SATELLITE IMAGERY IN WATER MANAGEMENT AND LAND USE

INTERNATIONAL PHD DISSERTATION

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Satellite imagery in water management and land use

Teledetección para la gestión del agua y uso del suelo

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An electronic version of this PhD Dissertation is available at: https://gredos.usal.es/

Supervisors' report regarding the Doctoral Thesis

Satellite imagery in water management and land use

Presented at the

Department of Cartographic and Land Engineering

By the PhD candidate

Laura Piedelobo Martín

The Doctoral Thesis *"Satellite imagery in water management and land use"*, presented by Laura Piedelobo Martín, represents a clear case of success to bridge remote sensing and stakeholders' needs into products that help in policy and decision-making, namely in water management and land use applications.

Remote sensing is an invaluable tool when direct measurements are difficult or impossible to perform and lack of knowledge results in costly expenditures, long delays or even wrong decisions. The evolution of optical remote sensing over the past few decades has enabled the availability of rich spatial, spectral and temporal information to remote sensing analysts, without forgetting its non-invasive and non-destructive character. In this way, the present Doctoral Thesis has been developed in response to two research questions: *"Which biophysical parameters are available as full, open and free?"* and *"How can biophysical parameters interpretation and local stakeholder needs be bridged?"*. To advance in both directions, this Doctoral Thesis combines deep theoretical studies with the development of practical tools, allowing a better comprehension of the freely available Copernicus products and their suitability to monitor the environment, specifically regarding water management and land use. The research is steps forward to the development of the Copernicus downstream sector in Europe.

Likewise, this Doctoral Thesis represents a line of research promoted and developed by the TIDOP Research Group (http://tidop.usal.es/) of the University of Salamanca, which is researching and developing software and hardware tools within competitive projects and in collaboration with other research groups and leading companies at national and international level. Specifically, this line is a topic of interest for the research group led by Dr. Andrea Taramelli, who is a well-known researcher in the field of remote sensing techniques applied to the monitoring and study of natural surfaces through multitemporal and multispectral analyses and the Italian National Delegate at the EU Copernicus User Forum for Operational Core Services Implementation.

As a result, Laura Piedelobo Martín conducted an eight-and-a-half-month-long research stay at the Institute for Environmental Protection and Research (ISPRA) in Rome. It is a reference centre worldwide, with great collaboration in European and international projects, mainly producing and validating Copernicus products annually for the Directorate-General for Defence Industry and Space (DG-DEFIS) of the European Commission.

The valuable results obtained through the development of this Doctoral Thesis pave the way to the publication of four scientific articles, all subjected to anonymous peer-review and currently published in prestigious journals in the field of remote sensing and agriculture. The journals are indexed in Journal Citation Report (JCR) database and some are the first of their category. It is also noteworthy that the results derived an intellectual property (HidroMap©), which highlights the research, implementation and knowledge-transfer capabilities of Laura Piedelobo Martín.

This Doctoral Thesis is completed with a proper section of conclusions and future perspectives in which the major contributions and recommendations for future works are precisely specified in order to complement this work, being fully integrated into the research line. Accordingly, this Doctoral Thesis brings the cutting edge in remote sensing and exploitation research closer to stakeholders of remote sensing technology. It will be a valuable reference to graduate students and researchers in the academia and the industry who are interested in keeping abreast with the current state-of-the-art, remote sensing techniques and its connection with Copernicus program.

Given the conditions put forward, the supervisors consider that the present Doctoral Thesis is suitable for submission and public defence in the form of *"Compendium of Publications"* and with *"International Mention"* since it presents more than sufficient original results according to the requirements and regulations established by the University of Salamanca in this regard. In witness whereof, this certificate has been signed.

Ávila, 10th July 2020

Prof. Dr. Diego González Aguilera

Dr. José Luis Molina González

Dr. Andrea Taramelli

List of publications

This Doctoral Thesis consists of a compendium of four scientific papers published in international journals of high impact factor, in accordance with the Doctoral Regulations of the University of Salamanca. The articles are the following:

I. Monitoring Green Infrastructure for Natural Water Retention Using Copernicus Global Land Products

Andrea Taramelli[1,2], Michele Lissoni[1], Laura Piedelobo[3], Emma Schiavon[1], Emiliana Valentini[2], Alessandra Nguyen Xuan[2] and Diego González-Aguilera[3]

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This article belongs to the Special Issue *EO Based Environmental Mapping Services: Matching Agriculture, Urban Areas and Protected Areas Information Needs*.

II. HidroMap: A New Tool for Irrigation Monitoring and Management Using Free Satellite Imagery

Laura Piedelobo[1], Damián Ortega-Terol[1], Susana Del Pozo[1], David Hernández-López[2], Rocío Ballesteros[1], Miguel A. Moreno[3], José-Luis Molina[1] and Diego González-Aguilera[1]

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This article belongs to the Special Issue *Free and Open Source Tools for Geospatial Analysis and Mapping*.

III. Scalable pixel-based crop classification combining Sentinel-2 and Landsat-8 data time series: Case study of the Duero river basin

Laura Piedelobo[1], David Hernández-López[2], Rocío Ballesteros[1], Amal Chakhar[2], Susana Del Pozo[1], Diego González-Aguilera[1], Miguel A. Moreno[3]

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Agricultural Systems **2019**, 171, 36-50

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IV. Assessment of Green Infrastructure in Riparian Zones Using Copernicus Programme

Laura Piedelobo[1], Andrea Taramelli[2,3], Emma Schiavon[2], Emiliana Valentini[3], José-Luis Molina[1], Alessandra Nguyen Xuan[3] and Diego González-Aguilera[1]

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To my yayo Beni,

Wish I could hug you one more time.

"We can't solve problems by using the same kind of thinking we used when we created them".

Albert Einstein

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To my warrior, Hugo de Rijke: There are no words to express your incredible support, not only to this work but as an inflexion point in my life. Thanks for fighting with me in our battlefield.

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Abstract

Earth's ecosystems are constantly changing due to the existing nature and atmospheric conditions and the pressure of human activities. Monitoring the environment and its condition helps to convert the feedback loop that exists between climate change impacts, ecosystem degradation and increased disaster risk. The interpretation of remotely-sensed biophysical parameters can substitute or complement classical vegetation monitoring methods (e.g., field surveys, photointerpretation or analysis of ancillary data). Using solely traditional techniques is not sufficiently effective to acquire vegetation dynamics, neither in long-term studies nor in large areas, since such techniques are time-consuming, outdated and frequently expensive. The launch of the Sentinel-2 (S2) B satellite platform, developed and operated by the European Space Agency (ESA), in March 2017 has allowed the Scientific Community to get freely high-resolution multispectral data every five days. The Multispectral Instrument sensor (MSI) on-board S2 has overcome the characteristics of the traditionally used Landsat series of Earth Observation (EO), operated jointly by the National Aeronautics and Space Administration (NASA) and the United States Geological Survey (USGS). As of January 2020, the European Commission Directorate-General for Defence Industry and Space (DG-DEFIS) is created to develop and consolidate all European Union (EU) space-related activities into one EU Space Programme, ensuring its global leadership in the space domain.

Part I introduces the state-of-the-art, motivation and objectives of this Doctoral Thesis. It presents the two research questions of this work: *"Which biophysical parameters are available as full, open and free?"* (responded by Part II) and *"How can biophysical parameters interpretation and local stakeholder needs be bridged?"* (responded by Part III). The first question conveys a better comprehension of the freely available products of biophysical parameters and their suitability to monitor the environment. The second question focuses on interpreting vegetation and water indices, calculated with open high-resolution multispectral satellite data, to address local stakeholder needs, with an emphasis on meeting European policies, namely the Common Agricultural Policy (CAP), the Water Framework Directive (WFD) and the 2020 Biodiversity Strategy (BS).

Part II outlines the availability of already processed and qualified products of bio-geophysical indices in Copernicus: the full, open and free EU EO and monitoring programme. Copernicus programme is comprised of three components: space, service and in-situ. The products of bio-geophysical indices are accessible inside the Copernicus Global Land Service (CGLS) and cover the world every 10 days at medium-to-low spatial resolutions. The analysis focuses on Natural Water Retention Measures (NWRM) due to their wide range of potential Ecosystem Services (ES), such as protection against natural hazards (e.g., floods or droughts), which contribute to achieving policy goals. The products' suitability to monitor NWRM and their benefits is evaluated through a scientific review. Simple flow diagrams are designed to

advice end-users, depending on the NWRM and/or benefit to monitor, on the index to use and the expected quality of the product in CGLS. Among traditional indices, the Normalized Difference Vegetation Index (NDVI) emerges as the most suitable and qualified.

CGLS products' coarse spatial resolution of 300 m and 1 km is a significant handicap. Local studies need higher resolution satellite-based data. Therefore, **Part III** of this Doctoral Thesis intends to bridge satellite remote sensing and local stakeholder needs in order to attain the aforementioned European policies. The case studies selected are the largest river basins in Spain and Italy: Duero and Po, respectively. Open-source satellite-based tools and approaches are developed with the following aims: (i) enhancing the monitoring of agricultural water use and crop types, and (ii) mapping and assessment of ecosystems and their services. The tools are potentially adaptable to new needs, other basins and European-to-global scales.

NDVI values, calculated with S2 MSI data, are used as the main input. NDVI single values are used to characterise vegetation healthiness and vigorousness whereas intra-annual signatures allow for differentiating vegetation types. The fusion of S2 with other satellite-based data is also examined: (i) in Duero river basin, with the Landsat-8 (L8) Operational Land Imager (OLI), to increase the temporal resolution of the input dataset and hence the possibility of using cloud-free images; (ii) in Po river basin, with Copernicus local datasets that define riparian zones and Natura 2000 sites in harmonised pan-European products.

The complementary desktop-GIS and web-GIS tools, developed for the Duero Hydrographic Confederation (HidroMap© software), use NDVI values and spatial information (i.e., parcel delimitations, irrigation rights, land use and unauthorised areas for irrigation) to automatically detect irrigated agricultural plots without irrigation rights. Higher priority is given to larger irrigated surfaces in water scarce areas, which are unauthorised for irrigation (WFD). Moreover, crop classification is performed automatically using Ensemble Bagged Trees (EBT). EBT is a machine learning classifier whose efficiency and accuracy have been increased by dividing the area in agro-climatic spatial regions and applying agro-climatic filters to the NDVI input dataset. The tools are currently used by the Hydrological Planning Office (HPO) and the River Surveillance Agency (RSA) to develop water management strategies accordingly and to plan surveillance visits efficiently.

As for Po river basin, the developed approach improves the applicability of the local Copernicus product of Riparian Zones to identify NWRM, detect their capacity to deliver regulative ES and assess their condition. NWRM's condition is interpreted using ES condition indicators defined by the European Environment Agency's (EEA) initiative on Mapping and Assessment of Ecosystems and their Services (MAES). The selected indicators are assessed through satellite remote sensing. The NDVI is complemented with the Enhanced Vegetation Index (EVI) and the Normalized Difference Water Index (NDWI) to interpret greening response and water stress, which define ecosystems' functional attributes. The model detects

NWRM's need of restoration and can thereby help policy and decision makers in planning environmental management strategies accordingly.

As reported in **Part IV**, this Doctoral Thesis proves the potential of remotely-sensed biophysical parameters to contribute to environmental policy and decision-making. Furthermore, the developed tools and approaches address decision makers' needs on data availability, possibility to monitor over time and access to high-spatial-resolution data. Firstly, HidroMap© has proved to help the HPO and the RSA of the Duero Hydrographic Confederation with monitoring agricultural water use and crop types, thereby accomplishing the CAP and the WFD. Secondly, the developed NWRM model helps the Member States of the EU with the mapping and assessment of ecosystems and their services, thereby accomplishing Action 5 of the 2020 BS: *"Improve knowledge of ecosystems and their services in the EU"*. Achieving these policy objectives contributes to the sustainable use of natural resources, effective spatial planning actions, Climate Change Adaptation (CCA) and mitigation actions, and Disaster Risk Reduction (DRR) and protection.

Finally, the importance of bringing together a wide array of representatives involved in EO research and environmental and socio-economic policies (e.g., scientists, end-users, public service bodies, industries and policy and decision makers) is outlined. This has been demonstrated through the successful application of EO-based tools to policy and decision making, bridging satellite remote sensing and stakeholders' needs. The final goal is maximising the benefits enabled by Copernicus data, services and downstream services. Such an approach shall allow for the development of an interdisciplinary EU EO Strategy that addresses evolving societal demands.

Resumen

Los ecosistemas de la Tierra están constantemente cambiando a consecuencia de las actuales condiciones naturales y atmosféricas y de la presión ejercida por las actividades humanas. Monitorizar el medio ambiente y su estado ayuda a transformar el círculo vicioso que existe entre los impactos derivados del cambio climático, la degradación del ecosistema y el aumento del riesgo de desastres. La interpretación de parámetros biofísicos obtenidos por teledetección puede suplir o complementar los métodos clásicos de monitorización de la vegetación (ej., visitas de campo, fotointerpretación o análisis de datos auxiliares). El uso exclusivo de técnicas tradicionales no resulta lo suficientemente eficaz para adquirir la dinámica de la vegetación, ni en estudios a largo plazo ni en grandes áreas, pues se trata de técnicas laboriosas, anticuadas y frecuentemente costosas. El lanzamiento de la plataforma satelital Sentinel-2 (S2) B, desarrollada y operada por la Agencia Espacial Europea (ESA), en marzo de 2017 ha permitido a la Comunidad Científica obtener de forma gratuita datos multiespectrales de alta resolución cada cinco días. El sensor Multiespectral (MSI) a bordo de S2 ha superado las características de la tradicionalmente utilizada familia de satélites de Observación de la Tierra (OT) Landsat, operada conjuntamente por la Administración Nacional de Aeronáutica y del Espacio (NASA) y el Servicio Geológico de Estados Unidos (USGS). En Enero de 2020, la Dirección General de Industria de Defensa y Espacio de la Comisión Europea (DG-DEFIS) ha sido creada para desarrollar y consolidar todas las actividades de la Unión Europea (UE) relacionadas con el espacio dentro de un único Programa Espacial Europeo, asegurándose el liderazgo en el ámbito espacial a nivel global.

La **Parte I** introduce el estado del arte, la motivación y los objetivos perseguidos en esta Tesis Doctoral. Presenta las dos preguntas de investigación en que se ha basado este trabajo: *"¿Qué parámetros biofísicos están disponibles como productos completos, abiertos y gratuitos?"* (respondida por la Parte II) y *"¿Cómo vincular la interpretación de parámetros biofísicos y las necesidades de los agentes interesados a nivel local?"* (respondida por la Parte III). La primera pregunta transmite una mejor comprensión de los productos de parámetros biofísicos disponibles de forma gratuita y de su idoneidad para monitorizar el medio ambiente. La segunda pregunta se centra en la interpretación de índices de vegetación y de agua, calculados con datos satelitales multiespectrales abiertos de alta resolución, con el objetivo de abordar las necesidades de los agentes interesados a nivel local, poniendo énfasis en el cumplimiento de políticas europeas, concretamente la Política Agrícola Común (PAC), la Directiva Marco del Agua (DMA) y la Estrategia de Biodiversidad 2020 (BS).

La **Parte II** destaca la disponibilidad de productos ya procesados y cualificados de índices bio-geofísicos en Copernicus: el programa europeo completo, abierto y gratuito de OT. El programa Copernicus consta de tres componentes: espacial, servicio e in-situ. Los productos de índices bio-geofísicos están disponibles dentro del Servicio Global de Monitorización de la Tierra (CGLS) y cubren el mundo cada 10 días con resoluciones espaciales medias a bajas. El

análisis se centra en las Medidas Naturales de Retención de Agua (NWRM) debido a la amplia gama de Servicios Ecosistémicos (ES) potencialmente proporcionados, como la protección frente a riesgos naturales (ej., inundaciones o sequías), contribuyendo a lograr objetivos políticos. La idoneidad de los productos para monitorizar NWRM y sus beneficios se ha evaluado mediante una revisión científica. Diagramas de flujo sencillos se han diseñado para orientar a los usuarios finales de los productos, dependiendo de la NWRM y/o beneficio a monitorizar, sobre el índice bio-geofísico adecuado y la calidad que se puede esperar del producto en CGLS. Los índices bio-geofísicos tradicionales, especialmente el Índice de Vegetación de Diferencia Normalizada (NDVI), sobresalen por su idoneidad y calidad.

La baja resolución espacial de los productos en CGLS, de 300 m y 1 km, representa una desventaja significativa. Los estudios a nivel local requieren de datos satelitales de mayor resolución. Por ello, la **Parte III** de esta Tesis Doctoral pretende vincular la teledetección satelital y las necesidades de los agentes interesados a nivel local con objeto de cumplir las políticas europeas mencionadas anteriormente. Los casos de estudio seleccionados son las cuencas hidrográficas más grandes de España e Italia, correspondientes a los ríos Duero y Po, respectivamente. Las herramientas y enfoques desarrollados, basados en dato satelital y código abiertos, persiguen los siguientes objetivos: (i) mejorar la monitorización del uso del agua en agricultura y del tipo de cultivos, y (ii) mapeado y evaluación de los ecosistemas y sus servicios. Las herramientas son potencialmente adaptables a nuevas necesidades, otras cuencas y escalas europea a global.

Los valores de NDVI, calculados con datos del sensor MSI de S2, son utilizados como principal dato de entrada. Los valores de NDVI son utilizados individualmente para caracterizar la salud y vigor de la vegetación en un momento determinado, mientras que las firmas anuales permiten diferenciar los tipos de vegetación. La fusión de S2 con otros datos satelitales también es estudiada: (i) en la cuenca hidrográfica del Duero, con datos del sensor *Operational Land Imager* (OLI) de Landsat 8 (L8), para aumentar la resolución temporal del conjunto de datos de entrada y, con ello, la posibilidad de utilizar imágenes sin nubes; (ii) en la cuenca hidrográfica del Po, con conjuntos de datos locales de Copernicus que definen zonas de ribera y la red Natura 2000 en productos paneuropeos armonizados.

Las herramientas de Sistemas de Información Geográfica (SIG) de escritorio y web, desarrolladas complementariamente para la Confederación Hidrográfica del Duero (software HidroMap©), utilizan valores de NDVI e información espacial (delimitaciones de parcelas, derechos de riego, uso del suelo y áreas no autorizadas para el riego) para detectar automáticamente parcelas agrícolas regadas sin derecho de riego. Se da mayor prioridad a las superficies regadas más grandes localizadas en áreas con escasez de agua, no autorizadas para el riego (DMA). Además, la clasificación de cultivos se realiza automáticamente utilizando *Ensemble Bagged Trees* (EBT). EBT es un clasificador de aprendizaje automático cuya eficiencia y precisión se han incrementado dividiendo la cuenca en regiones espaciales agroclimáticas y aplicando filtros agroclimáticos al conjunto de datos de entrada de NDVI. Actualmente, la Oficina de Planificación Hidrológica (OPH) y la Comisaría de Aguas (CA) utilizan las herramientas para, de acuerdo con los resultados, desarrollar estrategias de gestión del uso del agua y planificar eficientemente las visitas de la guardería fluvial.

En cuanto a la cuenca hidrográfica del Po, el enfoque desarrollado mejora la aplicabilidad del producto local de Copernicus de Zonas de Ribera para identificar NWRM, detectar su capacidad para ofrecer ES de regulación y evaluar la condición en que se encuentran. La condición de las NWRM se interpreta utilizando los indicadores de condición de ES definidos por la iniciativa de la Agencia Europea del Medio Ambiente (EEA) sobre Mapeado y Evaluación de los Ecosistemas y sus Servicios (MAES). Los indicadores seleccionados se evalúan mediante teledetección satelital. El NDVI se complementa con el Índice de Vegetación Mejorado (EVI) y el Índice de Agua de Diferencia Normalizada (NDWI) para interpretar la respuesta ecológica y de estrés hídrico, que definen atributos funcionales del ecosistema. El modelo generado detecta la necesidad de restauración que presentan las NWRM y, por tanto, puede ayudar a responsables políticos y de toma de decisiones a planificar estrategias de gestión ambiental conformemente.

Como se concluye en la **Parte IV**, esta Tesis Doctoral demuestra el potencial de los parámetros biofísicos obtenidos por teledetección para contribuir a la política y a la toma de decisiones a nivel ambiental. Además, las herramientas y enfoques desarrollados abordan necesidades de los responsables de la toma de decisiones en cuanto a la disponibilidad de los datos, posibilidad de monitorizar a largo plazo y accesibilidad a datos de alta resolución espacial. En primer lugar, el software HidroMap© ha demostrado ayudar a la OPH y la CA de la Confederación Hidrográfica del Duero a monitorizar el uso del agua en agricultura y los tipos de cultivo, cumpliendo con la PAC y la DMA. En segundo lugar, el modelo desarrollado de NWRM ayuda a los Estados Miembros de la UE con el mapeado y evaluación de los ecosistemas y sus servicios, cumpliendo la Acción 5 de la BS 2020: *"Mejorar el conocimiento de los ecosistemas y sus servicios en la UE"*. El logro de estos objetivos políticos contribuye al uso sostenible de los recursos naturales, medidas efectivas de planificación espacial, medidas de adaptación y mitigación del cambio climático, y a la reducción y protección frente al riesgo de desastres.

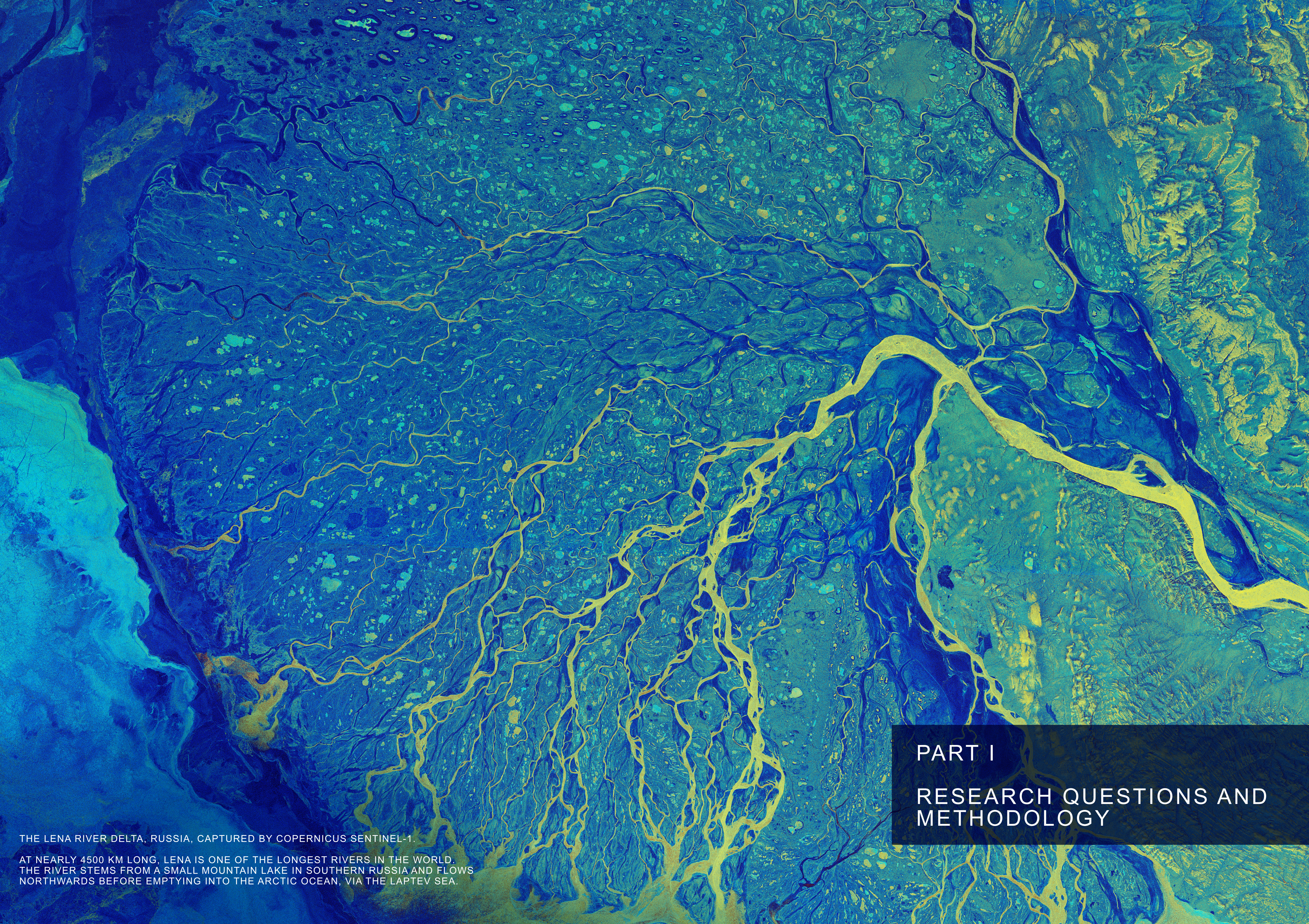
Finalmente, se destaca la importancia de reunir a una amplia gama de representantes involucrados en la investigación de OT y en políticas ambientales y socioeconómicas (ej., científicos, usuarios finales, organismos de servicio público, industrias, responsables de la toma de decisiones y de la elaboración de políticas). La relevancia de esta colaboración se ha demostrado a través de la aplicación exitosa de herramientas basadas en OT para la toma de decisiones y elaboración de políticas o estrategias, vinculando la teledetección satelital y las necesidades de los agentes interesados. El objetivo final es maximizar los beneficios de los datos y servicios del programa Copernicus. Este enfoque permitirá el desarrollo de una estrategia interdisciplinaria de OT en la UE que aborde demandas sociales evolutivas.

