*" or "introduced species*" or "non-native species*" or "nonnative species*" or "nonindigenous species*" or "non-indigenous species*" or "allochthonous species*" or "exotic species*" or "escaped species*" or "released species*" or "invader*" or "non-native plant"	50090
"aquatic*" or "marine*" or "river*" or "fluvial*" or "riparian*" or "macrophyte*" or "limno*" or "lentic*" or "freshwater*" or "watercourse*" or "coastal*" or "littoral*" or "estuari*" or "wetland"	1172256
"remote* sens*" OR "remote-sens*" OR "earth observation" OR "UAV" OR "drone" OR "unmanned aerial" OR "aircraft*" OR "airborne" OR "air-borne" OR "spaceborne" OR "space-borne" OR "AVHRR" OR "radiomet*" OR "high-resolution" OR "high resolution" OR "very-high resolution" OR "high spatial resolution" OR "very-high spatial resolution" OR "hyper-spectral" OR "hyperspectral" OR "multispectral" OR "multi-spectral" OR "image* fusion" OR "NDVI" OR "satellite*" OR "radar" OR "MODIS" OR "LiDAR" OR "sentinel*" OR "landsat*" OR "worldview*" OR "quickbird" OR "Hyperion" OR "Ikonos" OR "EnMAP" OR "Flex" OR "imagery" OR "sensor"	2510869

Table A2.2 - The final set of keywords relating to “invasive”, “aquatic environment” and “remote sensing” were combined with the string “AND”, used to perform the literature search in the field ‘title+abstract+keywords’ of ISI Web of Science and Scopus. Afterwards a google scholar search was done with the final resulting on 29 new articles from 50 total that was not found in the previous list of records under consideration.

Search terms (set of keywords)	Number records		
"Ecolog* invasion*" or "Invasion* biology*" or "Invasion* ecology*" or "Invasive species*" or "alien species*" or "introduced species*" or "non-native species*" or "nonnative species*" or "nonindigenous species*" or "non-indigenous species*" or "allochthonous species*" or "exotic species*" or "escaped species*" or "released species*" or "invader*" or "non-native plant*" AND "aquatic*" or "marine*" or "river*" or "fluvial*" or "riparian*" or "macrophyte*" or "limno*" or "lentic*" or "freshwater*" or "watercourse*" or "coastal*" or "littoral*" or "estuari*" or "wetland*" AND "remote* sens*" OR "remote-sens*" OR "earth observation" OR "UAV" OR "drone" OR "unmanned aerial" OR "aircraft*" OR "airborne" OR "air-borne" OR "spaceborne" OR "space-borne" OR "AVHRR" OR "radiomet*" OR "high-resolution" OR "high resolution" OR "very-high resolution" OR "high spatial resolution" OR "very-high spatial resolution" OR "hyper-spectral" OR "hyperspectral" OR "multispectral" OR "multi-spectral" OR "image* fusion" OR "NDVI" OR "satellite*" OR "radar" OR "MODIS" OR "LiDAR" OR "sentinel*" OR "landsat*" OR "worldview*" OR "quickbird" OR "Hyperion" OR "Ikonos" OR "EnMAP" OR "Flex" OR "imagery" OR "sensor"	SCOPUS	ISI	Google Scholar
	928	729	29/50

Search terms related to “Invasive” and respective number of retrieved records.

Table A2.3 - Search terms related to “invasive” and respective number of retrieved records.