Acronyms

The most common acronyms and abbreviations according to scientific literature are used in the text and listed hereunder.

ARVI	Atmospherically Resistant Vegetation Index
B	Blue
BOA	Bottom-Of-Atmosphere
BS	Biodiversity Strategy
CAP	Common Agricultural Policy
CCA	Climate Change Adaptation
CGLS	Copernicus Global Land Service
CICES	Common International Classification of Ecosystem Services
CLC	Corine Land Cover
CLLS	Copernicus Local Land Service
CLMS	Copernicus Land Monitoring Service
CNES	*Centre National d'Études Spatiales*
DG-DEFIS	European Commission Directorate-General for Defence Industry and Space
DG-ECHO	European Commission Directorate-General for European Civil Protection and Humanitarian Aid Operations
DG-ENV	European Commission Directorate-General for Environment
DRR	Disaster Risk Reduction
EBT	Ensemble Bagged Trees
EC	European Commission
ECV	Essential Climate Variable
EEA	European Environment Agency
EO	Earth Observation
ES	Ecosystem Service
ESA	European Space Agency
EU	European Union
EVI	Enhanced Vegetation Index
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
FMask	Function of Mask
GCOS	Global Climate Observing System
GEOSS	Global Earth Observation System of Systems
GI	Green Infrastructure
GIS	Geographic Information System
GNDVI	Green Normalized Difference Vegetation Index
HPO	Hydrological Planning Office
IPCC	Intergovernmental Panel on Climate Change
ISPRA	*Istituto Superiore per la Protezione e la Ricerca Ambientale*

L8	Landsat-8
LAI	Leaf Area Index
LC/LU	Land Cover/Land Use
LDCM	Landsat Data Continuity Mission
MAES	Mapping and Assessment of Ecosystems and their Services (EEA's initiative)
MAJA	Maccs-Atcor Joint Algorithm
MODIS	Moderate Resolution Imaging Spectroradiometer
MSI	Multispectral Instrument
NASA	National Aeronautics and Space Administration
NBS	Nature-Based Solution
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NIR	Near-Infrared
NWRM	Natural Water Retention Measure
OA	Overall Accuracy
OLI	Operational Land Imager
PROBA	Project for On-Board Autonomy
R	Red
R&I	Research and Innovation
RSA	River Surveillance Agency
S2	Sentinel-2
SAVI	Soil-Adjusted Vegetation Index
SDG	Sustainable Development Goals
SPOT	*Système Pour l'Observation de la Terre*
SWI	Soil Water Index
SWIR	Short-Wave Infrared
TIRS	Thermal Infrared Sensor
TOA	Top-Of-Atmosphere
UN	United Nations
USGS	United States Geological Survey
WFD	Water Framework Directive



PART I

RESEARCH QUESTIONS AND METHODOLOGY

THE LENA RIVER DELTA, RUSSIA, CAPTURED BY COPERNICUS SENTINEL-1.

AT NEARLY 4500 KM LONG, LENA IS ONE OF THE LONGEST RIVERS IN THE WORLD. THE RIVER STEMS FROM A SMALL MOUNTAIN LAKE IN SOUTHERN RUSSIA AND FLOWS NORTHWARDS BEFORE EMPTYING INTO THE ARCTIC OCEAN, VIA THE LAPTEV SEA.

Part I – Research questions and methodology

The aim of this chapter is providing an overview of the theoretical and policy background that lead to the research questions and support the methodology used in this Doctoral Thesis. The context, scope, motivation, objectives and structure of the research are discussed in the following pages.

1. Introduction

1.1. European context of Nature-Based Solutions (NBS): perspectives and potential of remote sensing

Degradation of natural capital, loss of Ecosystem Services (ES), climate change and the increased occurrence of natural disasters emerge among nowadays' focal threats (Guerry et al., 2015). Therefore, there is growing recognition and awareness of NBS' potential as sustainable, cost-effective, multi-purpose and flexible alternatives that use natural ecosystems and provide valuable ES (European Commission, 2015a). NBS deliver simultaneously environmental, social and economic benefits and help building climate change resilience (Calliari et al., 2019), thereby paving the way towards a more resource efficient, competitive and greener economy, supporting Europe's 2020 Strategy (EC, 2010a).

In this context, the European Union (EU) Green Infrastructure (GI) Strategy (EC, 2013b) defines GI as:

> *"A strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services"* (p. 3).

Grey infrastructure, especially in the water sector, is man-made engineered and serves a single objective. Instead, GI promotes multi-functionality and plays a key role in achieving EU policy objectives in interconnected environmental areas, especially when NBS are used to preserve natural capital (EC, 2014). However, the GI definition is still under discussion, especially due to its multi-functionality. Numerous studies capture both its potential and complexity (Hislop et al., 2019). Therefore, GI represents strength in terms of its flexibility and adaptability, but also weakness in terms of its overall tangibility (Matthews et al., 2015).

Particularly, GI supports policies regarding: (i) biodiversity conservation, i.e., the EU 2020 Biodiversity Strategy (BS) (EC, 2011a); (ii) territorial development and cohesion (EC, 2014); (iii) climate change mitigation and adaptation, i.e., the EU Strategy on Adaptation to Climate Change (EC, 2013a); (iv) agriculture, i.e., the Common Agricultural Policy (CAP) (EC, 2010c); (v) forestry, i.e., the EU Forests Strategy (EC, 2013c); and (vi) water management, i.e., the Water Framework Directive (WFD) (Directive 2000/60/EC), the Groundwater Directive (Directive 2006/118/EC) and the Floods Directive (Directive 2007/60/EC). The 2020 BS focuses its Target 2 on maintaining and enhancing ES and restoring degraded ecosystems by incorporating GI in spatial planning (EC, 2011a, p. 12). Action 6 of the BS relies on the Member States to set priorities to restore and promote the use of GI (EC, 2011a, p. 12). In this respect, the GI Strategy (EC, 2013b) details the main tactical developments, namely integrating GI into key policy areas, creating and improving the knowledge base, providing financial support, and carrying out EU GI projects.

The renewed EU Research and Innovation (R&I) policy agenda on NBS (EC, 2015a), implemented through Horizon 2020 (EC, 2011b), gives priority to the following themes: (i) assessing and forecasting changes in biodiversity and understanding ecosystems' dynamics; (ii) understanding the relationship between environment, society and economy to better manage, conserve and rehabilitate ecosystems in a sustainable way; (iii) developing advanced models and tools that help to mitigate natural capital degradation; (iv) assessing the role of biodiversity and ecosystems on natural, social and economic impacts of climate change and on relevant mitigation and adaptation strategies; and (v) building a comprehensive framework that supports individual hazards and multi-hazards' research and the integration of the risk-reduction chain for the development of prevention and mitigation strategies.

The European Environment Agency (EEA) has engaged in GI to support policy and decision makers in environmental impacts. Specifically, it has highlighted the importance of developing tools to detect and measure GI (European Environment Agency, 2011, 2014). Also, it has demonstrated the role of GI and ES in mitigating the impacts of weather- and climate change-related natural hazards (EEA, 2015). Important results on identifying ES and benefits to the environment, society and economy have been achieved at EU-level under the initiative on Mapping and Assessment of Ecosystems and their Services (MAES) (Maes et al., 2018), as well as categorising ES through the Common International Classification of Ecosystem Services (CICES) (Haines-Young & Potschin, 2018).

GI related specifically to the water sector is identified by the European Commission (EC) Directorate-General for Environment (DG-ENV) as Natural Water Retention Measures (NWRM). NWRM are defined as NBS that act upon water-dependent ecosystems to enhance the natural characteristics that enable them to retain water, minimising run-off peaks during wet periods, storing water during dry periods, and increasing resilience against extreme events, such as floods or droughts (EC, 2015b). Through a two-year-long initiative (EC, 2015b), DG-ENV has categorised NWRM types per sector (agriculture, forest, hydro-morphology and urban) and benefits provided. It considers biophysical impacts resulting from water retention, ES delivered and policy objectives from EU Directives, e.g., the WFD (Directive 2000/60/EC) or the Floods Directive (Directive 2007/60/EC), that NWRM´s implementation can help to achieve.

The Paris Agreement (UN, 2016) accentuates the need for new, transparent and integrated solutions to better understand Earth's ecosystems, minimise climate change impacts, support accountability towards long-term goals and inform climate services and decision-making. In this context, the current EU R&I funding programme 2018-2020 (EC, 2019c) outlines Earth Observation (EO) as a tool providing crucial information to support the 2030 United Nations' (UN) Sustainable Development Goals (SDG) (United Nations, 2015) on climate actions, water management and environmental protection, among other societal challenges.

Remote sensing or EO can be defined as:

> *"The art, science and technology through which the characteristics of object features/targets either on, above or even below the Earth's surface are identified, measured and analysed without direct contact existing between the sensors and the targets or events being observed. This allows for information about such object features to be obtained by sensing and recording reflected or emitted energy and processing, analysing, and applying that information"* (Awange & Kiema, 2019, p. 115).

Enhancements in sensor devices lead to availability of data with higher spatial, temporal and spectral resolutions, which has extended the precision to monitor vegetation characteristics and functions remotely (Houborg et al., 2015).

R&I actions must focus on developing applications to support users involved in the implementation of Climate Change Adaptation (CCA) and mitigation actions, thereby leading to better informed decision-making in environmental policy, ecosystem management and Disaster Risk Reduction (DRR) (UN, 2016). Moreover, actions are especially encouraged to make use of, contribute to, and feedback on, EU EO datasets and services, such as Copernicus programme (Regulation (EU) No 377/2014), as the EU EO programme (UN, 2016). Special attention is also given to multi-scale approaches with the ability to scale up and down from local-to-EU scales (EC, 2019c).

In conclusion, the EC is interested in fostering the development and implementation of a collaborative and integrated EU EO Strategy that supports R&I in the domain of EO. It plans to do it through an user-driven development of products and services that address societal needs and integrates EU EO data, both from the Global Earth Observation System of Systems (GEOSS) and its key European contributor, Copernicus, with other data sources (Regulation (EU) No 377/2014; EC, 2019c). The developed products must incorporate assimilation techniques and interoperability best practices, automatization, systemization and integrated web-based services that will potentially lead to pre-operational downstream services.

1.2. Copernicus: Europe's eyes on Earth

Historically, there has been very little coordination between satellite missions and programmes. Sensors and EO programmes have been frequently developed with duplication and competition with one another. Continuous changes in sensors and lack of continuity of the satellite missions have limited the capability to monitor ecological trends (Jones & Vaughan, 2010).

The EU EO programme, named Copernicus since April 2014 (Regulation (EU) No 377/2014), was set up with the aim of integrating European space programmes, making use of all available resources and providing efficiently the information needed by users at global, European and local scales (Aschbacher & Milagro-Pérez, 2012). As of January 2020, Copernicus is led by the EC newly created Directorate-General for Defence Industry and Space (DG-DEFIS). Copernicus is based on a partnership between the EU, the European Space Agency (ESA) and the Member States and its origins date back to May 1998 (Regulation (EU) No 911/2010). With seven Sentinel satellites already in orbit delivering data every day, Copernicus is the biggest provider of EO data in the world (Jutz & Milagro-Pérez, 2018). The programme aims to ensure an autonomous EU capacity for long-term development of space-based environmental monitoring services, making use of, and further developing, European skills and technologies (Regulation (EU) No 377/2014).

Copernicus provides accurate, reliable and near-real-time information in the fields of environment and security, tailored to the users' needs (EC, 2019a). It aims to benefit a wide range of EU policies and strategies, such as Horizon 2020 (EC, 2011b). Also, it aspires to contribute to reaching the objectives of the Europe's 2020 Strategy (EC, 2010a). In particular, by developing an effective space policy to provide tools to address key global challenges and meet the targets on climate change and environmental sustainability. Moreover, Copernicus data is available freely and openly to support the Digital Agenda for Europe (EC, 2010b), representing an influential tool for economic development and a driver of the digital economy.

Copernicus programme is comprised of three components: space, service and in-situ (Regulation (EU) No 377/2014). The space component comprises two types of complementary satellite missions, ESA's dedicated Sentinels and missions from other national and international space agencies, called contributing missions. Copernicus service consists of six core thematic areas: Land Monitoring, Marine Environment Monitoring, Atmosphere Monitoring, Emergency Management, services for Security applications, and Climate Change (Jutz & Milagro-Pérez, 2018). It produces value-added products, such as informative maps and datasets, by processing and analysing jointly space data, served by the Sentinels and the contributing missions, and environmental measurements (Jutz & Tassa, 2019). These products serve a wide range of application domains, namely agriculture, blue economy, climate change and environment, development and cooperation, energy and natural resources, forestry, health, insurance and disaster management, security and defence, tourism, transport and urban planning. Non-space data is referred to as in-situ data and is collected from providers external to Copernicus, from ground-based, sea-borne or air-borne monitoring systems. It also includes geospatial reference data, which refers to background topographic information, such as transportation network maps, administrative boundaries and digital elevation models (Marconcini et al., 2020).

Space component's evolution depends on analysing the options to meet evolving user needs, gathered regularly (EC, 2019a), and technological developments (Jutz & Tassa, 2019). On the other hand, Copernicus service component depends on an user-driven approach and thereby on the continuous and effective involvement of users in the services' uptake (Buontempo et al., 2019). Finally, to ensure reliable and consistent data provision over time, the in-situ component benefits from contributions of national monitoring infrastructures and international efforts to collect and share data, mainly from research groups and meteorological organizations (Marconcini et al., 2020). Therefore, the EC provides and updates technical specifications for all Copernicus services addressing aspects such as scope, architecture, technical service portfolios, indicative cost break-down and planning, performance levels, space and in-situ data access needs, evolution, standards, archiving and data dissemination (Regulation (EU) No 377/2014).

Copernicus service and space components are discussed further in the following subsections, specifically the ones used in this Doctoral Thesis, namely Copernicus Land Monitoring Service (CLMS) and Sentinel-2 (S2) satellite platform.

1.2.1. Copernicus Land Monitoring Service (CLMS)

Copernicus service provides products at global, pan-European and local scales in order to support global-to-local policies' requirements (Regulation (EU) No 377/2014). Specifically, CLMS (n.d.) aims to connect the producers of environmental data and decision-support tools with the end-users of these products. Thus, it involves many organizations at different levels with the aim of coordinating EO research and development in vegetation-based studies responding to climate change, ecosystems' management or the promotion of sustainable agriculture (Regulation (EU) No 377/2014). This Doctoral Thesis uses and evaluates products from the global and local components of CLMS.

The availability of operational medium-to-low resolution sensors (i.e., hectometric-to-kilometric spatial resolution), such as the Moderate Resolution Imaging Spectroradiometer (MODIS, 1999 up to date) (Justice et al., 1998), the *Système Pour l'Observation de la Terre* (SPOT-VGT, 1999 to May 2014) (Pasquier & Verheyden, 1998) and the Project for On-Board Autonomy (PROBA-V, June 2014 to October 2019) (Dierckx et al., 2014), allows the production of operational and qualified medium-to-low resolution products of bio-geophysical indices at global scale inside the CLMS. Copernicus Global Land Service's (CGLS) (n.d.) products monitor the status and evolution of the land surface at global scale and are offered both in near-real-time and as long-term time series. Some are recognised as Essential Climate Variables (ECV) by the Global Climate Observing System (GCOS) (World Meteorological Organization et al., 2011), such as the maps of burned areas, the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR), the Leaf Area Index (LAI) or the Soil Water Index (SWI) (Bojinski et al., 2014).

On the other hand, Copernicus Local Land Service (CLLS) offers products based on very-high-resolution (VHR) satellite imagery, i.e., 1.5 m SPOT-6 (September 2012 up to date), 2.0 m Pléiades (December 2011 up to date) (Campenon, 2009) and 2.5 m SPOT-5 (May 2002 to March 2015) (Dagras et al., 1995), in combination with other available datasets, i.e., high and medium resolution satellite data, mainly from 10 m S2 Multispectral Instrument sensor (MSI) (2015 up to date) (Drusch et al., 2012), and 30 m Landsat-8 (L8) Operational Land Imager sensor (OLI) (2013 up to date) (Irons et al., 2012) for gap-filling. CLLS is coordinated by the EEA (Regulation (EU) No 1089/2010) and aims to provide more detailed information, complementary to the pan-European component, to monitor hotspots, i.e., areas that are prone to specific environmental challenges.

For instance, Riparian Zones (Weisstener et al., 2016) and Natura 2000 products address land cover/land use (LC/LU) and characteristics of areas along river flows and grassland rich sites, respectively. These areas provide a wide range of ES (e.g., flood control, water storage, chemical filtration and aquatic life and wildlife support) (EC, 2015b). Therefore, these products support the objectives of several EU actions and policy initiatives, such as the 2020 BS (EC, 2011a), the Habitats (Council Directive 92/43/EEC) and Birds Directives (Directive 2009/147/EC) and the WFD (Directive 2000/60/EC) and Floods Directive (Directive 2007/60/EC). The rationale for these local products derives from the need to improve the mapping and assessment of green and blue infrastructure, monitoring biodiversity rich habitats, ES delivery and, most importantly, assessing whether these sites are being effectively preserved (EC, 2011a, 2015a). Nonetheless, lack of field data in sufficient detail remains a significant handicap that limits possibilities to validate the outcome products.

1.2.2. Copernicus space component: Sentinel-2 (S2)

Copernicus space component provides EO data to feed the wide range of Copernicus services. ESA develops and manages this core component (Regulation (EU) No 377/2014). The contributing missions, such as the aforementioned, make some data available for Copernicus. These satellite missions play a crucial role to ensure that observational requirements are satisfied and fall into the following categories: (i) Synthetic Aperture Radar (SAR) sensors for all-weather, day-and-night observations of land, ocean and ice surfaces; (ii) VHR, high, medium and low resolution optical sensors for targeting specific sites, security applications, supporting regional-to-national land monitoring activities, and monitoring land and ocean dynamics; (iii) high-accuracy radar altimeter systems for sea-level measurements and climate applications; (iv) radiometers to monitor land and ocean temperature; and (v) spectrometers for air quality measurements and atmospheric composition monitoring. The Sentinels have been specifically built for the programme and also carry a range of technologies, such as SAR and MSI, for monitoring land, ocean, climate and atmospheric composition (Marconcini et al., 2020).

Among the seven families of Sentinels, this Doctoral Thesis specifically uses S2. It is a polar-orbiting mission that offers a unique combination of global coverage with a wide field of view (swath width of 290 km), high revisit capability (five days with two satellites), high spatial resolution (10 m, 20 m and 60 m) and multispectral imagery with 13 spectral bands in the visible, Near-Infrared (NIR) and Short-Wave Infrared (SWIR) (Revel et al., 2019). The mission's main objective was to provide enhanced continuity of multispectral EO in comparison with the SPOT series of satellites for Copernicus operational products, such as LC/LU maps, LC/LU change detection maps and bio-geophysical variables, thereby contributing to the Land Monitoring (CLMS), Emergency and Security services (Drusch et al., 2012).

Moreover, S2 characteristics have overcome those of the last Landsat Data Continuity Mission (LDCM), L8, operated jointly by the National Aeronautics and Space Administration (NASA) and the United States Geological Survey (USGS), whose OLI sensor provides data with a spatial resolution of 30 m (visible, NIR and SWIR) every 16 days over a 185 km swath. Nevertheless, L8 comprises a second instrument on-board, the Thermal Infrared Sensor (TIRS) (100 m spatial resolution), and a panchromatic band (15 m spatial resolution), providing multispectral imagery with 11 bands that cover a wider wavelength of the electromagnetic spectrum than S2 MSI (Irons et al., 2012).

The use of S2 has shown its effectiveness for vegetation studies (Qiu et al., 2017). The capacity of S2 MSI's NIR and SWIR bands for geological remote sensing was first evaluated by van der Meer et al. (2014), concluding a good correspondence with L8 OLI. However, cloud-cover remains a major inconvenience when using optical imagery from passive systems. Thus, it is preferable to integrate multi-source satellite data rather than use data from a single satellite platform. The interoperability between S2 and L8 has been proven further by Mandanici and Bitelli (2016), concluding that the satellite platforms can be used jointly to collect data with higher temporal, spatial and spectral resolutions, increasing opportunities for more frequent cloud-free EO (Li & Roy, 2017).

1.3. Biophysical parameters

Spectral indices are calculated by mathematical combination of two or more of the original spectral bands. The bands are selected in such a way that the new index is more clearly related to biophysical parameters of interest, such as chlorophyll content, leaf nitrogen, biomass, photosynthesis, productivity, vegetation cover, canopy leaf area or water content (Xue & Su, 2017). These dimensionless variables derived from satellite data have become one of the foremost sources of information to monitor vegetation condition (agriculture, natural resources and ecosystems) and detect changes derived from climate pressures or human activities (Teillet et al., 1997).

Specifically, most vegetation indices are based on the sharp increase in reflectance that occurs at around 700 nm wavelength, the red-edge, which is characteristic of green vegetation. Indeed, the indices exploit the different reflectance in the NIR and Red (R) (Rouse et al., 1974). As for the study of vegetation water content, the approach for calculating the indices is based on the spectral bands in the near to mid-infrared. Specifically, the bands with stronger water-absorbing features are at around 970 nm, 1200 nm, 1450 nm, 1930 nm and 2500 nm wavelength (Jones & Vaughan, 2010). The depth of the absorption bands is greater at longer NIR wavelengths, but most sensors' accuracy decreases and the effect of radiation absorption from atmospheric water vapour is higher in this part of the spectrum (Gao, 1996).

This Doctoral Thesis uses three bio-geophysical indices: the Normalized Difference Vegetation Index (NDVI), the Enhanced Vegetation Index (EVI) and the Normalized Difference Water Index (NDWI) (Table 1). Extensive further details can be found in the references provided in Table 1. The NDVI is one of the most used and implemented indices, calculated as the normalized ratio between the NIR and R bands. NDVI single values allow estimating vegetation healthiness and vigorousness (Rouse et al., 1974). Moreover, each vegetation type shows a specific NDVI annual signature that defines its phenological stages (Serrano et al., 2019). Thus, this index has been commonly used in agriculture studies for identifying crop types and interpreting the status and productivity. Overall accuracies over 80% have been achieved validating the results with ground-truth data and LC/LU maps (Inglada et al., 2015).

Most of the alternative formulations proposed afterwards aim to correct NDVI's deficiencies. For instance, improving the sensitivity for dense vegetation with high LAI, i.e., the Green Normalized Difference Vegetation Index (GNDVI) (Gitelson et al., 1996), where the green band substitutes R; minimizing the noise caused by variation in the underlying soil reflectance or by atmospheric absorption, i.e., the Soil-Adjusted Vegetation Index (SAVI) (Huete, 1988), which adds a soil-adjustment constant factor; or reducing the variability introduced by atmospheric effects (Huete et al., 1997).

The latter remains a problem for most passive sensor-derived indices. Top-Of-Atmosphere (TOA) reflectance values can be up to 70% lower than measures at ground level (Cracknell, 1997). Therefore, adding the reflectance in the Blue band (B) was proposed to correct for atmospheric aerosols, i.e., the Atmospherically Resistant Vegetation Index (ARVI) (Kaufman & Tanré, 1992) or the EVI (Liu & Huete, 1995). Moreover, several processors have been developed as to correct for atmospheric, shadows and slope effects, converting S2 TOA reflectance (Level 1C) into Bottom-Of-Atmosphere (BOA) reflectance values (Level 2A). For instance, the Maccs-Atcor Joint Algorithm (MAJA), used by the *Centre National d'Études Spatiales* (CNES) (Hagolle et al., 2017); Sen2Cor, used by ESA (Louis et al., 2016); and the Function of Mask (FMask), used by the USGS (Frantz et al., 2018). As of January 2019, Copernicus systematically produces S2 Level 2A products, atmospherically corrected using Sen2Cor algorithm (Szantoi & Strobl, 2019). Still and all, MAJA processor has been used in this Doctoral Thesis (paper IV) since it improves atmospheric correction using multitemporal series of images instead of a single one, achieving an overall accuracy (OA) of around 91%. FMask performs similarly, with an OA of 90%, whereas Sen2Cor's OA is 84% (Baetens et al., 2019).

Table 1. Bio-geophysical indices used in this Doctoral Thesis (Note that NIR, R, B and SWIR stand as reflectance in the Near-Infrared, Red, Blue and Short-Wave Infrared bands; LAI as Leaf Area Index; MODIS as Moderate Resolution Imaging Spectroradiometer; and TOA as Top-Of-Atmosphere reflectance). Characteristics adapted from Jones and Vaughan (2010), Xue and Su (2017) and Serrano et al. (2019), apart from the main reference of each index, included in the Table.

Index	Formula	Characteristics	References
NDVI	(NIR-R)/(NIR+R)	Good for estimation of canopy growth or vigour. Sensitive response to green vegetation, even for low vegetation covered areas. Used in regional-to-global vegetation assessments. Related to canopy structure, LAI and canopy photosynthesis. Sensitive to the effects of soil brightness, soil colour, atmosphere, clouds and clouds shadows, slopes and leaf canopy shadows, thereby requiring remote sensing calibration. Sensitive when vegetation cover is sparse.	Rouse et al. (1974)
EVI	2.5(NIR-R)/(1+NIR+6R-7.5/B)	Simultaneous correction of the effects of soil background reflectance and atmospheric conditions. Improved sensitivity to densely vegetated areas. Lack of correction for the topographic effect, which also affect the noise in vegetation indices, especially in hilly areas. Adopted by the MODIS Land Discipline Group as the second global vegetation index for monitoring the Earth's photosynthetic vegetation activity. Used as the operational index for MODIS products where TOA reflectance is atmospherically corrected.	Liu and Huete (1995)
NDWI	$(NIR-SWIR_1)/(NIR+SWIR_1)$	Use of shorter mid-infrared wavelength, less affected by atmospheric absorption. Less sensitive to the effects of atmospheric conditions than NDVI, but the effects of soil background reflectance are not completely removed. Improved sensitivity to water-related features. Sensitive to changes in water content of vegetation canopies. Stress to plant canopies can be caused by impacts other than flood or drought, difficult to discern using solely NDWI. Thus, NDVI and NDWI should be used complementarily.	Gao (1996)

2. Motivation

The interest for performing this work arises from the increasing importance of continuously mapping and monitoring the environment (natural, semi-natural, agricultural and anthropic) to accomplish the EU policies discussed in Section 1.1. This helps in supervising the sustainable use of natural resources, adopting adequate protection, conservation or recovery policy measures, assessing their effectiveness, prioritizing managing activities and defining spatial planning measures. The use of EO data into automatic or semi-automatic procedures enables faster generation of mapping products in comparison to field data-based ones. Moreover, it allows reaching hardly accessible areas and ensures wide spatial and temporal product coverage. Therefore, it represents a less time-consuming and more cost-effective technique.

Copernicus programme, along with the Sentinels fleet, has made available to several users (private, institutional and scientific) a growing amount of full, open and free EO data and services that cover the world at several spatial resolutions in short revisit times. It has been created as an user-driven tool. Therefore, it has enabled the improvement of land monitoring, paving the way for the generation and delivery of demand-driven EO-based products and services, both experimental and consolidated, in the domains of agriculture, environmental degradation and natural hazards. In a process view, Copernicus value chain comprises three core elements: (i) data sources (i.e., Copernicus space and in-situ data), the upstream part of the supply chain; (ii) EO data acquisition and storage (i.e., Copernicus services information), the midstream part; and (iii) EO data processing and transformation into value-added information products, the downstream services. Hence, EO data brings value through the derived applications. The downstream market turns crucial in the value chain as representing the core link between the satellite technical features and the non-space community's (i.e., end-users and stakeholders) information needs.

In 2018, the benefits of Copernicus in the EU EO downstream market were estimated at between EUR 125 and 150 million, up from EUR 54 million in 2015, and are expected to grow at an average annual growth rate of around 15% (EC, 2019b). The main driver for the growth of this market is the remaining need for filling the gap between users' specific needs for tailored products and the current offer. This context represents a chance for continuously improving environmental geo-information by developing new, or adapting already available, algorithms and workflows (e.g., multi-source data integration). This leads to creating new products, tools and approaches (e.g., value-added information products, automatic or semi-automatic tools) and developing downstream applications and services in favour of stakeholders from both public and private sectors. Such developments can support, and improve the effectiveness of, environmental sustainability policy and decision-making tasks.

This Doctoral Thesis aims to present open-source tools for environmental monitoring based on satellite-derived bio-geophysical indices that give reliable information on the status, pressures and evolution of the land surface. The purpose is establishing downstream pre-operational or consolidated products that fall into Technology Readiness Levels (TRL) of 6 to 9 (EC, 2019d), thereby addressing the proven robustness of the developed technology in an operational environment of relevance, reliable processes and performances that match the expectations. Open-source satellite data, databases, programming languages and Geographic Information Systems (GIS) are used to allow the tools' scalability over time, to new needs and to national, European or global scales, as suggested in the current EU R&I funding programme 2018-2020 (EC, 2019c). The main purpose is supporting stakeholders and fulfilling their information needs, particularly those related to legal obligations, namely the CAP (EC, 2010c), the WFD (Directive 2000/60/EC) and the 2020 BS (EC, 2011a).

The Doctoral Thesis has been developed in response to two **research questions** (Table 2) and is divided in two main parts accordingly: *"Which biophysical parameters are available as full, open and free?"* (Part II) and *"How can biophysical parameters interpretation and local stakeholder needs be bridged?"* (Part III).

Table 2. Research questions, solutions proposed, methodologies followed and advantages and disadvantages of the approaches (Note that CGLS and S2 stand as Copernicus Global Land Service and Sentinel-2 satellite platform, respectively).

Question	**1. Which biophysical parameters are available as full, open and free?**	**2. How can biophysical parameters interpretation and local stakeholder needs be bridged?**
Solution	CGLS products of bio-geophysical indices.	Development of tools based on open high-resolution satellite data to help in specific decision-making tasks.
Methodology	Study of the suitability and quality of CGLS products to monitor NWRM and their benefits (review of scientific literature and reports).	Analysis of vegetation and water spectral indices.
Advantages	Wide range of already processed and qualified bio-geophysical indices' products on the status and evolution of the land surface, at global scale and with a short revisit time (every 10 days), complemented by the constitution of long-term time series.	Characterisation of vegetation types, greenness and water leaf response with high spatial and temporal resolutions.
Disadvantages	Medium-to-low spatial resolution (300 m and 1 km), not fulfilling studies' needs at local scale. Some products lack validation assessments.	Time-consuming scenes selection and pre-processing tasks. Cloud coverage. Feedback loop between the need of validation assessments and the lack of comparable reference data. S2 recent launch does not allow for long-term assessments.

Firstly, given the EC's interest in fostering EU EO capacity (Regulation (EU) No 377/2014; UN, 2016), the Doctoral Thesis examines the state of the research regarding the proposed bio-geophysical indices inside Copernicus programme. Given the fact that CGLS is currently the only EO programme offering these indices freely as processed and qualified products, the second research question enquires how to use the indices at local scale. Part III of the Doctoral Thesis addresses the development and implementation of demand-driven tools in local case studies.

The selected case studies are the largest river basins in Spain and Italy: Duero and Po, respectively. These basins are chosen as representatives of significant climate change effects, e.g., flood events, high intensity precipitation periods and impacts on water availability. A combination of multiyear droughts and low groundwater levels leads to water stress scenarios. The agriculture sector is hence likely to experience supply disruptions in the near and long-term as it represents over 80% of global water demand (Food and Agriculture Organization of the United Nations, 2018). Therefore, in agriculture, a shock like a drought can have a high impact on food supplies and the sustainable use of water reservoirs. Lastly, both basins account for 40% of national gross domestic product.

Therefore, the second research question takes into account stakeholders' requests and targets from the aforementioned EU policies, which settle the **specific objectives** of this Doctoral Thesis. Firstly, the Hydrological Planning Office (HPO) and the River Surveillance Agency (RSA) of the Duero Hydrographic Confederation need to fulfil the CAP (EC, 2010c) and the WFD (Directive 2000/60/EC). Therefore, the following specific objective is formulated: enhancing the monitoring of agricultural water use and crop types. Secondly, the Member States need to meet Action 5 of the 2020 BS: *"Improve knowledge of ecosystems and their services in the EU"* (EC, 2011a, p. 12). Therefore, the following specific objective is formulated: mapping and assessment of ecosystems and their services.

Tying to advance in the research questions and to overcome the disadvantages outlined in Table 2, this Doctoral Thesis deals with: (i) analysis of stakeholders' requests (geographical area, applications, and spatial and temporal resolutions' requirements); (ii) multi-source data integration (e.g., multi-source optical satellite imagery from passive sensors, field surveys and local datasets); (iii) analysis of available bio-geophysical indices, its suitability to monitor vegetation and interpretation of spatial and temporal patterns; (iv) delivery of mapping products of irrigated agricultural plots without irrigation rights and crop classification to help in planning on-the-spot checks to the most severe infringements (i.e., larger surface, further distance to a regulated well or unauthorised areas for irrigation due to water scarcity); (v) identification of GI and assessment of current status and regulative ES provided; (vi) development of new, or adaptation of already existing, algorithms and workflows according to S2 and L8 sensors' characteristics to automatically download and pre-process the input data; (vii) development of automatic or semi-automatic procedures to interpret bio-geophysical indices' values, together with available local and field data, in the perspective of offering downstream services; and (viii) development of open-source innovative and dedicated desktop-GIS and web-GIS tools based on EO, easy to use by decision makers, to provide the information they need, when they need it and in a comprehensible format. Where possible, the works also tackle the aspects of accuracy and validation.

3. Objectives

3.1. General objective

The general objective of this Doctoral Thesis is to develop a clear framework and methodology that bridges the interpretation of satellite-based biophysical parameters and the sustainable management of natural resources over time. The purpose is strengthening EO potential in environmental sustainability policy and decision-making, as suggested in recent EU R&I funding programmes (EC, 2019c), by bridging remote sensing research and stakeholders' demands into tools of scientific success.

This Doctoral Thesis contributes to discourses regarding problematic monitoring of agricultural water use, crop type mapping, identification of GI and ES and detection of degraded ecosystems. Moreover, it takes into account the increased interest of the EC in using EU EO datasets, especially Copernicus programme. Figure 1 holds a simple workflow of the methodology proposed.

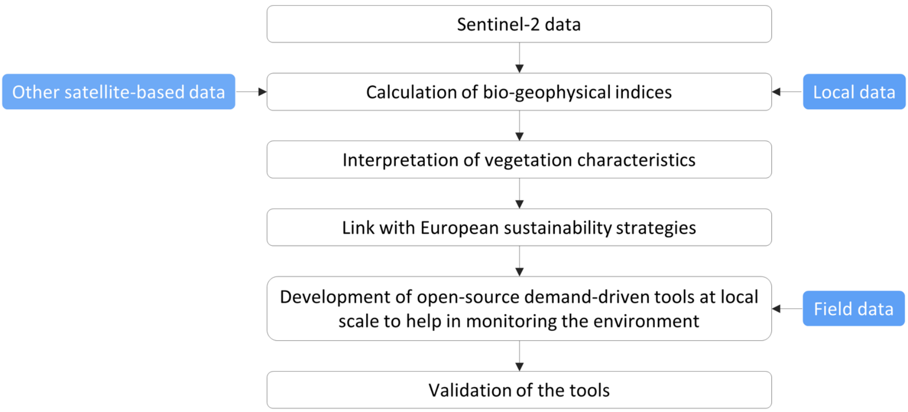


Figure 1. Flowchart of the methodology followed to develop open-source EO-based tools to monitor the environment at local scale based on the interpretation of bio-geophysical indices (Note that validation assessments are performed when comparable reference data is available).

The goal of the Doctoral Thesis is that water, agriculture and environmental policy and decision makers refer to, use, and feedback on, the developed tools and approaches, based on open-source satellite remote sensing. It is expected to stimulate demand-driven developments within EU EO research, particularly by improving the existing, or by developing new, Copernicus products and services to support EU actions and policies.

3.2. Specific objectives

Specific objectives pursued in this Doctoral Thesis are based on the previously presented targets from EU Directives and Strategies on environmental sustainability (Section 1.1). Specific requests from local stakeholders are considered as well. The aim is developing automatic or semi-automatic procedures to interpret biophysical parameters, calculated through open high-resolution satellite data, to help in near-real-time decision-making at local scale.

3.2.1. Enhancing the monitoring of agricultural water use and crop types

To fulfil the CAP (EC, 2010c) and the WFD (Directive 2000/60/EC) in this respect, this Doctoral Thesis proposes the development of complementary tools that can be used by the HPO and the RSA of a river basin Hydrographic Confederation. The tools are based on NDVI values, calculated with open high-resolution satellite imagery, and spatial information provided by the river basin. The goal is monitoring crop types and irrigation activity with high spatial and temporal consistencies over large areas, contributing to the sustainable use of natural resources. The tools are developed in close collaboration with the end-user in order to attend all the information needs and spatial and temporal requirements.

This objective is pursued within a regional project in Duero river basin: *"452-A.640.02.07/2015. RevelaDuero: Earth Observation image analysis system for the determination of irrigated plots and crop classification in the Duero river basin"*. The tools are periodically upgraded, such as within the project *"452-A. 640.02.02/2019. RevelaDuero: Maintenance and improvement of the Earth Observation image analysis system for the determination of irrigated plots in the Duero river basin"*.

Both a desktop-GIS and a web-GIS tool are developed for the Duero Hydrographic Confederation, with complementary functions, to accomplish the following objectives:

- To create cross-sectional tools for hydrographic management that support decision-making and problematic agricultural water use management.
- To allow the integration of internal procedures, serving a better and more efficient communication between the HPO and the RSA.
- To support territorial analysis and the implementation and monitoring of action plans.
- To facilitate the automatic querying, downloading, processing and structured storage of EO data that cover the study area.
- To provide the personnel of a river basin Hydrographic Confederation with the necessary training to consult and exploit EO data and spatial information in a simple and intuitive way.

- To develop functional computer tools that integrate the automatic management and analysis processes to exploit the available EO data and spatial information. These tools consist of an extension (or *plugin*) inside QGIS program and a web-based tool. All the data consumed through, and delivered by, the processes is hosted and updated inside a PostgreSQL/PostGIS database.
- To allow access to additional cartography datasets (e.g., the river basin's catalogue, the river basin's web-based tool, cadastral information, etc.) to reference agricultural plots, hydrological data, land uses or any spatial information of interest.
- To configure and control the users' access to data and functionalities of the GIS environment.
- To publish geospatial information as services in accordance to the Infrastructure for Spatial Information in the European Community (INSPIRE) Directive (Directive 2007/2/EC) and based on Open Geospatial Consortium (OGC) Standards (n.d.).

3.2.2. Mapping and assessment of ecosystems and their services

Action 5 of the 2020 BS (EC, 2011a, p. 12) calls the Member States to map and assess the state of ecosystems and their services in their regional territory with the assistance of the EC. A dedicated working group on MAES has been established to coordinate and oversee Action 5. The report adopted in 2018 (Maes et al., 2018) proposes a selection of indicators to map and assess the condition and pressures for main ecosystem types, based on datasets derived from reporting under EU environmental policies. This Doctoral Thesis proposes an approach based on ES condition indicators that can be assessed through remote sensing, namely capacity to provide ES, proximity to protected areas and ecosystems' functional attributes (greening response and water stress). The two first indicators are assessed through the integration of CLLS products, open high-resolution satellite data and available local datasets. The use of NDVI with two other bio-geophysical indices, EVI as a complementary vegetation index more sensitive to heavily vegetated areas, and NDWI as a water index, allows for interpreting the last ES condition indicator.

This objective is pursued within an European project on GI, funded by the EC Directorate-General for European Civil Protection and Humanitarian Aid Operations (DG-ECHO): *"G.A. ECHO/SUB/2016/740172/PREV18. GREEN: Green infrastructure for disaster risk reduction protection: evidence, policy instruments and marketability"*. The collaboration in this project arises from the predoctoral research stay at the *Istituto Superiore per la Protezione e la Ricerca Ambientale* (ISPRA), in Rome, Italy, to obtain the PhD *"International Mention"*.

From the **EC policy perspective**, this part of the Doctoral Thesis aims to achieve the following objectives:

- To provide a critical evaluation of satellite-based data, especially Copernicus data, as one of the best available sources of information for guiding policy and decision-making on complex environmental issues.
- To support the development and implementation of related policies on water, climate, agriculture, forest and regional planning.
- To provide robust, reliable and comparable data that facilitates spatial planning and the implementation of action plans.
- To contribute to targets of the Member States from 2020 onwards in view of CCA and DRR.
- To develop a coherent analytical approach to be applied by the EU and the Member States in order to ensure the delivery of consistent outcomes under Action 5 of the 2020 BS.
- To support EU actions through Copernicus uptake, increasing its usability to monitor prone areas where the lack of high-resolution time series of vegetation dynamics has jeopardised assessments on natural ecosystems.

From an **end-user perspective**, the following objectives are pursued:

- To provide maps that spatially explicit prioritisation and problem identification, especially in relation to synergies and trade-offs among different ecosystems and ES and between ES and protected areas.
- To provide maps that can be used as a communication tool to initiate discussions between policy and decision makers, visualizing the locations where valuable ES are produced and explaining the relevance of ES to the public in their territory.
- To allow a more detailed assessment of vegetation response to disturbances, such as droughts, floods or human influence.
- To monitor impacts on the ecosystems' functional attributes, taking into account the ecosystems' role in the delivery of ES.
- To highlight degraded areas playing a key role in the delivery of ES to support the implementation of action plans and monitoring their effectiveness.

4. Structure of the Doctoral Thesis

This Doctoral Thesis is presented as a *"Compendium of Publications"*. It consists of four scientific articles, published in high-impact international journals, in accordance with the Doctoral Regulations of the University of Salamanca. It has been structured in four parts. Parts II and III respond to the aforementioned research questions. After that, Part IV holds the conclusions derived and future developments.

Part I – Research questions and methodology
Part II – Full open and freely available biophysical parameters
Part III – Bridging biophysical parameters interpretation and local stakeholder needs
Part IV – Conclusions and future works

Part I provides an overview of the European context of NBS and EU environmental policies and strategies. It remarks the potential of EO to monitor the environment and the interest of the EC in fostering EU EO capacity. After that, it presents Copernicus programme and the bio-geophysical indices used in this Doctoral Thesis. The research questions that motivate this research work are established, as well as the general objective and specific objectives pursued. Finally, it sums up briefly the structure of the following parts.

Part II holds **paper I**, which analyses the suitability and quality of the vegetation and energy indices in CGLS to monitor NWRM and their benefits, namely biophysical impacts, ES delivered, and targets from EU policies that NWRM's implementation can help to achieve. Simple flow diagrams are designed to advice the end-user on the most suitable bio-geophysical index and quality that can be expected from CGLS products depending on the NWRM or benefit to monitor.

Part III holds papers II, III and IV. These papers present the developed tools and approaches, based on the interpretation of bio-geophysical indices calculated with high-resolution multispectral satellite data, to meet local stakeholder needs.

Firstly, **Papers II and III** refer to the regional project RevelaDuero (452-A.640.02.07/2015). The HPO and the RSA of the Duero Hydrographic Confederation requested open-source tools based on freely available satellite imagery from S2 and L8 for improving irrigation management (HidroMap©). Moreover, crop classification is performed automatically using machine learning classifiers through an efficient and accurate model that takes into account agro-climatic features. HidroMap© currently falls into TRL 9, representing a complete, competitive and qualified system in a fully operational environment. As for the crop classification model, it falls into TRL 7, as representing a demonstrated and validated model awaiting an upgrade to an open-source programming language.

Secondly, **Paper IV** refers to the mapping and assessment of ecosystems and their services and has been developed within the European project GREEN (G.A. ECHO/SUB/2016/740172/PREV18). The research provides an approach that allows identifying NWRM in riparian areas of a river network. Moreover, the capacity to provide regulative ES, such as flood or drought protection, is assessed, as well as the condition of each GI. It has been tested in Po river basin and, specifically, in its delta area. The developed model is used to prioritise GI's need of restoration. It falls into TRL 6, awaiting comparable reference data in a sufficient level of detail for its complete validation.

Part IV states briefly the main remarks that come up from the results obtained. Moreover, different approaches towards the continuity of the research line are discussed.

Finally, two additional appendices are considered appropriate. **Appendix A** outlines the impact factor of the journals in which the papers have been published. **Appendix B** summarizes the main features of HidroMap© (registered intellectual property with reference number SA-00/2019/2424), the GIS tool developed in RevelaDuero project (452-A.640.02.07/2015), and includes the Innovation Award gained.

PART II

FULL, OPEN AND FREELY AVAILABLE BIOPHYSICALPARAMETERS

THE GANGES RIVER DELTA, BANGLADESH, CAPTURED BY COPERNICUS SENTINEL-2.

THE DELTA IS PRONE TO SEVERE FLOODS, DEVASTATING THE AREA. CLIMATE CHANGE IS FEARED TO MAKE THE FLOODS EVEN MORE DESTRUCTIVE DUE TO MELTING HIMALAYAN GLACIERS AND SNOW.

Part II – Full, open and freely available biophysical parameters

Paper I: Monitoring Green Infrastructure for Natural Water Retention Using Copernicus Global Land Products

remote sensing

Review

Monitoring Green Infrastructure for Natural Water Retention Using Copernicus Global Land Products

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Abstract: Nature-based solutions are increasingly relevant tools for spatial and environmental planning, climate change adaptation (CCA), and disaster risk reduction (DRR). For this reason, a wide range of institutions, governments, and financial bodies are currently promoting the use of green infrastructure (GI) as an alternative or a complement to traditional grey infrastructure. A considerable amount of research already certifies the benefits and multi-functionality of GI: natural water retention measures (NWRMs), as GIs related specifically to the water sector are also known, are, for instance, a key instrument for the prevention and mitigation of extreme phenomena, such as floods and droughts. However, there are persisting difficulties in locating and identifying GI and one of the most promising solutions to this issue, the use of satellite-based data products, is hampered by a lack of well-grounded knowledge, experiences, and tools. To bridge this gap, we performed a review of the Copernicus Global Land Service (CGLS) products, which consist of freely-available bio-geophysical indices covering the globe at mid-to-low spatial resolutions. Specifically, we focused on vegetation and energy indices, examining previous research works that made use of them and evaluating their current quality, aiming to define their potential for studying GI and especially NWRMs related to agriculture, forest, and hydro-morphology. NWRM benefits are also considered in the analysis, namely: (i) NWRM biophysical impacts (BPs), (ii) ecosystem services delivered by NWRMs (ESs), and (iii) policy objectives (POs) expressed by European Directives that NWRMs can help to achieve. The results of this study are meant to assist GI users in employing CGLS products and ease their decision-making process. Based on previous research experiences and the quality of the currently available versions, this analysis provides useful tools to identify which indices can be used to study several types of NWRMs, assess their benefits, and prioritize the most suitable ones.

Keywords: copernicus services; green infrastructure; ecosystem services; natural water retention measures; vegetation and energy indices; regulating services; disaster risk reduction; climate change adaptation

1. Introduction

Green infrastructures (GIs) are often presented as nature-based solutions in the context of both spatial and environmental planning [1,2]. However, the concept can be applied to a greater variety of environments and remains extremely broad [3,4], to the point that, despite the increasing relevance of GIs in several policy areas, no universally-accepted definition exists [5–8]. In 2013, the European Union (EU) defined GI as "a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services [. . .]" [9].

This definition states that GIs are primarily spatial tools for the delivery of both green and blue (when considering aquatic systems) ecosystem services (ESs) in terrestrial, coastal, or marine areas [2–4,9–11]. ESs are classified either as (i) provisioning services, supplying natural resources; (ii) regulatory and maintenance; or (iii) cultural [12].

Multi-functionality is perhaps the most important characteristic of GIs, which are capable of delivering multiple benefits to both nature and human-beings [10,13]: Given their cost-effectiveness [14], it is advocated that, where possible, they should be preferred to single-purpose grey infrastructures. The restoration of a floodplain, a typical GI, is an example of this: Such a measure would provide flood risk reduction, water storage, biodiversity protection, and recreational opportunities [15], whereas only the first benefit would be delivered by grey flood defenses.

Over the past decade, GI's potential as a policy tool to promote the establishment of a resilient society and a sustainable economic development has been increasingly acknowledged by policymakers [10,12,13]. In 2011, the EU Biodiversity Strategy to 2020 [16] explicitly stated the importance of incorporating GIs into spatial planning in order to achieve its target two, the maintenance and enhancement of ESs and the recovery of at least 15% of the degraded ecosystems across Europe.

Then, in 2013, the European Commission formulated a specific GI strategy, aiming to promote their uptake among stakeholders, encouraging investments, and developing trans-European GI networks [9]. The strategy outlined the need to incorporate GIs into key policies, recognizing it as an important tool to achieve a variety of policy objectives. For instance, GI can be employed to:

- Store carbon, reduce greenhouse gas emissions, and lower the carbon footprint due to residential, transport and energy production sectors, as well as alleviate extreme weather events and natural disasters, thus supporting the EU Strategy on Adaptation to Climate Change [17].
- Improve the connectivity between Natura 2000 core areas, established by the Habitats [18] and Birds Directives [19] and enhanced by the 2020 Biodiversity Strategy [16], and integrate them with the surrounding environment.
- Avoid forest erosion, soil contamination, and the fragmentation and degradation of ecosystems, as required by the EU Forests Strategy [20].
- Achieve several objectives of the Common Agricultural Policy (CAP) [21] and encourage agricultural sustainable practices.
- Improve water quality and storage, treat waste water, reduce hydro-morphological pressures on river basins, and mitigate the impacts of floods and droughts, thus contributing to the goals of all EU water-related policies, including the Water Framework Directive [22], the Groundwater Directive [23], and the Floods Directive [24].

GIs related to the water sector are identified by the European Commission Directorate-General Department for Environment Policies (DG-ENV) as natural water retention measures (NWRMs). NWRMs are defined as "multi-functional measures that specifically aim to protect and manage water resources and address water-related challenges by restoring or maintaining ecosystems as well as natural features and characteristics of water bodies using natural means and processes [. . .]" [25]. Thus, their main function is to act upon water-dependent ecosystems to enhance the natural characteristics that enable them to retain water. This makes it possible to minimize runoff peaks during periods of abundant precipitation as well as to store water to cope with dry periods, increasing the resilience of the water ecosystem against extreme events, such as floods and droughts [17,26–28].

In 2013, the DG-ENV launched a two-year-long NWRM initiative [29], with the aim of developing a knowledge base and bringing together all parties interested in NWRM design and implementation. The initiative produced a catalogue of 53 NWRMs, classified per sector: Agriculture, forest, hydro-morphology, and urban. It also studied NWRM benefits, formulating a list of 17 NWRM biophysical impacts (BPs) resulting from water retention, 14 ecosystem services (ESs) delivered by NWRMs, and 14 EU policy objectives (POs) that NWRMs can help to reach.