Search terms	Number records
Ecolog* invasion*	116

Ecolog* invasion* or Invasion* biology	1000
Ecolog* invasion* or Invasion* biology or Invasion* ecology	1664
Ecolog* invasion* or Invasion* biology or Invasion* ecology or Invasive species	25001
Ecolog* invasion* or Invasion* biology or Invasion* ecology or Invasive species or Alien species	30026
Ecolog* invasion* or Invasion* biology or Invasion* ecology or Invasive species or Alien species or Introduced species	34027
Ecolog* invasion* or Invasion* biology or Invasion* ecology or Invasive species or Alien species or Introduced species or Non-native species	36421
Ecolog* invasion* or Invasion* biology or Invasion* ecology or Invasive species or Alien species or Introduced species or Non-native species or Nonnative species	36878
Ecolog* invasion* or Invasion* biology or Invasion* ecology or Invasive species or Alien species or Introduced species or Non-native species or Nonnative species or Nonindigenous species	37183
Ecolog* invasion* or Invasion* biology or Invasion* ecology or Invasive species or Alien species or Introduced species or Non-native species or Nonnative species or Nonindigenous species or Non-indigenous species	38067
Ecolog* invasion* or Invasion* biology or Invasion* ecology or Invasive species or Alien species or Introduced species or Non-native species or Nonnative species or Nonindigenous species or Non-indigenous species or allochthonous species	38163
Ecolog* invasion* or Invasion* biology or Invasion* ecology or Invasive species or Alien species or Introduced species or Non-native species or Nonnative species or Nonindigenous species or Non-indigenous species or allochthonous species or Exotic species	43128
Ecolog* invasion* or Invasion* biology or Invasion* ecology or Invasive species or Alien species or Introduced species or Non-native species or Nonnative species or Nonindigenous species or Non-indigenous species or allochthonous species or Exotic species or Escaped species	43128
Ecolog* invasion* or Invasion* biology or Invasion* ecology or Invasive species or Alien species or Introduced species or Non-native species or Nonnative species or Nonindigenous species or Non-indigenous species or allochthonous species or Exotic species or Escaped species or Released species	43204
Ecolog* invasion* or Invasion* biology or Invasion* ecology or Invasive species or Alien species or Introduced species or Non-native species or Nonnative species or Nonindigenous species or Non-indigenous species or allochthonous species or Exotic species or Escaped species or Released species or Invader*	49660
Ecolog* invasion* or Invasion* biology or Invasion* ecology or Invasive species or Alien species or Introduced species or Non-native species or Nonnative species or Nonindigenous species or Non-indigenous species or allochthonous species or Exotic species or Escaped species or Released species or Invader* or Non-native plant*	50090

Table A2.4 - Search terms related to “Aquatic environment” and respective number of retrieved records.

Search terms	Number records
Aquatic*	146390
Aquatic* or marine*	528562
Aquatic* or marine* or river*	892112
Aquatic* or marine* or river* or Fluvial*	901994
Aquatic* or marine* or river* or Fluvial* or riparian*	911545
Aquatic* or marine* or river* or Fluvial* or riparian* or macrophyte*	911550
Aquatic* or marine* or river* or Fluvial* or riparian* or macrophyte* or limno*	917753
Aquatic* or marine* or river* or Fluvial* or riparian* or macrophyte* or limno* or lentic*	917756
Aquatic* or marine* or river* or Fluvial* or riparian* or macrophyte* or limno* or lentic* or freshwater*	972313
Aquatic* or marine* or river* or Fluvial* or riparian* or macrophyte* or limno* or lentic* or freshwater* or watercourse*	973879
Aquatic* or marine* or river* or Fluvial* or riparian* or macrophyte* or limno* or lentic* or freshwater* or watercourse* or Coastal*	1111744
Aquatic* or marine* or river* or Fluvial* or riparian* or macrophyte* or limno* or lentic* or freshwater* or watercourse* or Coastal* or Littoral	1122899
Aquatic* or marine* or river* or Fluvial* or riparian* or macrophyte* or limno* or lentic* or freshwater* or watercourse* or Coastal* or Littoral or Estuari*	1136476
Aquatic* or marine* or river* or Fluvial* or riparian* or macrophyte* or limno* or lentic* or freshwater* or watercourse* or Coastal* or Littoral or Estuari* or Wetland*	1172256

Table A2.5 - Search terms related to “remote sensing” and respective number of retrieved records.

Search terms	Number records
Remote* sens*"	145433
Remote* sens*"" or remote-sens*	145433
Remote* sens*"" or remote-sens* or earth observation	150756
Remote* sens*"" or remote-sens* or earth observation or UAV	177866
Remote* sens*"" or remote-sens* or earth observation or UAV or drone	184218
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial	192004
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft*	286708
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne	352149
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne	353961
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne	359853
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne	363190
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR	368184
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet*	404827
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution	819258

Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution	819258
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution	819258
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution	838043
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution	838043
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution or hyper-spectral	838949
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution or hyper-spectral or hyperspectral	857630
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution or hyper-spectral or hyperspectral or multispectral	868221
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution or hyper-spectral or hyperspectral or multiespectral or multi-spectral	870651
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution or hyper-spectral or hyperspectral or multiespectral or multi-spectral or image* fusion	878613
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution or hyper-spectral or hyperspectral or multiespectral or multi-spectral or image* fusion or NDVI	885745
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution or hyper-spectral or hyperspectral or multiespectral or multi-spectral or image* fusion or NDVI or satellite	1117757
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution or hyper-spectral or hyperspectral or multiespectral or multi-spectral or image* fusion or NDVI or satellite or radar	1231389
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution or hyper-spectral or hyperspectral or multiespectral or multi-spectral or image* fusion or NDVI or satellite or radar or MODIS	1235299

Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution or hyper-spectral or hyperspectral or multispectral or multi-spectral or image* fusion or NDVI or satellite or radar or MODIS or LiDAR	1254476
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution or hyper-spectral or hyperspectral or multispectral or multi-spectral or image* fusion or NDVI or satellite or radar or MODIS or LiDAR or sentinel	1293184
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution or hyper-spectral or hyperspectral or multispectral or multi-spectral or image* fusion or NDVI or satellite or radar or MODIS or LiDAR or sentinel or landsat*	1298431
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution or hyper-spectral or hyperspectral or multispectral or multi-spectral or image* fusion or NDVI or satellite or radar or MODIS or LiDAR or sentinel or landsat* or worldview	1310422
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution or hyper-spectral or hyperspectral or multispectral or multi-spectral or image* fusion or NDVI or satellite or radar or MODIS or LiDAR or sentinel or landsat* or worldview or quickbird	1310491
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution or hyper-spectral or hyperspectral or multispectral or multi-spectral or image* fusion or NDVI or satellite or radar or MODIS or LiDAR or sentinel or landsat* or worldview or quickbird or Hyperion	1311677
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution or hyper-spectral or hyperspectral or multispectral or multi-spectral or image* fusion or NDVI or satellite or radar or MODIS or LiDAR or sentinel or landsat* or worldview or quickbird or Hyperion or Ikonos	1311765
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution or hyper-spectral or hyperspectral or multispectral or multi-spectral or image* fusion or NDVI or satellite or radar or MODIS or LiDAR or sentinel or landsat* or worldview or quickbird or Hyperion or Ikonos or EnMAP	1311770
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution or hyper-spectral or hyperspectral or multispectral or multi-spectral or image* fusion or NDVI or satellite or radar or MODIS or LiDAR or sentinel or landsat* or worldview or quickbird or Hyperion or Ikonos or EnMAP or Flex	1318732
Remote* sens*"" or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne ora ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution or hyper-spectral or hyperspectral or multispectral or multi-spectral or image* fusion or NDVI or satellite or radar	1367564

or MODIS or LiDAR or sentinel or landsat* or worldview or quickbird or Hyperion or Ikonos or EnMAP or Flex or imagery	
Remote* sens* or remote-sens* or earth observation or UAV or drone or unmanned aerial or aircraft* or airborne or ir-borne or spaceborne or space-borne or AVHRR or radiomet* or high-resolution or high resolution or very-high resolution or high spatial resolution or very-high spactial resolution or hyper-spectral or hyperspectral or multiespectral or multi-spectral or image* fusion or NDVI or satellite or radar or MODIS or LiDAR or sentinel or landsat* or worldview or quickbird or Hyperion or Ikonos or EnMAP or Flex or imagery or sensor*	2510869

Table A2.6 – Selection of keywords used on the search engines SCOPUS, ISI WEB of Science and Google Scholar.