In this work, we dealt with GIs, and specifically with NWRMs, by considering first the needs of users and stakeholders related to the implementation, monitoring, control, and management of actual or potential GIs. We then attempted to fulfil these needs by proposing solutions based on remotely-sensed data within the Copernicus regulation [30]. Such data, especially when freely available, up-to-date and in near-real-time, shows great potential, considering the constant changes undergone by Earth's ecosystems due to natural land and atmospheric conditions and under the pressure of human activities [31–33]. Its applications include the parametrization of a wide variety of ecosystem models, the reproduction of ecosystem dynamics, and the estimation of natural risks to ecosystems or future scenarios, which can improve the formulation of environmental and conservation policies [34–36].

In order to monitor and manage ecosystem changes, scientists have developed, in the framework of remote sensing applications, highly useful indices and approaches for evaluating both qualitatively and quantitatively the vegetative-water-energy nexus of natural surfaces through the execution of spectral measurements [33,34,36–39]. The worldwide known Copernicus Global Land Service (CGLS) [40], a component of the Land Monitoring Core Service of the Copernicus Earth Observation program, provides in particular a freely-available set of products based on qualified bio-geophysical indices. These products are arranged into long-term time series and monitor the status and evolution of the land surface on a global scale at mid-to-low spatial resolutions (300 m and 1 km) and in near-real-time. They can be used to monitor components and processes of the Earth system, including the vegetation, water cycle, energy budget, and terrestrial cryosphere.

Our study aimed to develop tools for users and stakeholders to ascertain the potential of CGLS products for the identification, monitoring, and assessment of GIs. As we were particularly interested in GIs for the reduction and mitigation of water-related hazards, such as floods and droughts, the analysis focused on determining the most suitable indices for the monitoring of NWRMs. Therefore, we performed a review of previous research experiences that employed the bio-geophysical indices provided in the CGLS vegetation and energy products and then used the review's results to assess whether each product could potentially be used to monitor several types of NWRMs and their benefits, also taking into account the quality of the products' currently-available versions.

Ultimately, the purpose of this review was building an evidence base that, merged with future research and developments, would allow us to understand the requirements to properly monitor and identify NWRM and their benefits using operational information data streams covered by current (or planned) Copernicus capacity. Performing this kind of analysis is essential to provide well-grounded advice for the future inclusion of new products and services inside the Copernicus framework to suitably cover institutional and private business processes and needs. Thus, products under demonstration, pre-operational, or operational conditions could benefit from these analyses, having a clear view of their current and potential use.

The present article is organized as follows: After describing in detail CGLS products and GI/NWRM characteristics, benefits, and regulating policies, the methodology section outlines the input data used for our review of the scientific literature, the results of which are expressed through the use of Sankey diagrams and flowcharts. The results section indicates which vegetation and energy indices, among those provided by the CGLS products, are potentially most useful for the monitoring of each NWRM, biophysical impact, ecosystem service, and policy objective. Moreover, this section indicates the quality that can be expected when using the CGLS bio-geophysical indices in terms of their continuity along the globe, spatial and temporal consistencies, and overall accuracy. The discussion section debates the results derived from the analysis and provides guidelines for users in the form of flow diagrams showing the most recommended products. Finally, all the conclusions derived from the study are summarized.

2. Materials and Methods

Our approach, shown in Figure 1, entailed firstly considering the review of previous scientific works that used or evidenced the potential use, either direct or indirect, of one of the bio-geophysical indices provided by the Copernicus Global Land Service (CGLS) vegetation or energy products to monitor a natural water retention measure (NWRM), observe a NWRM biophysical impact (BP), certify the delivery of a NWRM ecosystem service (ES), or verify the achievement of a NWRM-related policy objective (PO) from the targets of EU directives. We also focused on the actual quality that users could expect using the last-updated versions of the CGLS products in terms of the data continuity along the globe, spatial and temporal consistencies, and accuracy when compared with other satellite-based products [40]. Finally, the outcomes were combined in Sankey diagrams and flowcharts designed for the benefit of GI users.

Figure 1. Flowchart showing the steps followed to determine the most recommended vegetation and energy indices provided by the Copernicus Global Land Service for monitoring natural water retention measures and their benefits.

2.1. Catalogue

The first step of our approach was organizing a catalogue of the relevant NWRMs, BPs, ESs, and POs (Table 1). We made use of the catalogues developed by the DG-ENV NWRM initiative [29].

Table 1. Catalogue of the studied natural water retention measures (NWRMs), based on the NWRM project [29]. Short-names in bold are the ones displayed in the final diagrams.

Agriculture		Forest		Hydro-Morphology	
A1	Meadows and pastures	**F1**	Forest riparian buffers	**N1**	Basins and ponds
A2	Buffer strips and hedges	**F2**	Maintenance of forest cover in headwater areas	**N2**	Wetland restoration and management
A3	Crop rotation	**F3**	Afforestation of reservoir catchments	**N3**	Floodplain restoration and management
A4	Strip cropping along contours	**F4**	Targeted planting for catching precipitation	**N4**	Re-meandering
A5	Intercropping	**F5**	Land use conversion	**N5**	Stream bed re-naturalization
A6	No till agriculture	**F6**	Continuous cover forestry	**N6**	Restoration and reconnection of seasonal streams
A7	Low till agriculture	**F7**	Water sensitive driving	**N7**	Reconnection of oxbow lakes and similar features
A8	Green cover	**F8**	Appropriate design of roads and stream crossings	**N8**	Riverbed material re-naturalization
A9	Early sowing	**F9**	Sediment capture ponds	**N9**	Removal of dams and other longitudinal barriers
A10	Traditional terracing	**F10**	Coarse woody debris	**N10**	Natural bank stabilization
A11	Controlled traffic farming	**F11**	Urban forest parks	**N11**	Elimination of riverbank protection
A12	Reduced stocking density	**F12**	Trees in urban areas	**N12**	Lake restoration
A13	Mulching	**F13**	Peak flow control structures	**N13**	Restoration of natural infiltration to groundwater
		F14	Overland flow areas in peatland forests	**N14**	Re-naturalization of polder areas

The original catalogue of NWRMs contained 53 measures divided in four sectors: (i) Agriculture, (ii) forest, (iii) hydro-morphology, and (iv) urban. As the present analysis was involved in a research [41] specifically tackling rural GI development, its monitoring, and the management of water-related natural hazards, the review only studied the 41 NWRMs included in the first three categories (Table 1).

The catalogue of the biophysical impacts resulting from water retention was left unaltered: All 17 BPs, originally divided into either direct (i.e., runoff control) or indirect (i.e., pollution reduction, soil conservation, habitat creation, or climate alteration), were considered. On the other hand, the list of NWRM-related ecosystem services was significantly altered: Originally containing 14 ESs, classified as (i) provisioning, (ii) regulatory and maintenance, (iii) cultural, or (iv) abiotic services, this catalogue was reduced to the 9 ESs belonging to the first two categories, while the other two were excluded as none of the cultural (i.e., recreational opportunities) or abiotic services (i.e., navigation or energy production) were actually relevant for the final goal of monitoring and assessing GIs in rural environments for the reduction and mitigation of water-related natural hazards (Table 2).

Table 2. Catalogue of the studied biophysical impacts, ecosystem services, and policy objectives linked to natural water retention measures, based on the NWRM project [29]. Short-names in bold are the ones displayed in the final diagrams.

Biophysical Impacts		Ecosystem Services		Policy Objectives	
BP1	Store runoff	**ES1**	Water storage	**PO1**	Improving status of biology quality elements (WFD)
BP2	Slow runoff	**ES2**	Fish stocks and recruiting	**PO2**	Improving status of physicochemical quality elements (WFD)
BP3	Store river water	**ES3**	Natural biomass production	**PO3**	Improve status of hydro-morphology quality elements (WFD)
BP4	Slow river water	**ES4**	Biodiversity preservation	**PO4**	Improve chemical status and priority substances (WFD)
BP5	Increase evapotranspiration	**ES5**	Climate change adaptation and mitigation	**PO5**	Improve quantitative status (WFD)
BP6	Increase infiltration and/or groundwater recharge	**ES6**	Groundwater/aquifer recharge	**PO6**	Improve chemical status (WFD)
BP7	Increase soil water retention	**ES7**	Flood risk reduction	**PO7**	Prevent surface water status deterioration (WFD)
BP8	Reduce pollutant sources	**ES8**	Erosion/sediment control	**PO8**	Prevent groundwater status deterioration (WFD)
BP9	Intercept pollution pathways	**ES9**	Filtration of pollutants	**PO9**	Take adequate and coordinated measures to reduce flood risks (FD)
BP10	Reduce erosion and/or sediment delivery			**PO10**	Protection of important habitats (HD and BD)
BP11	Improve soils			**PO12**	More sustainable agriculture and forestry (BS)
BP12	Create aquatic habitat			**PO13**	Better management of fish stocks (BS)
BP13	Create riparian habitat			**PO14**	Prevention of biodiversity loss (BS)
BP14	Create terrestrial habitat				
BP15	Enhance precipitation				
BP16	Reduce peak temperatures				
BP17	Absorb and/or retain CO_2				

The list of EU policy objectives, finally, originally contained a list of 14 NWRM-related POs expressed by the Water Framework Directive (WFD) [22], the Floods Directive (FD) [24], the Habitats and Birds Directives (HD and BD) [18,19], and the 2020 Biodiversity Strategy (BS) [16]. This list was left mostly unaltered, with the sole exception of PO11, which is explicitly linked to GI deployment and was henceforth considered redundant, considering the method used to perform the literature review, further explained in Section 2.2.2 (Table 2).

2.2. Research Works Using Bio-Geophysical Indices

2.2.1. CGLS Vegetation and Energy Products

Nowadays, aerial and satellite remote sensing techniques are the foremost source of spatial information due to their capability to catch large areas and monitor bio-geophysical parameters with competitive spatial and temporal resolutions [42,43]. The bio-geophysical indices freely offered by the Copernicus Global Land Service through its vegetation and energy products can be applied to a wide range of thematic areas, such as global crop monitoring and food security; forest, water, and natural resources management; land carbon modelling; or weather and climate forecasting [40]. The indices have been validated using other existing global products derived from remotely-sensed data, mostly produced by the MODIS (Moderate-resolution Imaging Spectrometer) sensor platform [44]. Moreover, accuracy assessments have been performed through the comparison with ground-based reference data, especially from the 2012 Land Use and Cover Area frame Survey (LUCAS) [45].

Focusing on CGLS vegetation products (as of November 2018), the widely-used normalized difference vegetation index (NDVI) gives an indication of the current greenness of the natural surface [33,36]. Derived from this index are the VCI and VPI (vegetation condition and productivity indices; the latter has now been discontinued), which compare measured NDVI values respectively to its long-term average and to its historical maximum and minimum. Other products provide measurements of physical variables of the canopy: The leaf area index (LAI), the fraction of vegetation cover (FCOVER), and the fraction of radiation absorbed for the photosynthesis (FAPAR) quantify the density, extent, and health of the vegetation, respectively. On the other hand, dry matter productivity (DMP) and gross dry matter productivity (GDMP) feature the growth of standing biomass and have specific agronomic applications. The soil water index (SWI) adds complexity to the analysis by quantifying the moisture condition at various soil depths. Finally, the maps of burned areas delineate the zones of the globe that have been affected by fire events [34,46–65]. The Global Climate Observing System (GCOS) recognizes the maps of burned areas, FAPAR, LAI, and SWI as essential climate variables (ECVs) [40].

The energy bio-geophysical variables, on the other hand, assess the energy budget at the land surface. Top-of-canopy reflectance (TOCR) and surface albedo quantify the part of the sunlight reflected by the surface, respectively, dependent and independent from the angular observation conditions (the first has been discontinued). In addition, the land surface temperature (LST) indicates how hot or cold the ground is and depends on the surface albedo, vegetation cover, and soil moisture [66–69].

These bio-geophysical indices are useful for weather and climate forecasting as they are the resulting effect of key forcing variables controlling the energy exchanges between the continental surface and the atmosphere. Since they also detect how energy is distributed between the ground and vegetation, they have become essential for crop growth modelling. As a sensitive indicator of environmental vulnerability, surface albedo is especially efficient for the detection of land degradation and desertification [66–69]. Table 3 shows the CGLS products considered in the literature review together with their main characteristics.

Table 3. Main characteristics of the last-updated versions of the bio-geophysical indices considered in the literature review, provided by the Copernicus Global Land Service (CGLS) through its vegetation and energy products [40] (as of November 2018).

Index		Satellite Sensor	Spatial Resolution	Temporal Resolution	Temporal Coverage	Stage
Vegetation	FAPAR	PROBA-V SPOT-VGT, PROBA-V	300 m 1 km	10 days 10 days	01/2014–present 01/1999–present	Demonstration Operational
	FCOVER	PROBA-V SPOT-VGT, PROBA-V	300 m 1 km	10 days 10 days	01/2014–present 01/1999–present	Demonstration
	LAI	PROBA-V SPOT-VGT, PROBA-V	300 m 1 km	10 days 10 days	01/2014–present 01/1999–present	Demonstration
	NDVI	PROBA-V SPOT-VGT, PROBA-V	300 m 1 km	10 days NRT [1]: 10 days LTS [2]: 6 months	01/2014–present 04/1998–present 01/1999–12/2017	Operational
	VCI	PROBA-V SPOT-VGT	1 km 1 km	10 days 10 days	06/2014–present 01/2013–05/2014	Demonstration Operational
	VPI	PROBA-V SPOT-VGT	1 km 1 km	10 days 10 days	06/2014–07/2017 01/2013–05/2014	Demonstration Operational
	DMP/GDMP	PROBA-V SPOT-VGT, PROBA-V	300 m 1 km	10 days 10 days	01/2014–present 01/1999–present	Demonstration
	Burned Area	PROBA-V PROBA-V	300 m 1 km	10 days 10 days	04/2014–present 04/2014–08/2018	Pre-operational
	SWI	METOP(A&B)/ASCAT	25 km	SWI: 1 day SWI10 [3]: 10 days SWI-TS [4]: 6 months	01/2007–present 01/2007–present 01/2007–present	Operational
Energy	LST	METEOSAT (MSG); GOES; MTSAT/Himawari	5 km	LST: 1 hour LST10-DC [3]: 10 days LST10-TCI [5]: 10 days	10/2010–present 01/2017–present 01/2017–present	Operational
	Surface Albedo	PROBA-V SPOT-VGT	1 km 1 km	10 days 10 days	05/2014–present 12/1998–04/2014	Demonstration Operational
	TOCR	SPOT-VGT, PROBA-V	1 km	10 days	01/1999–08/2018	Demonstration

[1] Near-real time. [2] Long term statistics. [3] 10-day statistics of daily values. [4] Reformatting to time series format of daily values. [5] Thermal condition index with 10-day composites.

2.2.2. Literature Review

Having established a catalogue of the relevant NWRMs and related benefits (Section 2.1), we proceeded to perform a review of the scientific literature in order to estimate the potential of the vegetation and energy indices provided in the CGLS products to:

- Study natural water retention measures (NWRMs).
- Monitor their biophysical impacts (BPs).
- Observe the delivery of NWRM-linked ecosystem services (ESs).
- Assess the achievement of NWRM-related policy objectives (POs) expressed by EU directives and strategies.

Thus, we searched for scientific articles using the Google Scholar search engine, attesting whether a certain index had already been used, directly or indirectly, to detect or monitor the items in our catalogue. Google Scholar was the chosen tool to make the queries since more advanced bibliographical search engines display results based on the authors' names, the title of the article, and keywords that the article is associated with. However, the main title and the keywords usually concern the main topic or the final results of the research, rather than the followed methodology.

The querying procedure entailed, first, the choice of the search terms: Typing the name of a specific vegetation or energy index among those provided by the CGLS (Table 3) along with a word or expression describing one of the catalogued NWRMs, BPs, ESs, or POs (Tables 1 and 2). The search then yielded a list of articles, each of which was critically analyzed to ascertain whether it proved that the index had actually been used, or could be potentially used, to study the NWRM, BP, ES, or PO.

To critically decide whether an article actually proved a link between an index and a NWRM or benefit, a number of criteria were established, as described in step 2 of the followed procedure (Figure 2). It should be noted that a valid article did not necessarily have to cite the Copernicus program, nor did the indices it used have to be calculated using remote sensing data. It was also not necessary for a valid article to explicitly mention GIs or NWRMs or explicitly discuss ecosystem services and policy objectives.

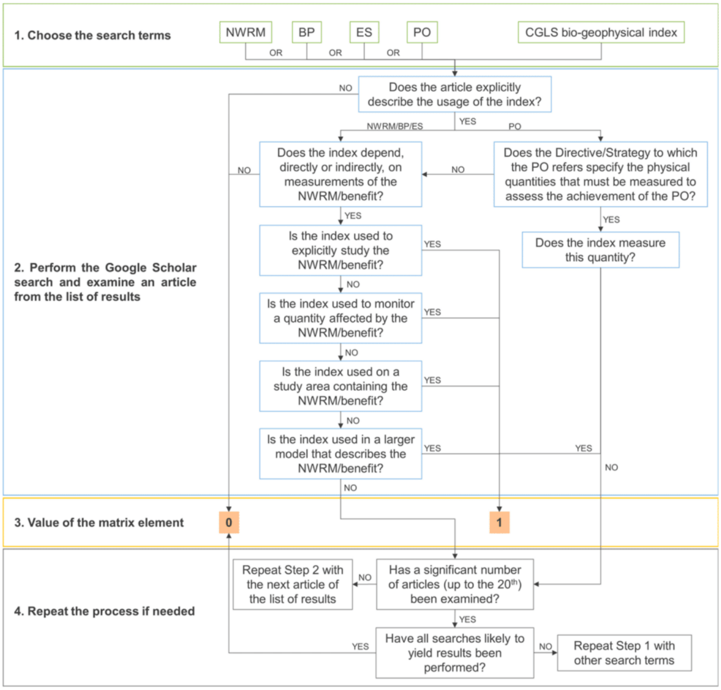

Figure 2. Flowchart of the followed procedure to perform each query and ascertain whether a given article was valid and effectively proved the existence of an actual or possible link between a bio-geophysical index and a NWRM, BP, ES, or PO.

The results of the literature review (i.e., the proven link between an index and a NWRM or benefit) were represented in a matrix form: Six matrices were prepared, displaying the links to CGLS products respectively of agriculture NWRMs, forest NWRMs, hydro-morphology NWRMs, BPs, ESs, and POs. Thus, each matrix cell corresponded to a given type of NWRM or related benefit and to a CGLS index. Should at least one article be found to prove a link between the two items, the cell value would be 1, else it would be 0.

2.3. *Quality of CGLS Products*

To obtain the final diagrams, we did not only assess, by reviewing the scientific literature, the actual or possible link between the bio-geophysical indices and each of the NWRMs and their resulting benefits; we also evaluated the quality that users could expect when using CGLS products. We thus carried out a well-grounded study of each vegetation and energy product, studying in deep detail the validation and accuracy assessment reports and user guides as of November 2018 [40,46–69] to fully understand the input data used, the algorithm developed, and the resulting output product. Using this information, a quality assessment was formulated for each version of every available product, which is shown in Table 4.

Table 4. Quality and accuracy assessments of the bio-geophysical indices provided by the Copernicus Global Land Service (CGLS) vegetation and energy products, evaluating the product continuity, spatial consistency, temporal consistency, and accuracy as either good (G), acceptable (A), moderate (M), or poor (P) as in the consulted references [40] (as of November 2018).

Index		Spatial Resolution	Product Continuity	Spatial Consistency	Temporal Consistency	Accuracy	References
Vegetation	FAPAR	300 m 1 km	P G	A A	A G	G A	[46–48]
	FCOVER	300 m 1 km	P G	A A	A G	P A	[46–48]
	LAI	300 m 1 km	P G	A A	A G	G A	[46–48]
	NDVI	300 m 1 km	G G	G G	- G	- -	[46,49]
	VCI	1 km (SPOT-VGT) 1 km (PROBA-V)	G G	G G	G G	- -	[50,51]
	VPI	1 km	G	G	G	-	[51,52]
	DMP/GDMP	300 m 1 km	M G	A A	A G	M M	[53]
	Burned Area	300 m 1 km (PROBA-V) 1 km (SPOT-VGT)	- - -	G - -	- - P	- G P	[54–63]
	SWI	25 km	G	A	G	G	[64,65]
Energy	LST	5 km	G	A	G	G	[66,67]
	Surface albedo	1 km (PROBA-V) 1 km (SPOT-VGT)	P P	A G	G G	P G	[68,69]
	TOCR	1 km	P	A	G	-	[66,67]

As previously shown in Table 3, almost all vegetation indices from CGLS offer two products with different spatial resolutions (SRs), either of 300 m or 1 km, except for VCI and VPI, currently just calculated using the NDVI 1 km product, and SWI, with a 25 km SR. On the other hand, energy indices are available with either 1 km (surface albedo and TOCR) or 5 km (LST) SRs. As for their temporal resolution (TR), almost all products are acquired every 10 days. NDVI 1 km, SWI, and LST offer both near-real time data and long-term composites with different TRs. Specifically, the NDVI 1 km product provides data every 10 days but also as a 6-month composite; the SWI product gives new data daily, every 10 days, as statistic composites and every 6 months as time series; and finally, LST is available hourly, daily, and every 10 days as composites of the daily values.

The quality was assessed on the basis of the product continuity, spatial and temporal consistencies, and accuracy and according to the categories of good, acceptable, moderate, or poor, as used along the consulted reports from the CGLS. The product continuity depended on the existence of large fractions of missing values or noisy and unreliable distributions around the globe, with no correlations between homogeneous sites. Thus, some products showed a bad continuity due to not properly covering the entire globe, showing large fractions of missing values in Northern latitudes, equatorial areas, and during winter time.

On the other hand, spatial and temporal consistencies measured whether there were large discrepancies between values relative to homogeneous areas and consecutive dates, respectively. The temporal consistency also took into account whether the temporal profiles were smooth or noisy. As for the accuracy, it was considered poor when values were either over or under-estimated compared to ground-truth data [45] or MODIS products [44]. For instance, FCOVER showed a poor accuracy over flooded vegetation, but positive results for bare and harvested areas, in comparison with FCOVER calculated with MODIS satellite sensor, according to the consulted reports [46–48].

Overall, the quality assessment was either good or acceptable for most of the products, being poor mainly for the newest versions of 300 m SR and still in the "demonstration" stage, such as FAPAR, FCOVER, LAI, or DMP [46–48,53]. That said, FCOVER remains a good candidate for replacing classical vegetation indices for the monitoring of ecosystems due to its sensitiveness to the vegetation amount without depending on the illumination direction [34].

As for the FAPAR and LAI 300 m versions, they showed poor or acceptable product continuity and spatial and temporal consistencies, but accuracy was good when comparing values with reference data [46–48]. VCI and VPI directly depend on the NDVI 1 km product and hence on the length of historical series available, the cloud contamination in the dataset, or existence of snow, which sometimes leads to below normal values, not corresponding to low vegetation activity, of all the indices. Hence, the user should always consider new products and see if the trend persists [50–52].

As for the energy indices, the overall quality was good. A "poor" assessment was given only to the product continuities of surface albedo and TOCR due to missing values over Northern latitudes and equatorial areas in wintertime. Spatial consistencies were considered acceptable since reliable and consistent values are obtained globally but unrealistic values result when analyzing locally snowy or cloudy areas. The temporal profiles, finally, are reliable when comparing PROBA-V, SPOT-VGT, and MODIS values, showing a good intra-annual precision [66–69].

2.4. Diagrams

The results of the literature review (Section 2.2) and the quality assessments (Section 2.3) were represented through Sankey diagrams. Moreover, since interpreting results derived from Sankey diagrams might be difficult due to the significant amount of illustrated information, even though the foremost aspects are easily visualized, user-friendly flowcharts were also produced.

2.4.1. Sankey Diagrams

A Sankey diagram is a particular type of flow diagram. Within such a diagram, entities (nodes) are represented by rectangles or text, connected by lines whose thickness expresses the quantitative relationship between them. These diagrams are particularly suited to represent results organized in matrices [70]. Plotly was the chosen tool to construct the Sankey diagrams since it supported coding in Python [71]. Six Sankey diagrams were constructed, one for each of the matrices obtained from the literature review (Section 2.2) (Table 5).

Each diagram is arranged in 4 columns. The columns contain nodes corresponding to, from left to right: (i) catalogued agriculture NWRMs, forest NWRMs, hydro-morphology NWRMs, ESs, BPs, or POs; (ii) bio-geophysical indices provided by the CGLS vegetation and energy products; (iii) product versions depending on the available spatial resolutions; and (iv) characteristics considered in the quality assessments (see for example Figure 3, representing the agriculture NWRM diagram).

Table 5. Matrix representing the links of the evaluated agriculture NWRM and CGLS. Cell values of 1 or 0 indicate, respectively, whether an article indicating the actual or potential use of a given index to monitor a given agriculture NWRM was found or not during the review of research works.