Invasive species related	Refs	Environment related	Refs	Remote sensing related	Refs	
Ecolog* invasion*	Buchadas et al. 2017	aquatic*	expert knowledge	Earth observation*	Vaz et al. 2018	
Invasion* biology		marine*		Satellite data	Thamaga et al. 2017	
Invasion* ecology		river*		Monitoring		
Invasive species		Fluvial*		Cloud computing	Singh et al. 2020	
Alien species		riparian*		Machine learning		
Introduced species		macrophye*		Mapping		
Non-native species		limno*		Remote sensing		
Nonnative species		lenthic*		Satellite		
Nonindigenous species		freshwater*		Soil-adjusted vegetation index	Ghoussein el al. 2019	
Non-indigenous species		watercourse*		Sentinel-2		
allochthonous species		Coastal	Brando et al. 2007	Water spectral library	Cavalli et al. 2007	
Exotic species				Water compound map		
Released species				Sentinel-1	Rajah et al. 2018	
Escaped species			Littoral	Vegetation Indices		
Invader*				Support Vector Machine		
Non-native plant*		Vaz et al. 2018	Estuari*	Klemas V., 2011	Hyperspectral imaging	Rowan et al. 2020
Invasion effect			Wetland*		Extent mapping	
Ecosystem service		Ta et al. 2017			Species discrimination	Song et al. 2020
Invasive species management	Unmanned aircraft vehicle					
Biological control	Vegetation index					
Ecosystem engineers	GIS					
Aquatic vegetation	Multi-spectral					
Submerged aquatic vegetation	Rowan et al. 2020	Accuracy Assessment			Alwan et al. 2019	
Aquatic weed*	Thamaga et al. 2017	Open source				
Control mechanisms		Airborne sensors			Bostater et al. 2009	
Eutrophication		Airborne imagery				
Aquatic plants		Hyperspectral sensing				
Eichhornia crassipes	Singh et al. 2020	Multispectral imagery				
Invasive weed*		Hyperspectral remote sensing			Bostater et al. 2017	
Alien species invasions	Rajah et al. 2018	Underwater detection				
Managment	Brando et al. 2007	Synthetic images				
Macrophyte control	Jia et al. 2016	Simulation				
Trophic status	Han et al. 2019	Water surface reflectance				
Plant height		Chlorophyll absorption				
		Bottom reflectance				
		Remote sensing algorithms				
		Remote sensing extraction			Yu et al. 2018	
		WorldView-2			Zheng et al. 2017	
		Water depth				

	Multispectral	Kovacs et al. 2008
	Classification	
	Landsat	
	Hyperspectral reflectance	Everitt et al. 2011
	Spectral signature	
	Ecological niche modelling	He et al. 2015
	Habitat suitability modelling	
	Hyperspectral and multispectral data	
	LidAR and Radar metrics	
	LidAR metrics	
	Radar metrics	
	Predictor and response variables	
	Predictor variables	
	Response variables	
	Spatial resolution	
	Temporal resolution	
	Spatial and temporal resolution	
	NDVI	Cho et al. 2008
	SAV	
	Machine learning	Han et al. 2019
	UAV	
	Spectral unmixing	Heblinski et al. 2010
	Photo interpretation	Madden M., 2004
	Satellite imagery	
	Geographic Information System	
	GPS	
	Global Positioning System	
	Light detection and ranging	
	MODIS	
	Moderate resolution Imaging Spectroradiometer	
	PAN	
	Panchromatic	
	Landsat TM	Nelson et al. 2006
	Water-column correction	Niroumand-Jadidi et al. 2019
	Spectroscopy	
	WorldView-3	
	High spatial resolution	O'Neill et al. 2013
	Hyperspectral reflectance	Robles et al. 2015