Agriculture NWRM	FAPAR	FCOVER	LAI	NDVI	DMP/GDMP	Burned Area	SWI	LST	Surface Albedo	TOCR
A1	1	1	1	1	1	1	1	1	1	1
A2	0	1	1	1	0	0	0	0	0	1
A3	1	1	1	1	1	1	1	0	1	1
A4	0	0	1	1	0	0	0	0	0	0
A5	1	1	1	1	1	0	0	0	1	1
A6	1	1	1	1	1	0	0	0	1	1
A7	0	1	1	1	1	0	0	0	1	1
A8	0	1	1	1	1	0	0	1	1	1
A9	1	0	1	1	1	0	0	0	1	1
A10	0	1	1	1	1	0	0	0	1	1
A11	0	0	1	1	0	0	0	0	0	0
A12	0	1	1	1	1	0	0	0	1	1
A13	0	1	1	1	1	1	0	0	1	1

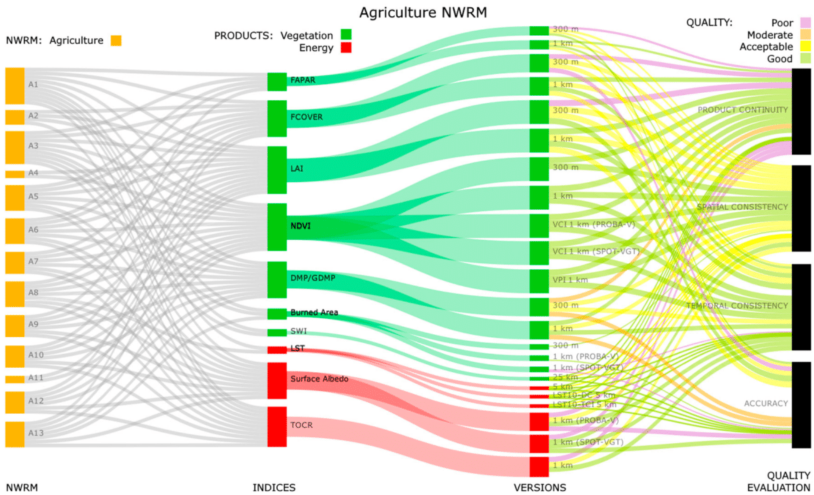

Figure 3. Sankey diagram linking the vegetation and energy indices to the agriculture NWRM that they can be employed to study and monitor, according to previous research works, and to their versions available in the Copernicus Global Land Service, which are in turn linked to expected quality. The short-names of the catalogued NWRM are explained in Table 1.

The nodes in the two leftmost columns are linked by lines, which mirror the cells of the matrix to which the Sankey diagram is related: If the value of a matrix cell (T_{ij}), concerning an i-th index and a j-th NWRM, ES, BP, or PO, is equal to 1, a line linking the respective nodes exists, whereas if T_{ij} is equal to 0, no such line is represented. The index nodes in the second column are then connected to their available versions, as provided by CGLS, in the third column. Finally, these versions are linked to the quality assessment parameters in the fourth column via color-coded lines: The line color indicates whether a product version has been evaluated with respect to a particular parameter as poor, moderate, acceptable, or good (Table 4).

It is worth mentioning that the NDVI node in the second column is linked to nodes in the third column relative to the available NDVI, VCI, and VPI versions, in light of the fact that the two latter products are derived directly from the former [40,50–52].

The width of each node of the three leftmost columns (represented as N_j, P_i, and V_{ik}, corresponding to NWRM or benefits, indices, and versions, *k* being the product version number) depends on the following equations (Equations (1)–(3)):

$$N_j = \sum_i T_{ij}, \quad (1)$$

$$P_i = \sum_j T_{ij}, \quad (2)$$

$$V_{ik} = \frac{1}{2} P_i, \ \forall k. \quad (3)$$

Thus, the width of a NWRM, BP, ES, or PO node depends on how many indices have been indicated by previous scientific works to be suitable for the direct or indirect study of the said NWRM, BP, ES, or PO. The width of an index node, on the other hand, shows how many NWRMs, BPs, ESs, or POs that index can study, again on the basis of previous research works.

2.4.2. User-Friendly Flowcharts

With the aim of merging all the information and assisting actual GI users in selecting the potentially most suitable remotely-sensed bio-geophysical indices for analyzing NWRMs and their benefits, we designed user-friendly decision flows. These flowcharts lead from a given category of NWRMs, BPs, ESs, or POs to the CGLS index that is most appropriate for studying a wider variety of items belonging to the aforementioned category, on the basis of previous scientific research, and inform the user on the spatial resolution and temporal coverage (which is important for long time-series analyses) that are available in CGLS.

3. Results

3.1. Interpreting the Sankey Diagrams

The main result of the work that we performed is the linking of the vegetation and energy indices freely available in the CGLS to NWRMs, BPs, ESs, and POs, on the basis of scientific articles that were found through a deep literature review. Sankey diagrams are useful to visualize the proportional flow and relationships between the different nodes within a network. They were thus well-suited to the representation of the above-mentioned links.

The six diagrams designed are meant to quickly show which vegetation and energy indices, available from the CGLS products, appear as the most suitable (according to previous research works) for the study and monitoring of NWRMs, ESs, BPs, and POs. Moreover, the diagrams show the quality that can be expected when employing the various versions of the CGLS products.

All the produced Sankey diagrams are displayed in Appendix A. As an example to interpret them, Figure 3 shows explicitly the diagram for the agriculture NWRMs. The linking lines between the nodes of the two leftmost columns (respectively representing the agriculture NWRMs and the bio-geophysical indices and hence their connection according to the reviewed works) are based on the matrix shown in Table 5, and hence on the cell values being either 1 or 0, as explained in detail in Section 2.4.1. The links with the two other columns are instead based on the data displayed in Table 4.

Overall, the diagram reveals, by analyzing each node width and the links between them along the different columns, the following information:

- Which NWRMs or benefits (Tables 1 and 2) have been successfully connected to the greatest number of bio-geophysical indices. This information can be ascertained from the widths of the diagram's nodes of the leftmost column. In this specific diagram, the agriculture NWRMs that were suitably highlighted using most of the CGLS indices are meadows and pastures (A1) and crop rotation (A3), while solely two links and just with vegetation indices were found for strip cropping along contours (A4) and controlled traffic farming (A11).

- Which CGLS vegetation indices have been used to identify and monitor the greatest number of NWRMs and benefits. The width of the green nodes of the second column, which depends on the number of connections to the nodes of the first column (i.e., how many NWRM or benefits each bio-geophysical index can actually or potentially study, according to the scientific literature), communicates this information. In this diagram, the normalized difference vegetation index (NDVI) and the leaf area index (LAI) are the vegetation indices showing the largest number of links to agriculture NWRMs and hence the greatest width, which implies they are capable of studying a wider variety of agriculture NWRMs. They are followed by the fraction of vegetation cover (FCOVER) and the dry matter productivity (DMP)/gross dry matter productivity (GDMP). The burned area and soil water index (SWI) are the least used vegetation indices.
- The most used CGLS energy indices. The width of the red nodes of the second column, which depends again on the number of linking lines leading to them and hence on the indices' suitability to monitor the NWRM or benefits in the first column, conveys this information. In this case, top-of-canopy reflectance (TOCR) is the energy index with the largest width and thus is capable of monitoring more agriculture NWRMs, closely followed by surface albedo. On the other hand, land surface temperature (LST) appears as the least used energy index.
- The available versions (depending on the existing spatial resolutions) and the quality that users can expect when using the products. This information is shown in the third and fourth columns. Most of the products show a proper continuity along the globe with a minor amount of lost data, especially in Southern latitudes and during summertime, and a good temporal consistency for long-term analysis, with smooth temporal profiles (green lines). As for the spatial consistency, it is acceptable (yellow lines) for more than half of the products, with discrepancies when comparing values between homogeneous areas. Accuracy varies widely and has not been assessed for a significant number of product versions (Table 4). It is worth highlighting that the lines connecting the third and fourth columns are equivalent in all six Sankey diagrams.

3.2. Understanding the User-Friendly Flowcharts

As previously mentioned, Sankey diagrams display such a large amount of information that we deemed it necessary to create more easy-to-read flowcharts to show just the most substantial results. All these charts are held in Appendix B and their aim is to help users in their decision-making tasks by indicating solely the most appropriate indices (according to the reviewed research works) for the monitoring of each category of items (NWRMs, BPs, ESs, and POs). The diagrams also show the temporal coverage of each version (300 m and 1 km) of these indices. This way, users can decide whether a better spatial resolution or a longer temporal coverage is preferable for their analyses and choose the most suitable product accordingly. Figure 4 is presented to illustrate how the final charts look.

Clearly, these flowcharts are easier to comprehend than Sankey diagrams, though it is the latter that truly hold all the outcomes of our research. This chart was specifically created for NWRM and shows that NDVI and LAI are both the indices that allow the monitoring of the greatest number of agriculture NWRMs. NDVI remains the index that lets us study the widest range of forest NWRMs, while TOCR is the recommended index for identifying hydro-morphology NWRMs. All the above-mentioned vegetation indices are available in the CGLS as two different products: 300 m and 1 km spatial resolutions; while TOCR is currently just offered as a 1 km product.

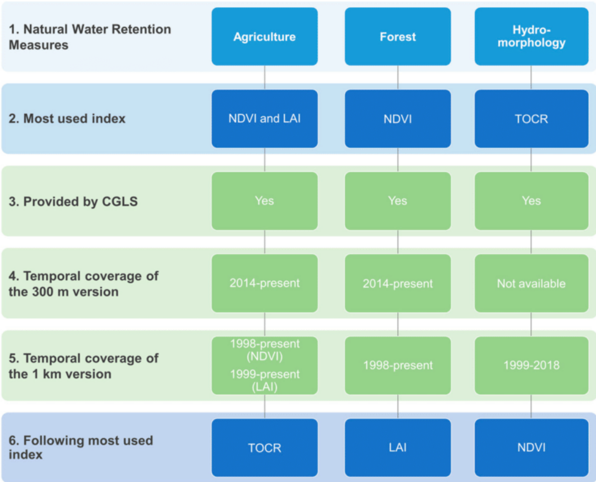

Figure 4. Decision flowchart indicating the most suitable indices available in the Copernicus Global Land Service for the monitoring of natural water retention measures.

4. Discussion

Nowadays, supporting the development of nature-based measures, such as GIs or, more specifically, NWRMs, is very appreciated by policy makers since it contributes simultaneously to the achievement of several policy goals from water-related EU directives and climate change policies [10,12,13]. However, the lack of a well-grounded framework that allows the assessment of the multiple benefits of green infrastructures, including the improvement of the resilience of ecosystems, the achievement of policy goals, and cost-effectiveness, makes its implementation not yet truly operational [25,26]. Stakeholders and decision makers need to properly monitor and evaluate the effectiveness and impacts of the measures they are implementing [26,29,41]. Thus, aiming to support the successful implementation of NWRMs by promoting the use of the best available monitoring techniques, we reviewed the use of the bio-geophysical indices that are obtained from remotely-sensed earth observation data (and that are freely available in the CGLS [40]). Overall, they have proved to be certainly suitable to monitor most of the catalogued NWRMs, biophysical impacts, ecosystem services, and policy objectives (Table 2).

Analyzing both the final decision flowcharts (Appendix B) and the Sankey diagrams (Appendix A), some general trends can be noticed. For instance, NDVI is the most successfully used index, not only for the monitoring of agriculture and forest NWRMs but also for NWRM-related biophysical impacts. This is partly to be expected, given that this well-known parameter has actually been the most widely used vegetation index for decades, especially for monitoring vegetation health and growth [33,36,72,73], and hence an extensive scientific literature employing NDVI exists, starting from its first use in 1973 [74]. According to the reviewed articles, LAI also stands out as one of the most suitable indices for the monitoring of both agriculture NWRMs and "direct" biophysical impacts (slowing and storing run-off and reducing run-off), while TOCR is the following most used index in both categories (Figures 4 and A8 in Appendix B).

Turning to the detection of the accomplishment of policy objectives from the Water Framework [22], Floods [24], Habitats [18], and Birds [19] EU Directives and the 2020 Biodiversity Strategy [16], it would appear that energy indices are the ones potentially most useful for this purpose. Specifically, TOCR is recommended for detecting the accomplishment of policy objectives linked to the first four directives, while DMP is the first choice for assessing the goals of the biodiversity strategy. In both cases, surface albedo is the following choice. Both TOCR and DMP have a very competitive temporal coverage, offering data from 1999 with 1 km spatial resolution globally. The main disadvantage of TOCR is that it is not available with a spatial resolution of 300 m yet (although we should point out that the TOCR 1 km version has been discontinued in 2018, awaiting the transition to Sentinel-2 data, which will solve this handicap) [40]. Thus, use of it would depend on the user's needs: Desired level of detail and range of temporal coverage. The use of 300 m DMP products, which offer data from 2014, might be a better approach when analyses require a better spatial resolution (Figure A10 in Appendix B).

Regarding the delivery of ecosystem services, DMP stands out as the most recommended index for identifying NWRM-related provisioning services. On the other hand, a large set of indices is attested to be suitable for monitoring regulatory and maintenance services: NDVI, LAI, FCOVER, and TOCR. Except for TOCR, all indices are available in the CGLS as 300 m global products and data is offered from 1999 (1998 for NDVI) using 1 km versions [40] (Figure A9 in Appendix B).

It must be recognized that the bio-geophysical indices that appear to be the most recommended ones to identify and monitor NWRMs and their benefits are also the most consolidated, meaning that more scientific works employing them exist. FCOVER is an exception to this: It is a relatively new index, but it is considered as a promising replacement for classical vegetation indices [34,46–48] and this is visible in the developed diagrams, where its suitable use is frequently almost equivalent to LAI, NDVI, and DMP. On the other hand, FAPAR, burned area, and SWI seem to be overall the least used vegetation indices according to the literature review. Only in the Sankey diagram concerning the policy objectives addressed in the EU directives and the 2020 Biodiversity Strategy [16,18,19,22,24] does FAPAR show the same potential as FCOVER and LAI, mostly due to its links to biodiversity-related objectives (Figure A6 in Appendix A).

Let us now consider how suited NWRM and NWRM benefits are at being studied using CGLS products, which would definitely help in the framework of their truly operational implementation [25, 26]. Agriculture NWRMs stand out as the nature-based measures for water retention that could be conceivably monitored through a larger set of bio-geophysical indices. This is especially true for meadows and pastures (A1) and crop rotation patterns (A3) (Figure A1 in Appendix A). Also, forest riparian buffers (F1) and land use conversion (F5) are linked to a high number of indices (Figure A2). It should be noted that riparian vegetated buffer strips have been widely discussed in the literature due to their ability to enhance and protect water quality, soil moisture, and river streams [15,75], more economically than would be possible to achieve through the implementation of traditional grey defenses [76].

On the other hand, no links were found for some forest-based measures, such as sediment capture ponds (F9) or overland flow areas in peatland forests (F14). A first hypothesis could be that this happens because energy and vegetation indices are not particularly suitable for the identification of hydrological features. However, wetland restoration and management (N2), floodplain restoration and management (N3), and restoration of natural infiltration to groundwater (N13) are hydro-morphology measures linked to a relatively large set of vegetation and energy indices (Figure A3). This fact highlights the potential of CGLS indices for the study of most NWRMs, even the aquatic ones. Thus, these apparently harder-to-monitor NWRMs might also be the least established in the scientific literature and hence hotspots to consider in future developments and research as pilot projects to test the hands-on condition and effectiveness of these NWRMs.

Our results thus show that NDVI and LAI are the indices that allow the monitoring of most NWRM-related biophysical impacts, as well as most agriculture and forest NWRMs. However, TOCR and DMP stand out as the most appropriate indices when studying the accomplishment of EU policy objectives, in line with the result obtained for NWRM-related ecosystem services.

A significant limitation of the present work that must be acknowledged is that our approach was solely reliant on the review of existing already-published literature. Thus, it could be argued that some NWRMs or related benefits could be monitored by more indices than those revealed by our review, even though no one has performed this analysis in the past [25,26,29,40]. It is even more likely that some of the newly developed bio-geophysical indices may have a great potential not yet assessed through scientific experiences. We are also aware that we might not have found articles linking the study of a given NWRM, ES, BP, or PO with the use of a certain index, in which case the matrices developed would contain false negatives (zeros).

Finally, users exploiting our results should not neglect to verify, even for highly recommended indices, that the available spatial and temporal resolutions are adequate to their needs. To this end, understanding the observation needs by collecting and consolidating GI users' requirements will lead to maximization of their fulfilment [77].

In this sense, the temporal resolution of most of the CGLS products is very competitive, offering new data every 10 days at a global scale, which might fulfil the user requirements for any scale of their analyses and examined phenomenon. The issue of the spatial resolution is however more complex: CGLS products are currently available with either 300 m or 1 km spatial resolutions, which might or might not be acceptable for the users, highly dependent on the required level of detail. Thus, when GI users might need an analysis to be performed at a local level of detail, these products will almost surely not accomplish their requirements, which probably call for a spatial resolution of around 10 m (such a resolution is, for instance, currently provided by the Sentinel-2 MSI satellite sensor). It is for this reason that we advise that, as we analyzed in this work the suitability of the global Copernicus Land products for studying GIs/NWRMs and their benefits and policy goals, so should the appropriateness of the pan-European and local Copernicus products be assessed in future research, even if entailing different kinds of products [40].

5. Conclusions

From the obtained results, we are able to draw the following main conclusions:

- Remotely-sensed satellite data keeps proving its high potential for monitoring the Earth, easing spatial planning and land use management tasks in large areas.
- The examined vegetation and energy bio-geophysical indices, freely provided by the Copernicus Global Land Service (CGLS) products, are able to monitor most natural water retention measures (NWRMs) and their benefits, by which we mean NWRM biophysical impacts, delivered ecosystem services, and the accomplishment of NWRM-related policy objectives. Overall, the most suited vegetation indices are firstly the normalized difference vegetation index (NDVI) and secondly the leaf area index (LAI), while the most used energy index is top-of-canopy reflectance (TOCR).
- We can thus see that the apparently most useful indices are the older ones, which can be used in a wide variety of contexts. NDVI remains the most suitable index based on the literature review.
- Some newly-developed indices are also promising alternatives: The fraction of green vegetation cover (FCOVER), in particular, has shown its potential to replace or complement consolidated indices and we are implementing new research in that direction [78].
- Just 8 out of the 80 catalogued NWRMs and related benefits were not linked to any index, which shows the indices' potential for testing real NWRM pilot cases, providing a first baseline that, combined with future multidisciplinary research, eases the successful implementation of the same or similar measures. This may be due to: (i) No studies having been carried out on that specific subject or (ii) no indices being actually capable of monitoring the item. Future research could focus on studying this issue in detail.
- Potential users should consider that the CGLS was not conceived as a database of complete and final products but as input data for researchers and institutions to develop new down-streaming services and evolve more detailed and scalable models, policies, strategies, planning, or management tools, with the aim of enhancing Earth monitoring and the detection of land changes and land uses, as well as assessing and encouraging the use of nature-based solutions for climate change adaptation.
- The developed Sankey diagrams and final user-friendly flowcharts will hence help GI users in their decision-making tasks, providing information on the most suitable indices (according to the scientific literature) to monitor both NWRMs and their benefits. Moreover, the diagrams

indicate the quality and accuracy that the user can expect when downloading and using the CGLS products.

- The temporal coverage of the CGLS products is very competitive, particularly considering that most of them cover the globe every 10 days, surely fulfilling several users' requirements on this regard, for any level of detail of their analyses. Also, most of the 1 km versions provide data from 1999, which allow studies using very long-term data series, also taking advantage of a good overall temporal consistency and data continuity along the globe, especially with almost no gaps during summertime and in Central and Southern latitudes. When instead analyzing data in Northern latitudes or wintertime, users should consider double-checking consecutive dates, homogeneous areas, and temporal profiles. Spatial consistency and accuracy should also be verified by the users, checking data from different sensors or for the same areas in several locations, since the reviewed technical documents show overall low, acceptable, or not-yet-assessed results for these two quality parameters.
- Since Copernicus aims to meet the needs for ecosystem analyses on a global scale coming from national and regional public agencies countries and political/economic unions, such as the USA and the EU, a global and systematic acquisition system (i.e., able to acquire the Earth surface almost continuously and systematically with very competitive spatial resolutions) is a fundamental requirement for the Copernicus evolution. Specifically, referring to the spatial resolution, our study highlights the need for the Copernicus program to develop 300 m versions of all global indices, as this would make them considerably more useful, at least for intra-national and global scale analyses of the provided data. A coarse spatial resolution is unfortunately a significant handicap (e.g., as proven for the TOCR product). Accuracy assessments should also be provided for all the product versions.
- The findings of this study are also valuable for the performance of a gap analysis between the available Copernicus products and operational user needs, as we are starting to work on [77]. Indeed, the European Commission has placed increasing interest in the collection of requirements to support the work of different institutional and private communities among the Member States. Thus, stakeholder needs, in terms of Copernicus products and services, can be identified through elicitation techniques and compared to the review hither performed in order to validate the information collected. This integration would provide the baseline not only for the advancement in technological provision, but also for the elaboration of policy recommendations in the domain of agriculture and environmental protection.

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Appendix A. Sankey Diagrams

This appendix contains all the Sankey diagrams derived from the presented review. Section 2.4.1 explained how these diagrams were developed. Each catalogued item was identified with an acronym (Tables 1 and 2) while the main characteristics and quality assessment of the Copernicus Global Land Service (CGLS) products are shown in Table 4.

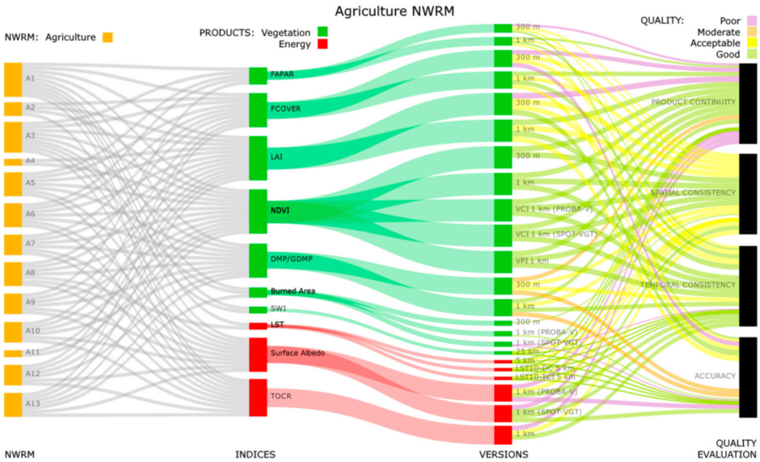

Figure A1. Sankey diagram linking the agriculture NWRM (A) and the CGLS vegetation and energy indices that are suitable for their monitoring, according to previous research experiences.

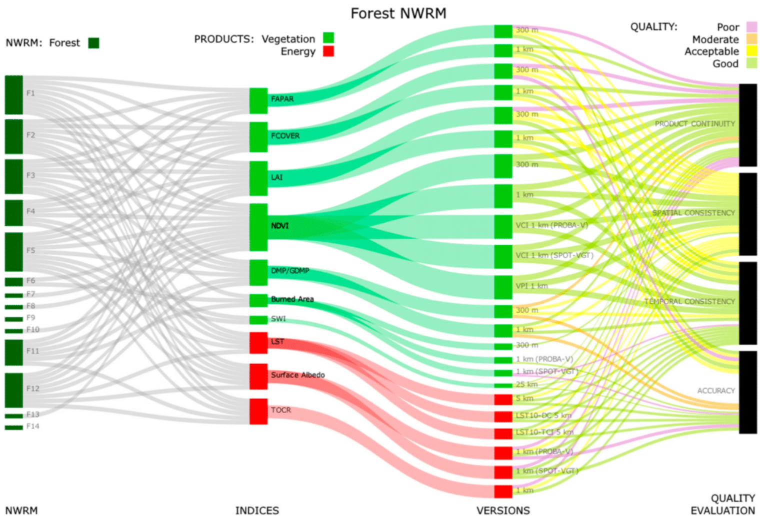

Figure A2. Sankey diagram linking the forest NWRM (F) and the CGLS vegetation and energy indices that are suitable for their monitoring, according to previous research experiences.

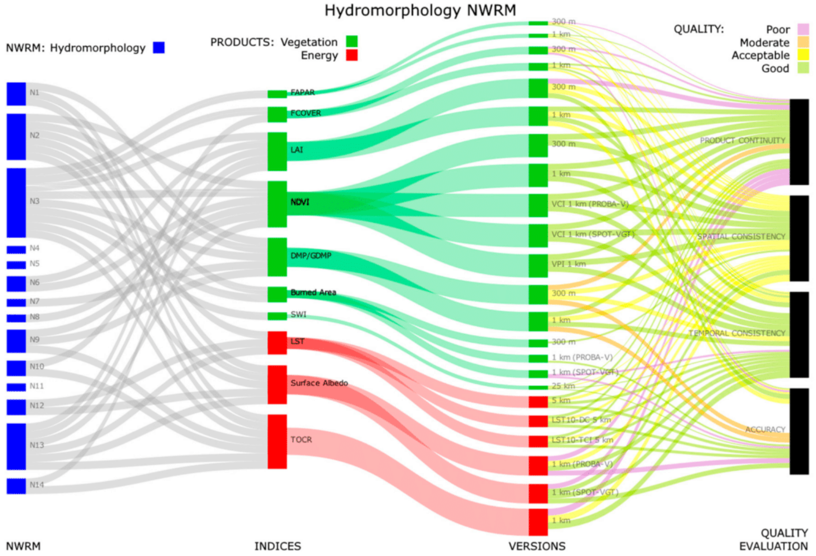

Figure A3. Sankey diagram linking the hydromorphology NWRM (N) and the CGLS vegetation and energy indices that are suitable for their monitoring, according to previous research experiences.

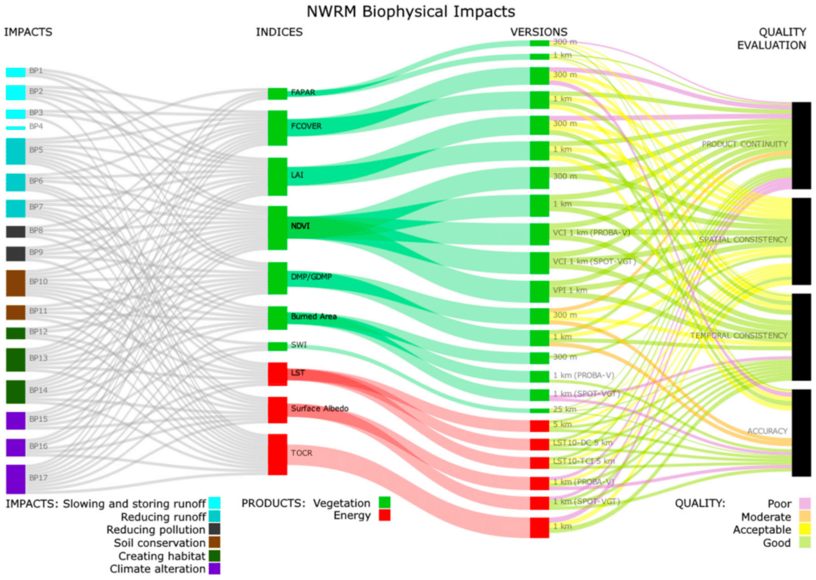

Figure A4. Sankey diagram linking the vegetation and energy indices that according to previous experiences are suitable for monitoring the biophysical impacts (BP) resulting from the application of natural water retention measures (NWRMs).

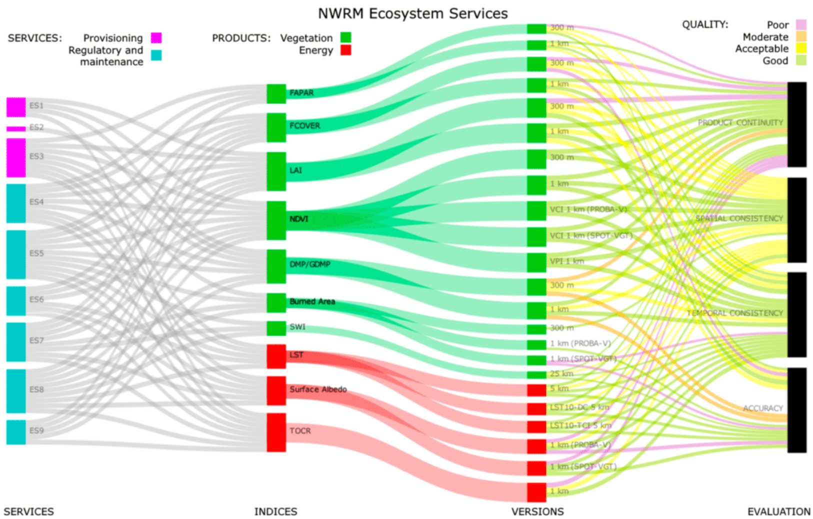

Figure A5. Sankey diagram linking the vegetation and energy indices that according to previous experiences are suitable for monitoring the ecosystem services (ES) delivered by natural water retention measures (NWRMs).

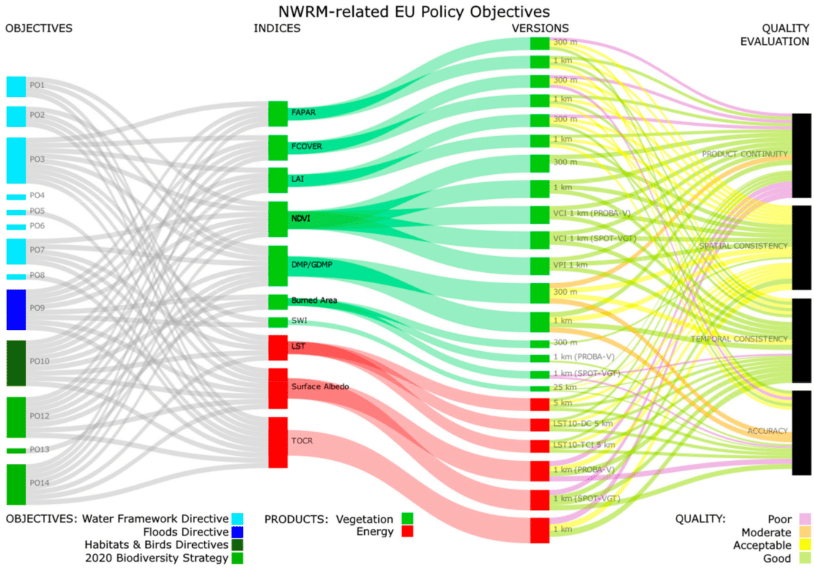

Figure A6. Sankey diagram linking the vegetation and energy indices that according to previous experiences are suitable for monitoring the achievement of policy objectives (PO) through the application of natural water retention measures (NWRMs).

Appendix B. Decision Flowcharts

This appendix contains all the final user-friendly flowcharts derived from the presented review. Section 2.4.2 explained how these diagrams were developed. Each catalogued item was identified with a short name (Tables 1 and 2) while the main characteristics of the Copernicus Global Land Service (CGLS) products are shown in Table 3.

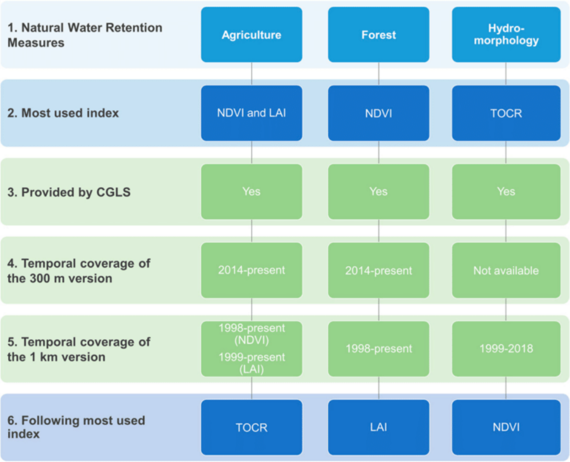

Figure A7. Decision flowchart indicating the most suitable indices available in the Copernicus Global Land Service for the monitoring of natural water retention measures.

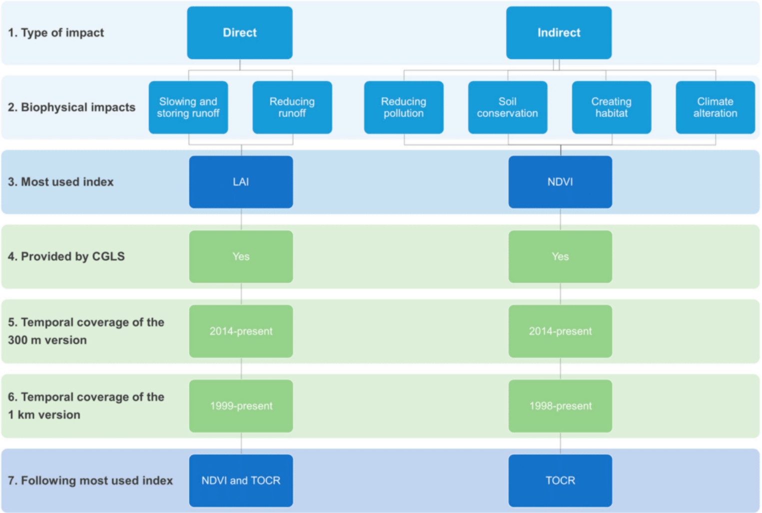

Figure A8. Decision flowchart indicating the most suitable indices available in the Copernicus Global Land Service for the monitoring of NWRM biophysical impacts.

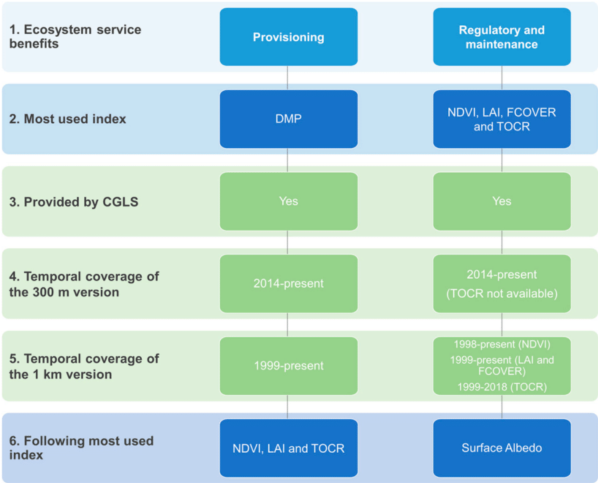

Figure A9. Decision flowchart indicating the most suitable indices available in the Copernicus Global Land Service for the monitoring of ecosystem services provided by NWRMs.

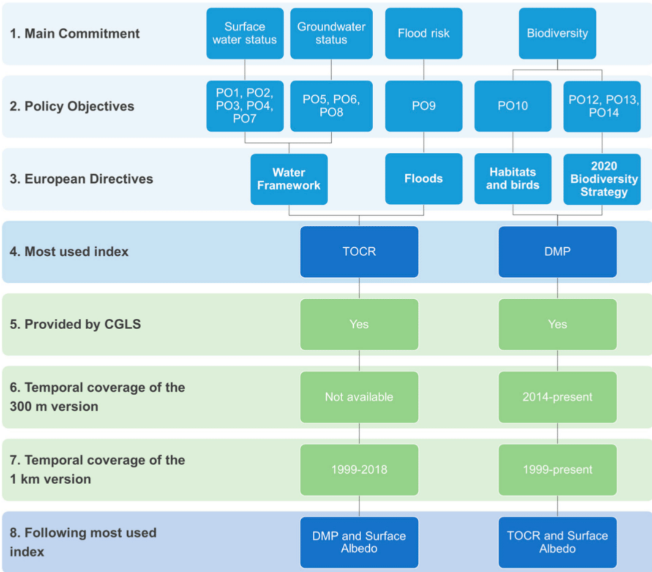

Figure A10. Decision flowchart indicating the most suitable indices available in the Copernicus Global Land Service for the monitoring of the achievement of NWRM-related EU policy objectives.

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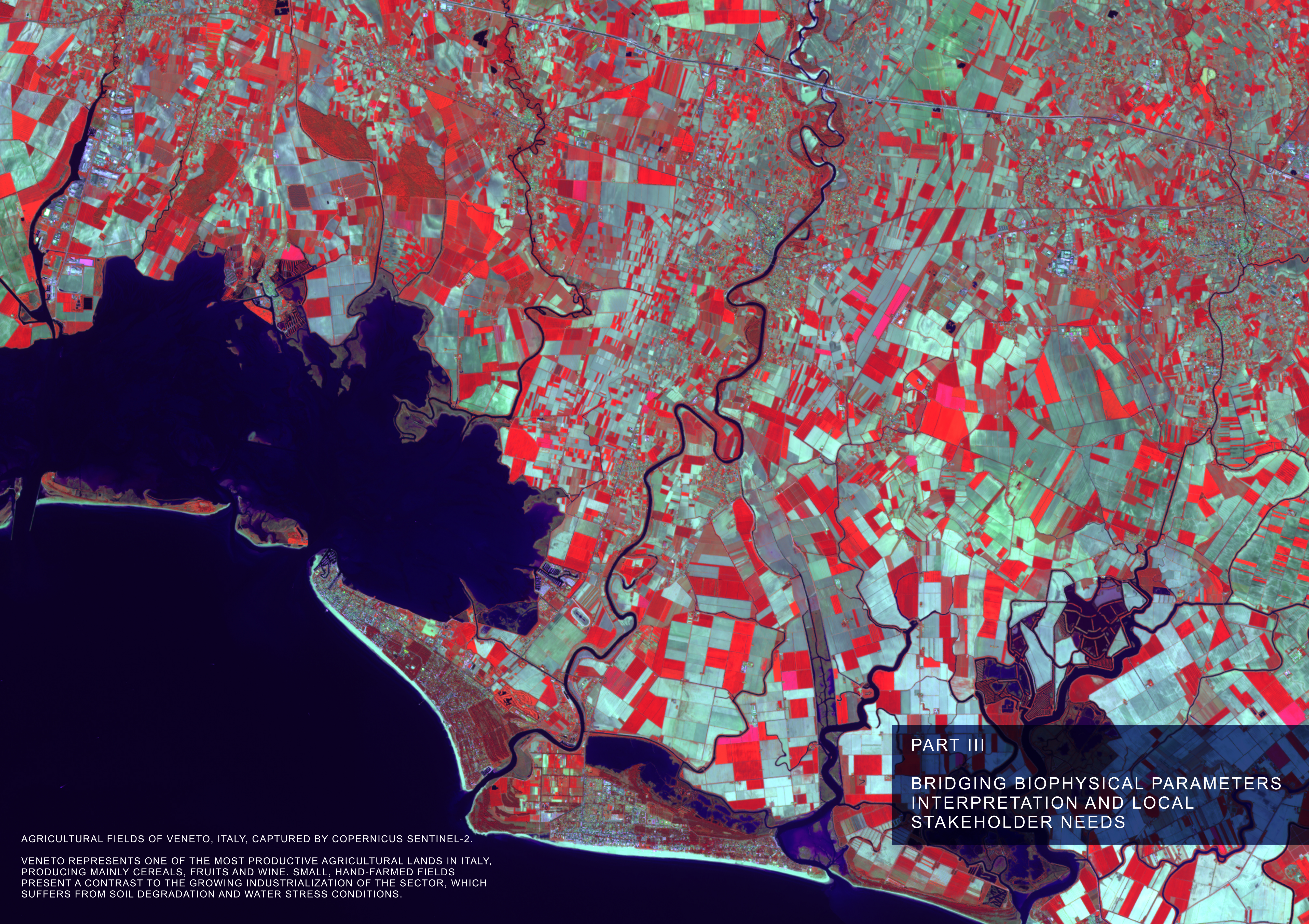

PART III

BRIDGING BIOPHYSICAL PARAMETERS INTERPRETATION AND LOCAL STAKEHOLDER NEEDS

AGRICULTURAL FIELDS OF VENETO, ITALY, CAPTURED BY COPERNICUS SENTINEL-2.

VENETO REPRESENTS ONE OF THE MOST PRODUCTIVE AGRICULTURAL LANDS IN ITALY, PRODUCING MAINLY CEREALS, FRUITS AND WINE. SMALL, HAND-FARMED FIELDS PRESENT A CONTRAST TO THE GROWING INDUSTRIALIZATION OF THE SECTOR, WHICH SUFFERS FROM SOIL DEGRADATION AND WATER STRESS CONDITIONS.

Part III – Bridging biophysical parameters interpretation and local stakeholder needs

Paper II: HidroMap: A New Tool for Irrigation Monitoring and Management Using Free Satellite Imagery

International Journal of *Geo-Information*

MDPI

Technical Note

HidroMap: A New Tool for Irrigation Monitoring and Management Using Free Satellite Imagery

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Abstract: Proper control and planning of water resource use, especially in those catchments with large surface, climatic variability and intensive irrigation activity, is essential for a sustainable water management. Decision support systems based on useful tools involving main stakeholders and hydrological planning offices of the river basins play a key role. The free availability of Earth observation products with high temporal resolution, such as the European Sentinel-2B, has allowed us to combine remote sensing with cadastral and agronomic data. This paper introduces HidroMap to the scientific community, an open source tool as a geographic information system (GIS) organized in two different modules, desktop-GIS and web-GIS, with complementary functions and based on PostgreSQL/PostGIS database. Through an effective methodology HidroMap allows monitoring irrigation activity, managing unregulated irrigation, and optimizing available fluvial surveillance resources using satellite imagery. This is possible thanks to the automatic download, processing and storage of satellite products within field data provided by the River Surveillance Agency (RSA) and the Hydrological Planning Office (HPO). The tool was successfully validated in Duero Hydrographic Basin along the 2017 summer irrigation period. In conclusion, HidroMap comprised an important support tool for water management tasks and decision making tackled by Duero Hydrographic Confederation which can be adapted to any additional need and transferred to other river basin organizations.

Keywords: remote sensing; irrigation; satellite imagery; landsat-8; sentinel-2; NDVI; desktop-GIS; web-GIS; software development

1. Introduction

Water plays a key role in all natural ecosystems. It is the essential resource for the survival of all living organisms. Irrigation farming consumes around 70% of the total annual withdrawal of fresh water [1], which contributes to increasing agricultural productivity, mainly in unproductive arid lands [2,3]. However, irregular water uses and climate change effects involves the overexploitation of a large number of aquifers and the degradation of water quality sources [4]. This unsustainable water balance and the variability of water world cycles turn water to an increasingly scarce and limited resource [5–7]. Therefore, in order to stop and reverse this process, it is essential to adopt several measures focused on controlling runoff water and groundwater uses in the framework of farming irrigation [8,9]. Many studies and projects were conducted to assess and control agricultural irrigation activity [10–12]. For example, many efforts have been made by Irrigation Advisory Services involving not only important water conservation achievements, but also irrigation water management improvements [13]. This research work presents HidroMap, a new tool to monitor water uses in agriculture almost in near-real-time. This tool was developed to support Hydrological Planning Offices (HPOs) as a decision support tool including all actors involved in water management and water policy-makers at field level.

Within this framework, several political actions, such as European Water Framework Directive (EWFD; 2000/60/EC), encourage sustainable use of this resource and ensure the conservation of biodiversity. Spanish Ministry of Agriculture, Food and Environment have made significant efforts to improve water management through developing national plans and actions related to water quality, use and conservation following the guidelines of EWFD. Efforts made by the Spanish HPOs are also remarkable since they involve different hydrological plans for the different national basins. These actions represent a challenge for society. It is essential to develop a quality set of data that allows to monitor irrigation activity. In addition, a proper information management system that allows the geospatial integration of all data is crucial for preventive actions to be successful.

Aerial and satellital remote sensing have been recognized as excellent tools to acquire a large amount of spatial information [14]. This is due to their capability to cover large areas and so monitor crop biophysical parameters and control crop water uses along growing seasons [15–17]. In this regard, relevant changes related to the policy of National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) have allowed open access to georeferenced Landsat and Sentinel images in near real time [18,19]. Images from Landsat-8 and Sentinel-2 satellites have been used in this research as they offer a high spatial and temporal resolution, thanks to the recent launch of Sentinel-2B in March 2017.

Regarding data integration in geospatial environments, several decision support systems based on web-GIS technologies have been developed with different aims [20–22]. However, most of these applications are not open source and they are only available for private uses [23]. Focusing on remote sensing applied to agronomic studies, there are previous experiences in crop assessment development. For example, Pleiades, based on satellite imagery, allows transferring crop water requirements over the growing season to final users [24]. In the southeast of Spain, different geospatial applications have been also used in this regard; for example, the SPIDER software that initially used Landsat-5 imagery and now a combination of Landsat-8 and Sentinel-2A to estimate water requirements based on normalized difference vegetation index (NDVI) [18,25,26].

Improving the management and monitoring of water uses not only requires farmers respect the legal framework and water consumption limits, but also developing tools that provide accurate information to water users and managers [27]. This research work was mainly focused on developing a multifunctional and open source tool. Thus, HidroMap allows us to: (i) automatically detect, prioritize, quantify and manage illegal irrigation as well as to generate maps and other supporting material for surveillance and inspection tasks; and (ii) monitor the agricultural irrigation activity in near real time through multitemporal satellite data. With these aims, PostgreSQL/PostGIS database [28] and standard Open Geospatial Consortium (OGC) services (both open-source) were created. HidroMap can be considered a very useful tool for the HPOs as it has been validated as a decision support system to control the irrigation activity, especially in large areas with high water demand. In brief, this open source tool offers a shared GIS environment for stakeholders, water policy makers and water managers.

In order to describe the functionalities offered by HidroMap, the technical note was organized as follows: after the introduction, Section 2 describes the study area where the tool was validated, Section 3 describes in detail all data requirements and the methodology proposed, Section 4 shows the tool as well as its main results, and finally, Section 5 summarizes all conclusions derived after testing the tool in the Duero River Basin during the 2017 summer irrigation campaign.

2. Study Area: The Duero River Basin

The study area selected for testing, evaluating and validating HidroMap was the part of the Duero Hydrographic Basin belonging to Spain (Figure 1). This area covers 78,859 km^2 including 488,491 ha of declared irrigation crops [29,30].

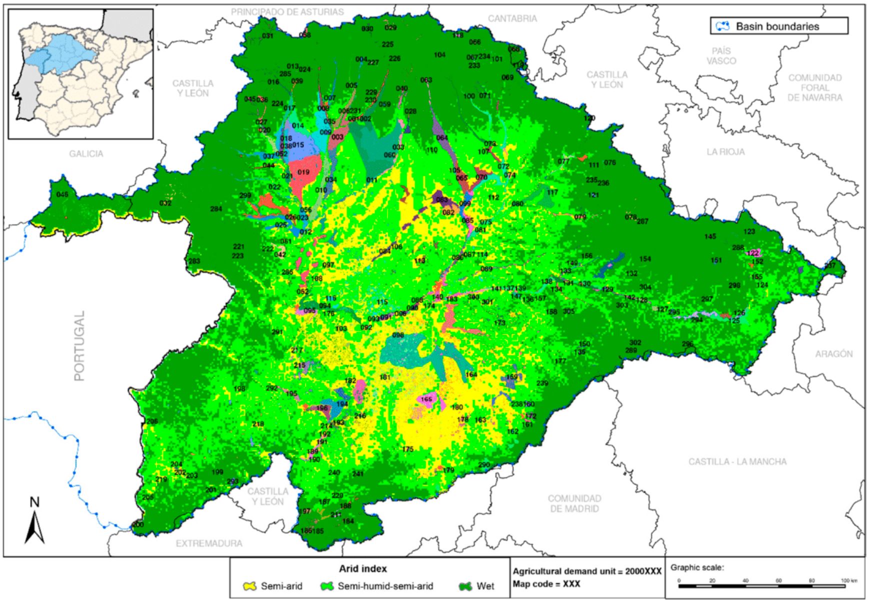

Figure 1. Duero Hydrographic Basin. Arid areas and agricultural demands (Source: Spanish National Hydrological Plan 2015–2021).

The Duero basin has a continental climate and according to the UNESCO's climate classification (1979), it is divided into 3 regions: a wet area located on the edges of the basin, a semi-arid zone in the center, and a semi-humid-semi-arid area placed between the two previous ones (Figure 1). The pluviometric regime is characterized by an average annual rainfall of 612 mm/year with high spatial and seasonal variability involving different ecosystems with high biological value. The average rainfall is 350–500 mm/year, 500–700 mm/year and 1400–2000 mm/year respectively in each climate region. Similarly, large temperature differences could be also found depending on the climate area, from an average of less than 6 °C, oscillating between 8 °C and 13 °C, and above 17 °C, being 10.7 °C the average of the whole basin. That is why it represents a handicap for managing and monitoring water sources and crops [31,32]. The hydrological year of 2016–2017, defined from 1 October 2016 to 30 September 2017, was classified as an extremely dry year by the National Hydrological Plan [30]. It was during this year that HidroMap was tested and validateed. It is important to highlight that this hydroclimatic variability involves a high vulnerability to environmental problems related to agricultural productivity, aquifer recharge, fires and soil degradation [33]. This is mainly due to the water deficit in summer, a pronounced irregularity in the rainfall regime (both temporally and spatially) and a noteworthy frequency of dry periods without appreciable rainfall. This hydrological variability takes place mainly in the Southern part of the basin [34–36]. In this context, it is important to develop a tool for sustainable water planning since the agriculture sector generates more than 80% of the water demand [32].

Therefore, testing and validating HidroMap in this area is a challenge, not only due to the large area covered by the basin but also due to its agroclimatic and hydrological variability. HidroMap was tested on the whole irrigated area of the basin, but also in those irrigated areas without irrigation rights (from here "cases").

3. Materials and Methods

3.1. Data Description

HidroMap requires different kind of inputs, that is, raster, vector and alphanumeric, to be managed by a shared desktop-GIS and web-GIS environment. Mainly, the tool combines data from: satellite platforms, field agronomic inspections, cadastre and information about irrigation rights, among others.

3.1.1. Satellite Earth Observation Data

Landsat-8 (L8), fom the United States Geological Survey (USGS), and Sentinel-2 (S2), from the European Space Agency (ESA), were chosen as satellite image data sources to analyse the agricultural lands. An area of 170 × 185 km and 100 × 100 km was covered by every L8 and S2 scene respectively. Thus, 11 scenes from L8 (Path/Row: 200/31, 201/30, 201/31, 201/32, 202/30, 202/31, 202/32, 203/30, 203/31, 203/32 and 204/31) and 18 granules (belonging to orbits 37, 94 and 137) from S2 were required. S2 products were a compilation of elementary granules of fixed size along with a single orbit. A granule was the minimum indivisible portion of a product (containing all possible spatial brands). For Level 1C and Level 2A products, the granules, were 10,000 km^2 ortho-images in ETRS89 UTM zone 30 N projection. With respect to the degree of data processing, Level 1T images were used from L8 and Level 1C from S2, both projected at EPSG 25830 (ETRS89 UTM zone 30 N). The spatial reference system was established by the Duero HPO since any official cartography product must be georeferenced under this coordinate reference system (CRS) in Spain [37].

This satellite data was downloaded and preprocessed automatically, as explained in the following point 3.2.1, under the CRS and time zone mentioned above, being the Duero HPO who selected the date range of interest for the analysis.

Since NDVI is the most widely used vegetation index to remotely monitor large areas and assess agricultural irrigation activity [38], it was integrated into HidroMap desktop tool. NDVI has been used to perform crop classification in many areas around the world with high accuracy in the discrimination between different types of crops with values of overall accuracy that could reach up to 90% [39]. After identifying irrigated plots, the final user should analyse the multitemporal variation of the NDVI through the Web-GIS module to determine the type of crop established and make decisions in this regard. In this study values of NDVI at the top of the atmosphere ($NDVI_{TOA}$) instead of at the bottom of the atmosphere ($NDVI_{BOA}$) were analysed to avoid atmospheric corrections optimizing processing times as both indexes indicate, in a relative way, the health/vigour of vegetation. Both indexes, whether or not corrected for atmospheric effect, are ratios between the reflectivity values in the near infrared (NIR) and the red wavelenghths of th spectrum (1).

$$NDVI_{TOA} = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}}, \tag{1}$$

Being ρ_{NIR} and ρ_{RED} the TOA reflectivities at the near infrared and red wavelengths corrected from solar angle.

In addition of $NDVI_{TOA}$ images, false color images were created to visualize irrigated crops and water areas. The combination of bands for the false color imagery which represented crop areas were 6/5/4 for L8 and 11/8/4 for S2 (Table 1). For visualizing water areas, 7/5/3 and 12/8/3 band combination was used for L8 and S2 respectively. Table 1 detailed the main characteristics of the bands selected for each satellite platform.

Table 1. Main characteristics of satellites and band set used by HidroMap.

	Landsat-8	Sentinel-2 (A & B)
Sensor:	Operational Land Imager (OLI)	Multispectral Instrument (MSI)
The spatial resolution of the bands used:	30 m	10 m [1], 20 m [2]
Temporal resolution:	16 days	5 days [3]
Radiometric resolution:	12 bits	12 bits
Band set used:	Band 3 (Green: 0.525–0.600 μm) Band 4 (Red: 0.630–0.680 μm) Band 5 (Near Infrared: 0.845–0.885 μm) Band 6 ($SWIR_1$: 1.560–1.660 μm) Band 7 ($SWIR_2$: 2.100–2.300 μm)	Band 3 (Green: 0.560 μm) Band 4 (Red: 0.665 μm) Band 8 (Near Infrared: 0.842 μm) Band 11 ($SWIR_1$: 1.610 μm) Band 12 ($SWIR_2$: 2.190 μm)

[1] Visible and Near Infrared, [2] Short-wave Infrared (SWIR), [3] 5 days due to Sentinel-2B images availability (launched in March 2017) [40], 10 days before.

3.1.2. Agronomic Data

Field inspections were performed to detect irrigated plots, validate the results obtained by HidroMap but also to calibrate the model to ensure accuracy results. These inspections also allowed to collect info regarding crops. This task was performed by the River Surveillance Agency (RSA), which belongs to river basin authority. Through a customized CartoDruid application [41], the RSA collected agronomic data the type of crop inspected, its phenological stage (emergence, jointing, heading, soft dough and ripe) and the irrigation system used.

All this data was stored in a SpatialLite database [42] through the CartoDruid app. The incorporation of this data into the HidroMap system was automatic since an analogous model to the one implemented in the PostgreSQL/PostGIS database was designed with that aim. Therefore, HidroMap desktop-GIS environment allowed an automatic generation of reports including agronomic information and cartographic maps to assist the RSA inspections during the 2017 irrigation campaing.

Regarding roles, only HPO users currently have autority to view and either change or add any relevant agronomic data.

3.1.3. Water Rights for Irrigation

The Duero Hydrographic Confederation had its own web-GIS system, named *Mírame-Duero* [43]. It included, among many other products, vector reference layers with information about water rights for irrigation. This information was constantly updated. HidroMap used not only the most recent and current copy of that information but also the most recent available satellite data to perform the analysis.

3.1.4. Cadastral Parcel Information

The Geographic Information System of Spanish Agricultural Plots (SIGPAC) [44] allowed us to identify all declared plots for cultivation and their cadastral information. This information was necessary to identify and register all irrigated plots, with or without rights for irrigation, within the same GIS environment. Thus, SIGPAC (Geographic Information System of Spanish Agricultural Plots) was considered as a reference cartographic information for the digitization of the HidroMap cases.

3.1.5. Complementary Data Sources

There were many other complementary data sources that helped interpret, locate and visualize results. Especially, several vector layers with information about the basin demarcation, urban centers, and divisions of the basin to be inspected by the RSA, areas with particular irrigation features and areas with specific limitations were used. In addition, the most recent orthophotos from the National Plan for Aerial Orthophotography (PNOA) [45], offered by the Spanish Geographic Institute, were used as a cartographic base for visualizing and printing reports.

3.2. Methodology

A proper methodology was required to process all data in an efficient and accurate manner (Figure 2). HidroMap engine is a PostgreSQL/PostGIS database and the methodology implemented (Supplementary Materials) converges in a dual GIS environment with the goal of: (i) managing all required information to perform the analyses; and (ii) visualizing and monitoring results in this regard.

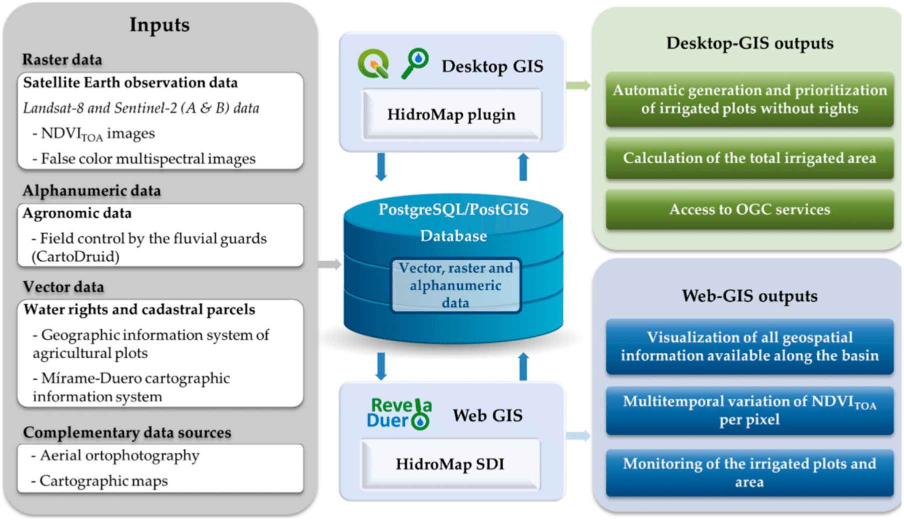

Figure 2. Flowchart of the HidroMap tool functionalities and main engines: PostgreSQL/PostGIS database, desktop-GIS, and web-GIS modules.

3.2.1. Data Acquisition and Pre-Processing

The first step of the methodology is the acquisition and pre-processing of all the data required to be analysed together. Three processes are involved:

1. Automatic download and preprocessing of Earth observation images

A specific script was developed to report the available Earth observation data along the basin regarding the temporal resolution of each platform (L8 and S2). This script also allows to pre-process raw downloaded images to obtain (i) NDVI$_{TOA}$ images and (ii) false color images to highlight crop and water areas for both platforms. NDVI$_{TOA}$ ranges from -1 to 1 (see Equation (1)), being values close to 1 those that correspond to dense and healthy vegetation. This behaviour is due to the radiation absorption/reflection by the photosynthetic pigments of plants at the different spectral ranges. Less dense vegetation areas are described by close to zero NDVI$_{TOA}$ values, and negative values occur when free water surfaces and clouds are represented. These NDVI$_{TOA}$ images are the basis of both HidroMap modules, desktop-GIS and web-GIS, thanks to which agricultural plots with a high probability of being irrigated can be detected and analysed.

Both USGS and ESA provide services for querying and downloading L8 Level 1T and S2 Level 1C products. In both cases, these services could be used through application programming interfaces (API), so the developed approach made use of these interfaces.

First, a query is made in order to obtain the list of L8 Level 1T and S2 Level 1C available products for both the area of interest and the time range. This time range includes the 20 days prior to the exact date of the query. For the S2 products, the query is made to the "Copernicus Data Hub" using the OpenSearch protocol [46]. As for L8 products, the query is made to the USGS search and download service [47].

Afterwards, the following actions were automatically carried out to obtain the pre-processed products and publish them in the web-GIS tool viewer:

- Download S2 Level 1C and L8 Level 1T products using the previously provided URLs by the query.
- Registration of downloaded products in the system catalog.
- Calculation of RGB (Red, Green and Blue) false colour images through the combination of the specific bands for each sensor: 6/5/4 and 7/5/3 for L8, 11/8/4 and 12/8/3 for S2, for highlighting crops and water areas respectively.
- Calculation of $NDVI_{TOA}$ images (1).
- Registration of the previous pre-processed products in the system catalog.
- Publication of the pre-processed products in the web-GIS tool viewer through the map server (geoserver).

2. Division of SIGPAC information by municipalities

The SIGPAC information originally consisted of more than 11 million agricultural plots within the 9 provinces of the study area. Thus, a hierarchical structuring of this information was required and performed. A division of the municipalities was made by creating a PostgreSQL scheme with 2067 spatial tables, deleting the original information and hence avoiding data duplications and overlapping. This process guaranteed both an optimal management and visualization of the cadastral divisions and the geospatial intersection of layers.

3. Integration of all initial information in the PostgreSQL/PostGIS spatial database

All inputs required the design of an adequate spatial database. Specifically, a PostgreSQL alphanumeric database with a PostGIS spatial extension was designed to optimize users' management and transfer all the information between both tool modules as thick and thin clients. The design also included the management of user accounts and roles, controlling the access to the resources depending on the user in each case, personnel from the HPO or RSA. Desktop-GIS and web-GIS modules consumed and stored information in this database

3.2.2. Desktop-GIS Module

The main functionality of the HidroMap desktop-GIS environment was to support HPO managing the irrigation activity from a quantitative point of view. In addition, it facilitated communication between HPO and RSA. The tool was developed with Python programming language for QGIS (PyQGIS).

Specifically, it allowed us to automatically perform three different processes through an intuitive user interface (Figure 3): (i) detecting those agricultural plots with non-regulated irrigation activity; (ii) prioritizing them based on different parameters; and (iii) estimating the total irrigated area and agricultural plots involved for an area of interest. Thanks to the prioritization, it was possible to detect the most relevant cases by establishing more or less restrictive criteria based on different parameters, prevailing the larger areas. Apart from these three main functionalities, it also allowed:

- To access and manage the PostgreSQL/PostGIS database with permission for such purpose by users.
- To visualize products derived from Earth observation data for different dates.
- To automatically generate reports, maps and support material.

- To incorporate information about cases and relevant data from field inspections in the database through forms designed for that purpose.
- To consult and visualize results from different dates to carry out temporary controls.

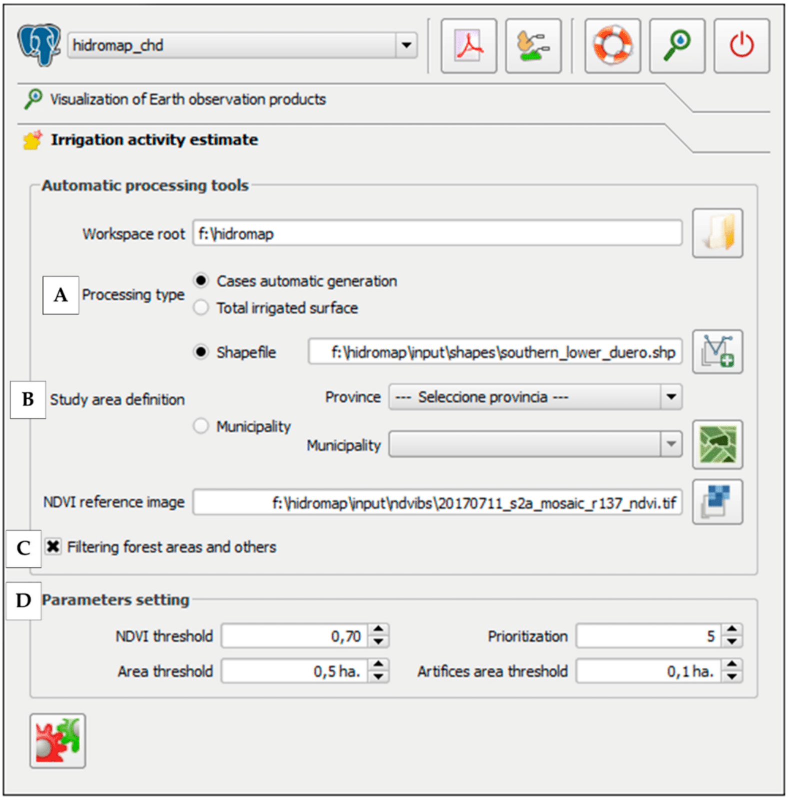

Figure 3. HidroMap desktop-GIS module interface. (**A**) Processing type; (**B**) Study area definition; (**C**) Filtering forest areas and others; and (**D**) Parameters setting.

The algorithms implemented in this tool module took advantage of all the available geo-processing tools in QGIS (gdal and the System for Automated Geoscientific Analyses, SAGA) since they allow effective spatial intersections between several layers as well as different calculation operations. Figure 4 shows the inputs required, processes implemented and the outputs of the HidroMap desktop-GIS module. A specific area of interest defined by a shapefile or by establishing a municipality from the database was part of the inputs required together with the $NDVI_{TOA}$ image of the date of interest.

First, the total irrigated surface and number of plots involved could be obtained. The next step is the SAGA spatial difference algorithm, intersecting initial results with several layers provided by the Duero Hydrographic Basin. Moreover, this process was enhanced in order to take out all the invalid and incorrect geometries generated per intersection. After the geometric validation, a final shapefile with all cases is generated. These cases hold all the information about SIGPAC cartography and fluvial guard sectors involved and the hierarchization according to the established priority. Outputs from every sub-process may be added to QGIS map canvas with a settled style so the user was able to analyse all of them.

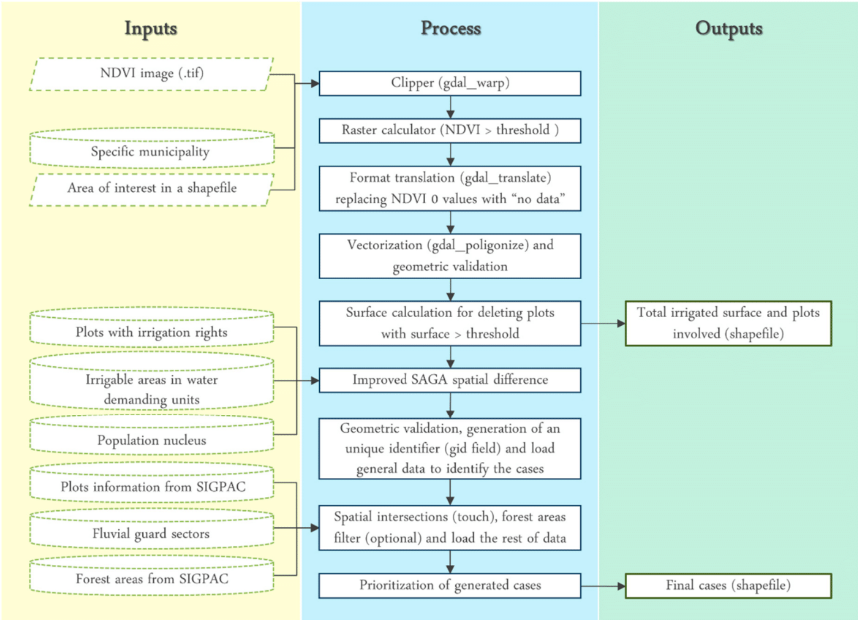

Figure 4. Main flowchart of the proposed methodology for estimating agricultural plots with non-regulated irrigation activity and irrigated surface and plots involved in an area of interest (yellow background: inputs; blue background: flux or process; green background: outputs).

The three main functionalities offered by the HidroMap desktop-GIS environment are described hereafter:

1. Detecting those agricultural plots with non-regulated irrigation activity

As already mentioned, thanks to the algorithm implemented in this module, it was possible to detect, with a single mouse click, the non-regulated irrigation activity that was being carried out in a specific area of interest (defined by the user) and for a given date. In addition, thanks to the availability of cadastral information integrated into the database, it was possible to extract all this information for each individual agricultural plot and observe temporal evolution of irrigation activity. This process can be performed for each $NDVI_{TOA}$ image, free of clouds and every 5 days (thanks to the temporal resolution offered by the Sentinel-2B platform).

The tool allowed final users from HPO, who were previously formed in this matter, to define the $NDVI_{TOA}$ and the minimum surface area (ha) as thresholds, determining if a plot can be identified as a case or not. However, by default, 0.7 was established as the $NDVI_{TOA}$ threshold and 0.5 ha as a minimum surface. In addition, the tool allowed filtering those SIGPAC plots whose use was assigned as forestry or non-agricultural lands.

All cases detected were stored in a vector layer with the following linked information per case: province and municipality belonging, SIGPAC identification, geographical coordinates, surface (ha), defined $NDVI_{TOA}$ threshold, date of generation, $NDVI_{TOA}$ image identification, satellite sensor and the priority of the case within all those detected (Figure 5). HPO users can finally consult and either change or add any additional data.

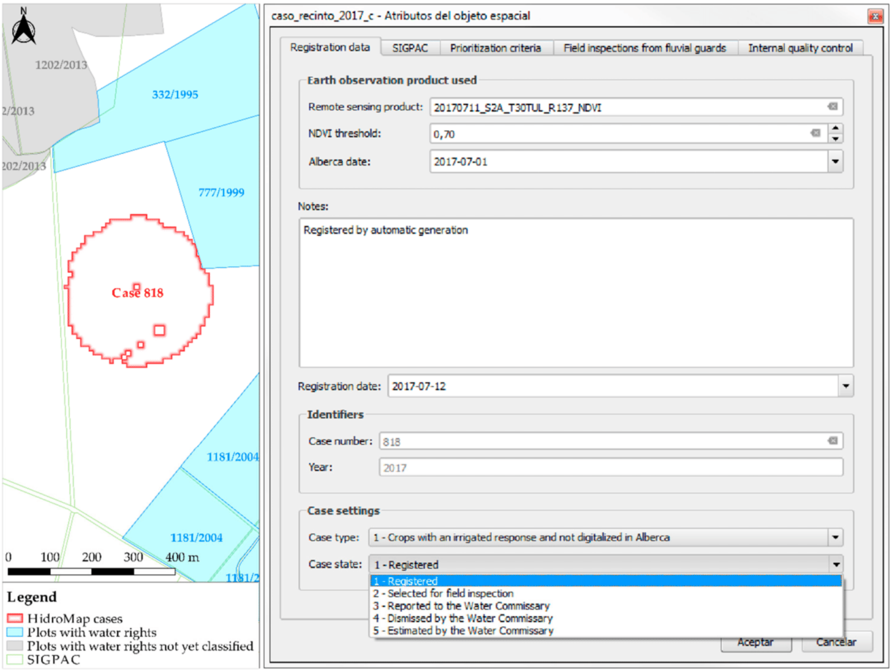

Figure 5. Crops resulted from spatial intersections of an irrigated normalized difference vegetation index (NDVI) response and layers with information of the existence of irrigation concession, SIGPAC parceling and river inspection sectors. Detection and definition of HidroMap cases and temporally monitoring of the information stored in forms.

2. Prioritization of cases

Regarding the prioritization of cases, HidroMap desktop-GIS module allowed to hierarchize all cases detected according to different criteria. For those cases detected during summer irrigation period in 2017, the Duero Hydrographic Confederation established the severity of cases based on the total irrigated area (cases type A) and the distance to the nearest regulated well (cases type B). In addition, agricultural plots with both a concession lower than 7000 m^3/ha/year and a surface larger than 9 ha were also classified as cases to be investigated with more priority (Article 54.2 of the Spanish National Water Law; cases type C).

Thanks to the tool versatility, it was possible to detect the most severe cases for different areas of interest, that is, the entire basin, a municipality, a river or any other area defined by a shapefile. HidroMap also stored the story of all detected cases. Then recurrence of illegal irrigation controlling can be performed. The number of cases to be prioritized (set as 5 by default) was adaptive and may be defined by the user.

3. Estimating total irrigated area and agricultural plots involved in an area of interest during a period of time

It was possible to estimate the irrigation activity that was being carried out in a specific area of interest and for a given range of dates. It did not require crossing results with layers about irrigation rights or SIGPAC information controlling temporal patterns of irrigation activity in an area of interest. The estimation result was displayed in a pop-up window.

The interface not only allowed to select the area and period of interest but also adapting the irrigation activity indicator, the $NDVI_{TOA}$ threshold.

3.2.3. Web-GIS Module

The HidroMap web-GIS environment supports RSA tasks by visually monitoring in near-real-time not only the irrigation activity but also type of crops and crop growth. It was implemented through Open Geospatial Consortium (OGC) services and all the information produced by the desktop-GIS module was stored in the database. Both WMS (Web Map Service) and WCS (Web Coverage Service) services were implemented so derived products from both satellite platforms (RGB false colour images and $NDVI_{TOA}$ images) could be visualized from the desktop and web-GIS tools. WMS temporal dimension (WMS-T) was also consumed so the user could request the specific date range of interest for which the products will be displayed.

As shown in Figure 6, the user could quickly visualize all available Earth Observation products ($NDVI_{TOA}$ and false colour images for L8, S2 or both) for any area of the basin fettered by the bounding box of the viewer and the period of time selected on the timeline provided. Also, the user could see a multi-temporal evolution of the $NDVI_{TOA}$ of different crops through a graph just by clicking a pixel. In addition, some cartographic layers such as the plots with irrigation rights and declared crops to the Common Agricultural Policy (CAP) [48] can be displayed in order to analyse different information sources. In this way, this tool module contained very useful information and served as a consulting and complementary environment to the desktop-GIS module.

Specifically, the web-GIS tool was developed with the aim of being used by agronomic specialists of the river basin organization. Since variations of $NDVI_{TOA}$ values through time were related to the different phenological stages [38,39,49–51], they were analysed (as later shown in Figure 9) and used as support to the decision-making process. Thus, experts can determine with high accuracy the type of crop grown in each plot. In this way, resources of the river surveillance service could be optimized, avoiding late field inspections of already harvested crops.

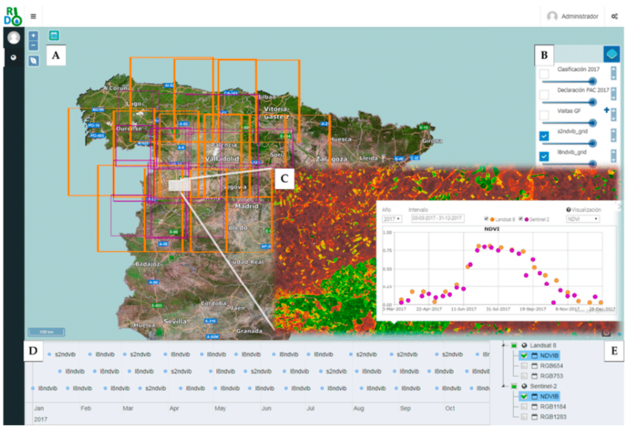

Figure 6. Screenshot of the web-GIS module. (**A**) web-GIS viewer; (**B**) Several layers to visualize, i.e. S2 and L8 grids, 2017 crop classification (source: Agrarian Technological Institute of Castilla y León, ITACYL), crop declarations to the Common Agricultural Policy (CAP) and field inspections; (**C**) Usual NDVI variation graphic for an irrigated summer crop: user could choose to visualize NDVI values from L8, S2 or both satellite platforms; (**D**) Timeline and images availability depending on the area shown by the viewer; (**E**) Selection of derived products to visualize: RGB (Red, Green and Blue) false colour and NDVI images from both L8 and S2.

4. Results

The main results derived from the use of HidroMap in the Duero Hydrographic Basin in 2017 summer irrigation period (June–September) are presented, detailing results derived from the use of desktop-GIS tool for managing irrigation activity and from the use of the web-GIS environment for visualization, interpretation and multi-temporal crop monitoring.

4.1. Derived Products from the Desktop-GIS Environment

Selected thresholds were: 0.7 for $NDVI_{TOA}$ value and 0.5 ha as minimum plot area to detect. 4097 cases were detected, 1110 of them located in an area with limited irrigation activity due to drought. The total irrigated surface without water concession was 7120 ha. The largest case occupied 39.26 ha and the largest distance to the nearest regulated well was 4.7 km. Finally, the largest plot that infringed the Article 54.2 of the Spanish National Water Law had 3.49 ha.

The prioritization of those cases was established by the HPO and consisted of detecting the 10 most severe cases in terms of surface and the 4 most severe cases per municipality involving two of lager surface, one of longer distance to the nearest regulated well and one of larger surface that did not fulfil the article 54.2 of the National Water Law. Once hierarchized, the cases were printed and distributed according to the river surveillance agency to carry out the subsequent inspections. The largest number of cases detected was located in the province of Ávila. Regarding the 10 most flagrant cases at basin level, 4 were located in Valladolid, 3 in Salamanca, 2 in Ávila and 1 in Zamora.

Figure 7 shows those cases detected in the Southern-lower Duero agrarian area (province of Valladolid) corresponding to the area of greatest irrigation restrictions of the entire Duero basin due to drought and overexploitation of the aquifers. These cases were obtained with Sentinel-2 $NDVI_{TOA}$ images on 11 July 2017.

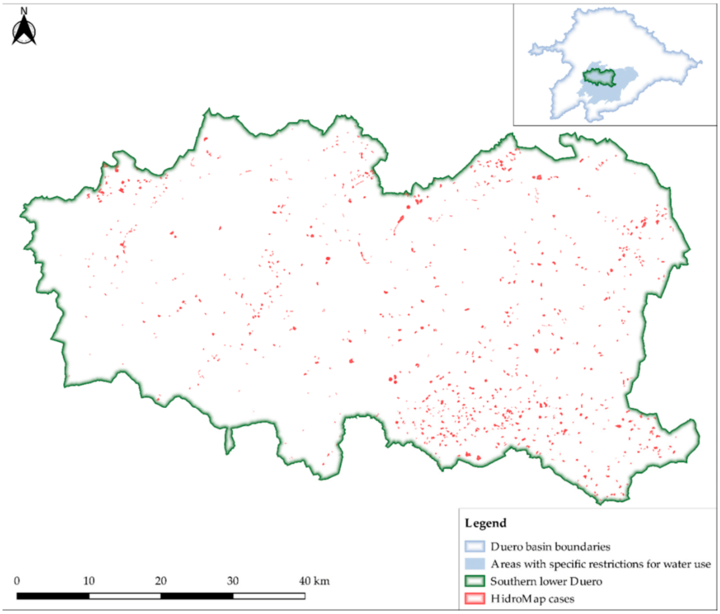

Figure 7. HidroMap cases in the Southern-lower Duero agrarian area in 2017. Plots detected with irrigation activity for an $NDVI_{TOA}$ threshold of 0.70, a minimum area of 0.5 ha and filtering forest surfaces.

Regarding field inspections, 320 of the 4097 cases detected were examined during August and September by the Duero RSA. They were intended to control illegal irrigations and simultaneously validate HidroMap. They were scarce, but they revealed the main limitations and errors derived from the automated system implemented in HidroMap.

The main errors found in the field inspections of 2017 were: 9.4% due to late inspections (already harvested crops) and 18.7% caused by false positives (non-irrigated sunflowers).

To avoid the first incidence, it was recommended to carry out a continuous follow-up of the inspections to guarantee that they were carried out regularly and prioritizing the date in which the cases were generated.

Regarding the second error, it was verified that the defined parameters (mainly the $NDVI_{TOA}$ threshold) were not suitable because some rainfed crops were classified as irrigated crops (false positives). This error was a direct consequence of providing maximum automation to the process. It should be highlighted that the sunflower crop has an almost identical spectral response under irrigation and rainfed conditions so non-irrigated sunflower crops are commonly confused with other irrigated summer crops [49,50]. To avoid such errors, an examination of the cases generated prior to their delivery to the RSA office was recommended. This process can be carried out by agronomists or by any user thanks to the crop phenological information offered by the HidroMap web-GIS environment.

Finally, regarding total irrigated area estimation, an analysis was performed in the province of León, including an area of special interest for the Duero River Basin Organization due to its extension and water demand for the agricultural activity. This area was known as Payuelos and it had a total surface of 37,000 ha where 62% was irrigated (23,000 ha). This area corresponded around the 80% to spring irrigation and 20% to summer irrigation according to the National Hydrological Plan [32,43].

Total irrigated area estimation using HidroMap for the range of dates between the end of June and August 2017 was 4824 ha of summer irrigated crops (Figure 8, Table 2). This value was a bit higher than the mentioned above due to some HidroMap cases detected in this area. In addition, according to the informative notes from water users, assigned allocations in operation were 4800 m^3/ha. Therefore, water consumption values of 23.25 hm^3 could be estimated during the summer period considering summer crops detected, which represented around 20% of the total demand during the hydrological year 2016/2017 according to the annual inform [30].

Table 2. Irrigated area estimation results in Payuelos during the summer irrigation period (León, Spain).

Analysis of the Irrigated Area in Payuelos (León, Spain)	
Total extension	36,990.57 ha
Extension declared for irrigation activity	23,005.68 ha
Extension for spring and summer irrigation assigned in the HP15 [1]	20,334 ha
Extension declared for spring and summer during the hydrological year 2016/2017	18,468 ha
Summer irrigation extension estimate by HidroMap	4824.10 ha

[1] Spanish National Hydrological Plan 2015–2021.

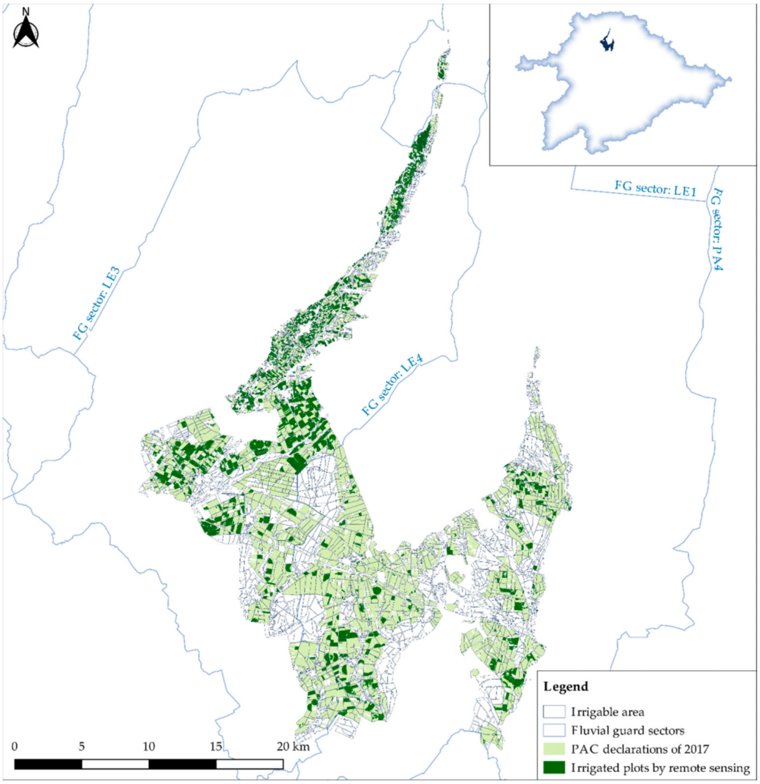

Figure 8. Comparison between the estimation of the irrigated area offered by HidroMap and extension declared for that purpose by the water users of Payuelos for the summer of 2017.

4.2. Derived Products from the Web-GIS Environment

It was possible to quickly visualize and optimally monitor the agricultural plots with positive irrigation response for the entire basin thanks to the available Earth observation data set. Especially, spectral responses of those crops detected by the desktop-GIS tool can be analysed here.

All this information was significant for the Duero HPO as its personnel can perform multi-temporal controls, in near-real-time, for lands under irrigation and crops grown in each agricultural plot. Multi-temporal analysis of crops (comparison of different $NDVI_{TOA}$ profiles) allowed agronomic specialists to control the irrigation activity, quickly verifying the type and phenological stage of each crop. Therefore, the web-GIS module allowed, among other things, to control the veracity of the declarations made by farmers to CAP in 2017. This process was complemented by the RSA field inspections. A continuous monitoring of the agricultural plots by means of this tool can minimize, by a high percentage, the late inspections in which the crop could already be harvested.

Figure 9 illustrates the detection of a sugar beet crop using HidroMap web-GIS tool, which showed a distinctive spectral signature with an especially long vegetated period in comparison to other summer crops, normally harvested in September (as previously shown in Figure 6) [51].

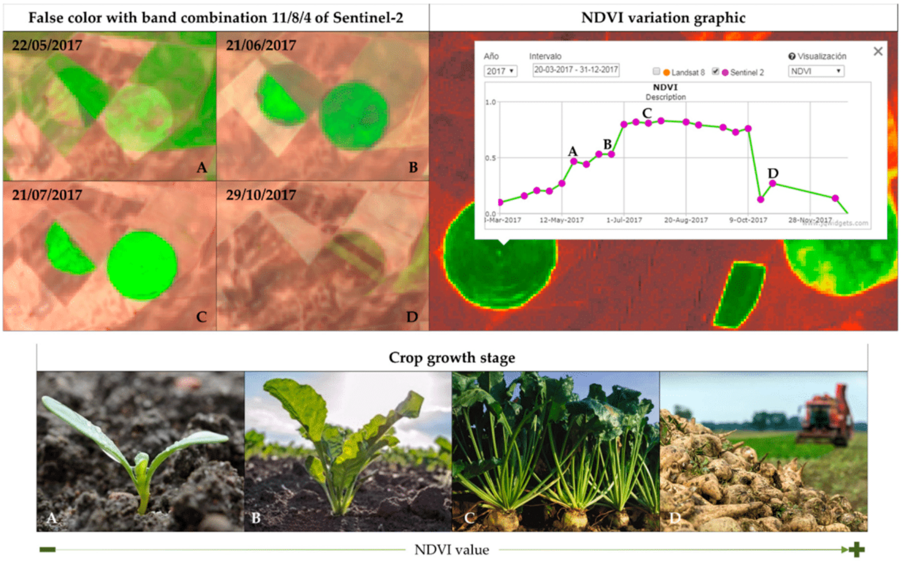

Figure 9. False color images from Sentinel-2 (combination of bands 11, 8 and 4) and a graph of the variation of $NDVI_{TOA}$ values for different dates. This graph represents the growing season profile, including phenological stages, of a sugar beet crop.

5. Conclusions

This paper presents HidroMap, a powerful and versatile open source tool with great interest and utility for the HPOs and RSAs for water resources planning and control. The tool offers a combined GIS solution: a desktop-GIS plugin that allowed carrying out tasks of management, control and surveillance of irrigated areas and illegal irrigation; and a web-GIS system that allowed carrying out quickly inspections and irrigated area monitoring, as well as visualizing crops and phenological patterns in a simple and intuitive way.

HPO was the manager and main user of the HidroMap while RSA was the validator and betta tester of its results. In addition, RSA personnel have the important task of providing feedback about agronomic data in order to improve the tool's algorithm. Therefore, desktop-GIS module mainly supported HPO tasks of detecting and controlling water resources while the web-GIS helped RSA so inspections were made in a reliable and accurate way. All this results in a greater and better communication between the personnel involved, and therefore better water control and planning.

From a conceptual and application point of view, HidroMap achieved a fourfold objective:

- Immediate and automatic detection of incidents

The free disposition of the Earth observation data used, the script developed for downloading and processing the mentioned data as well as the desktop-GIS tool for the automatic detection of cases and estimation of the irrigated surface, allowed obtaining results by a single-Mouse-click on an area of interest defined by users. This tool, available for the River Inspection Office (RIO), allowed to inspect possible incidents in near real time.

- Management of illegal irrigation

Combining information about plots with water rights for irrigation (assigned by the Duero HPO) with the results provided by the developed tool allowed to detect anomalies related to possible unregulated irrigations and agricultural plots with water rights that were not irrigated. A proper quality control of these cases based on field inspections by the RIO provided feedback for the developed methodology.

- Optimization of resources of the RIO

It was possible to adapt the results obtained to the requirements of RIO by defining more or less restrictive input criteria. For example, increasing $NDVI_{TOA}$ and surface thresholds, determining the priority of plots based on the importance in those areas with higher irrigation demands. In addition, the web-GIS environment allowed real-time visualization of $NDVI_{TOA}$ patterns for each crop. This can be considered very useful since analysing $NDVI_{TOA}$ patterns allow an accurate monitoring of crop growth and development behaviour, involving the improvement of irrigation schedules and farm operation management plans.

- Temporal monitoring of the irrigated area

Web-GIS environment also allowed monitoring irrigated plots patterns for the whole basin in a flexible way. This tool will allow to: (i) identify almost in real time those irrigated crops without irrigation rights and/or those not declared by farmers to CAP and (ii) optimize field inspections, minimizing late visits; all through a friendly interface.

The dual GIS environment offered by HidroMap was an important challenge for any river basin organization for management and planning of available water resources. In addition, it can be adapted to any type of further requirement.

Future Developments

As future developments, both tools will be improved every year, especially by taking challenges from RSA's feedback in order to merge information coming from field inspections and satellite imagery. An increase and optimisation of field inspections in both their material and human resources, as well as a reduction of its randomization, will provide very valuable information to calibrate HidroMap desktop-GIS tool so its outputs have a greater reliability.

- In-depth analysis of the corresponding NDVI value for each crop and growing period in order to detect the current crop in each field and rigorously deduce its phenological stage and irrigation needs. Increasing field inspections will be required in order to ensure reliable results.
- Cross-validation of "false positives" in order to both minimize them and increase the tool operability. Again, field inspections must be increased.
- Increasing the use of the web-GIS module to support crops irrigation management by a deeper analysis of NDVI patterns and continuously monitoring the growth stage of each crop.

Supplementary Materials: Developed tool is available online at https://github.com/TIDOP/hidromap.

Author Contributions: Conceptualization, D.O.-T. and D.G.-A.; Methodology, D.O.-T., D.H.-L., R.B. and M.A.M.; Software, D.O.-T. and D.H.-L.; Validation, L.P. and S.d.P.; Formal Analysis, L.P., S.d.P. and D.O.-T.; Investigation, L.P., D.O.-T., S.d.P., D.H.-L., R.B., M.A.M. and J.-L.M.; Resources, D.O.-T., D.H.-L. and D.G.-A.; Data Curation, L.P., D.O.-T., S.d.P., D.H.-L., R.B. and M.A.M.; Writing-Original Draft Preparation, L.P., S.d.P., J.-L.M. and D.G.-A.; Writing-Review & Editing, L.P. and S.d.P.; Visualization, D.G.-A.; Supervision, D.G.-A.; Project Administration, D.G.-A.; Funding Acquisition, D.G.-A.

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Paper III: Scalable pixel-based crop classification combining Sentinel-2 and Landsat-8 data time series: Case study of the Duero river basin

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Scalable pixel-based crop classification combining Sentinel-2 and Landsat-8 data time series: Case study of the Duero river basin

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A R T I C L E I N F O

Keywords:
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Abstract: Satellite imagery is the foremost source of information to analyze and monitor land covers in several time ranges, especially over large areas. However, it is not always either freely available or easily compatible for the final users due to the different resolutions offered by sensors onboard the satellite platforms. Crop classification is an important task to control and make decisions related to the agricultural practice and its regulation. However, it is not trivial, especially for extensive areas. Thus, this paper proposes a new approach for crop classification in large areas by a combined use of multi-temporal open-source remote sensing data from Sentinel-2 (S2) and Landsat-8 (L8) satellite platforms. Having to deal with different spatial and temporal resolutions, special spatial regions (called Tuplekeys) were created within a local nested grid to allow a proper integration between the data of both sensors. Temporal variation of the Normalized Difference Vegetation Index (NDVI) was the chosen input to classify crops. Moreover, due to the massive quantity of data collected, filters considering some agronomic and edaphic criteria were applied with the dual goal of decreasing redundancies and increasing the process efficiency. Out of three different machine learning classifiers analyzed, a plot-based approach was considered for the algorithms calibration while a pixel-based approach was used for the final classification process. The methodology was both tested and validated in the Duero river basin (Spain), 78,859 km^2, for the 2017 spring and summer seasons. Finally, classification outputs were analyzed throughout their overall accuracy (OA), not only for the whole basin but also for each of the Tuplekeys so that the OA spatial distribution was evaluated as well. The Ensemble Bagged Trees (EBT) algorithm showed the maximum OA, 87% and 92%, when classifying crops individually (15 classes) and grouped (7 classes), respectively, proving both the accuracy and efficiency of the developed approach.

1. Introduction

The current increase in the demand for agricultural products due to the rising worldwide population requires the proper management and planning of the available resources. A well-grounded and detailed knowledge of agricultural areas and crop types is essential to perform economical, ecological and sustainable strategies (Cai et al., 2018; Davis et al., 2016; Zaks and Kucharik, 2011). Given the dynamic character of agriculture, crop monitoring turned out to be crucial to control both its evolution and trend. Among other parameters, cultivated surface, crops production and distribution and their water demand can be accurately estimated using alternative technologies (Burke and Lobell, 2017; Cai et al., 2018; Durgun et al., 2016; Murmu and Biswas, 2015).

Satellite remote sensing (RS) has been proven as a very valuable technique to provide large scale multi-temporal data. Thus, both land cover and natural resources maps are currently performed using this technique (Hasmadi et al., 2017; Piedelobo et al., 2018; Shelestov et al., 2017). However, for crop monitoring, proper spatial and temporal resolutions are required to assess crops at their different phenological stages (Ballesteros et al., 2014).

Nowadays, several open-source satellite platforms improve Earth

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Observation (EO) capabilities for both agricultural management and crop monitoring. Specifically, Copernicus Open Access Hub and Earth Explorer are open data providers offering Sentinel-2 (S2) A and B and Landsat-8 (L8) images, respectively (Colkesen and Kavzoglu, 2017). Both satellite platforms have been successfully used in the agriculture field (Azar et al., 2017; Hansen and Loveland, 2012; Immitzer et al., 2016; Kussul et al., 2016, 2017; Piedelobo et al., 2018; Sexton et al., 2013; Skakun et al., 2016; Townshend et al., 2012). However, its individual use may entail significant limitations: (i) lack of spatial, temporal or spectral resolutions and (ii) clouds contaminating the images (Cai et al., 2018; Kussul et al., 2017; Skakun et al., 2017). Overcoming these limitations is conceivable using several platforms jointly, so that denser temporal, spatial and spectral input data can be collected (Hao et al., 2014; Roy et al., 2014).

Integrating RS data from several sources is not a trivial issue. Firstly, a proper interoperability between the satellite-based data is required, which entails efficient information management (Shelestov et al., 2017). As this fact has been proven for the freely available L8 and S2 images (Mandanici and Bitelli, 2016), authors decided to use both remotely-sensed data jointly for crop classification.

Specifically, multi-temporal series of the Normalized Difference Vegetation Index (NDVI), which has been the most widely used vegetation index for decades, were analyzed in this study. NDVI is highly sensitive to vegetation cover variations (Rouse et al., 1973) and hence can estimate crop productivity and monitor vegetation health and growth (Immitzer et al., 2016; Inglada et al., 2015; Peña et al., 2014; Piedelobo et al., 2018; Schultz et al., 2015; Sesnie et al., 2008; Wardlow and Egbert, 2008). However, using jointly multi-temporal NDVI data from both satellite platforms led to an extremely large amount of input information. This requires a proper data management, especially for a large agricultural area, which cannot be achieved by a single calibrated classification model.

This paper proposes a new accurate and efficient classification approach for crop mapping. Its development has considered: (i) a well-organized management of input data through special spatial regions, (ii) image pre-processing and feature extraction using NDVI statistics and considering special filters based on agronomic and edaphic criteria, (iii) the selection of proper ground-truth samples, (iv) the use of the most accurate classifiers and (v) accuracy assessment (Lu and Weng, 2007). A deep review has been made along several experiences regarding crop classification results worldwide, checking different algorithms, sensors, number of crops classified, ground-truth samples and study areas, among other parameters (Table 1).

As shown in Table 1, crop type mapping at very large scales and with high resolution imagery does not exist in the literature. The main challenge when performing a crop classification in large study areas remain in the heterogeneous climates, landscapes and phenology. Therefore, testing and validating the developed crop classification approach in the Spanish part of the Duero basin (78,859 km^2) required zoning the study area. Thanks to the creation of special spatial regions (called Tuplekeys) and filters based on agronomic and edaphic criteria, input data was efficiently organized and preprocessed to take the classification process. All this management of the input data improved the efficiency of the classification process without decreasing its accuracy.

Concerning the reference data, both field inspections made by the fluvial guards of the river basin and farmers' statements to the Common Agricultural Policy (n.d.) (CAP) were used, so enough samples calibrated the model and assessed its accuracy. 2017 crop classification in Duero basin was performed using three machine learning classifiers: (i) Decision Trees (DT), (ii) Ensemble Bagged Trees (EBT) and (iii) Weighted Nearest Neighbor (WNN). These algorithms were selected because of their proved accuracy and efficiency (Table 1).

Regarding the number of crop types classified, 15 individual classes and 7 grouped classes were labeled and hence classification algorithms were applied twice. Finally, both salt and pepper algorithm and masks for filtering artificial raw elements and forest areas were applied.

Finally, overall accuracy (OA) was calculated for both the whole basin and each of the Tuplekeys. Thereby, areas with worse classification accuracy, either due to less availability of satellite data or ground-truth data, were also evaluated. Among the three classifiers, EBT showed the best OA, 87% and 92%, when classifying crops individually and grouped, respectively. In addition, very competitive processing times were obtained considering the huge amount of satellite-based data for such a long time and large area analyzed. 16 h were enough for analyzing the whole basin using a commercial computer.

To describe the developed crop classification approach, the paper is organized as follows: after the Introduction, Section 2 describes input data requirements, proposed methodology and the study area where it has been tested and validated. Section 3 shows the results and accuracies obtained for each of the classifiers; Section 4 discusses the results and, finally, Section 5 summarizes all conclusions derived after testing the proposed crop classification methodology in the Duero river basin.

2. Materials and methods

2.1. Case study: the Duero river basin

The study area selected for testing, evaluating and validating the developed classification approach was the Spanish part of the Duero Hydrographic Basin (Fig. 1). This case study was chosen not only due to its large area and significant agricultural activity, but also to its noteworthy spatial and temporal hydroclimatic variability, which also defines its wide diversity of crops, landscapes and phenologies (ITACyL and AEMET, 2013; Fernández Pereira et al., 2015; Herrero Lizano, 2017). Thus, the crop classification approach could be entirely evaluated, including its efficiency, accuracy and required processing time when applied to large areas.

The Spanish part of the Duero river basin is mainly located in the Community of Castile-Leon, in the central-North area of the Iberian Peninsula (Ministry of Environment, 2007), covers 78,859 km^2 and has a continental climate, mostly considered semi-humid-semi-arid. Average annual rainfall is 612 mm/year with a high spatial and seasonal variability ranging from 350 to 2000 mm/year (ITACyL and AEMET, 2013; Ceballos et al., 2004; Fernández Pereira et al., 2015; Herrero Lizano, 2017).

According to the last hydrological plan of the basin, 3.7 million (Fernández Pereira et al., 2015) and 488,491 ha (2017 CAP statements) corresponded to rain-fed and irrigated crops in 2017, respectively. Most crops were wheat (21%), corn (19%) and barley (15%), with almost 200,000 declared plots. Other representative crops were sunflower (7%), fallow (6%), alfalfa (6%), beet (4%) and potato (3%).

2.2. Materials

2.2.1. S2 and L8 multispectral imagery

The presented work used jointly Landsat-8 (L8) and Sentinel-2 (S2) satellite data for the following reasons: (i) they are freely available, (ii) the interoperability between both platforms has been proven (Mandanici and Bitelli, 2016) and (iii) they are able to monitor large surfaces with high spatial, temporal and radiometric resolutions. This may explain their worldwide use as input data for land cover / land use monitoring and decision-making applications (Azar et al., 2017; Cai et al., 2018; Hansen and Loveland, 2012; Immitzer et al., 2016; Kussul et al., 2017; Piedelobo et al., 2018; Schultz et al., 2015; Sexton et al., 2013; Skakun et al., 2016; Townshend et al., 2012).

Specifically, multi-temporal variation of the well-known Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1973) was used to perform the crop classification in the study area. NDVI profiles have a specific shape depending on the crop type and describe the three most important phenological stages: onset of greenness,

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Table 1
Review of crop classification experiences worldwide.

Research	Azar et al., 2017	Ustuner et al., 2017	Ok et al., 2017	Immitzer et al., 2016
Study area	Italy, > 10,000 km^2	Turkey, ~100 km^2	Turkey, ~95 km^2	Austria, ~1,000 km^2 and Germany, < 100 km^2
Number of crops classified	7	2 crops (3 stages for each) and 6 features	6 main classes 13 subclasses	7
Sensor / number of bands used	L8 / 5 (2,3,4,5,7)	RapidEye / 5	SPOT 5 / 4	S2 / 10
Image analysis	PB[b]	PB[b]	OB[a] and PB[b]	OB[a] and PB[b]
Index	EVI[d], NDFI[e], RGRI[f]	Statistical learning	Spectral signatures, statistics and Gini index	Band-metrics for OB[a] and reflectance for PB[b]
Ground-truth data	561 training fields and 287 validation fields (CUAA[g] 2013)	11,585 training pixels. 60 in-situ GPS and 828 Google Earth validation points (AD[l] and LCLU[m])	1,021 field samples (field surveys)	452 field samples (field surveys)
Number of images	26	1	1	1
Classification algorithms	MLC[h], EMD[i], SAM[j], NN[k]	SVM[n] and MLC[h]	MLC[h] and RF[c]	RF[c]
Overall accuracy	92%	81–85%	77 and 85%	76%

Research	Inglada et al., 2015	Tatsumi et al., 2015	Schultz et al., 2015	Peña et al., 2014
Study area	12 test sites worldwide 1,000–17,000 km^2	Peru, ~230 km^2	Brazil, ~7,150 km^2	USA, ~2,650 km^2
Number of crops classified	2–20	8	5	9
Sensor / number of bands used	SPOT 4 / 4, L8 / 6 (2,3,4,5,6,7) and RapidEye / 5	L7 ETM+ / 3 (1,3,4)	L8 / 3 (4,5,6)	ASTER / 9
Image analysis	OB[a] and PB[b]	PB[b]	OB[a]	OB[a]
Index	Surface reflectance, NDVI[o], NDWI[p] and brightness	EVI[d]	Statistics, NDVI[o] and brightness	10 vegetation indices (i.e. NDVI[o], VIgreen[s], GNDVI[t])
Ground-truth data	Number not mentioned (field surveys and LCLU[13])	11,781 training pixels and 105,994 validation pixels (field surveys and photointerpretation)	677 training fields and 2,502 validation fields (field visits and photointerpretation)	1,007 field samples (field visits and LCLU[13])
Number of images	9–41	53	2	2
Classification algorithms	SVM[n], DT[q], GBT[r] and RF[c]	RF[c]	RF[c]	DT[q], LR[u], SVM[n] and NN[k]
Overall accuracy	> 80%	81%	80%	79–89%

[a] Object-based.
[b] Pixel-based.
[c] Random Forest.
[d] Enhanced Vegetation Index.
[e] Normalized Difference Flood Index.
[f] Red Green Ratio Index.
[g] Annual Agriculture Land Use Map.
[h] Maximum Likelihood Classification.
[i] Euclidean Minimum Distance.
[j] Spectral Angle Mapper.
[k] Neural Networks.
[l] Ancillary Data.
[m] Land Cover / Land Use.
[n] Support Vector Machines.
[o] Normalized Difference Vegetation Index.
[p] Normalized Difference Water Index.
[q] Decision Trees.
[r] Gradient Boosted Trees.
[s] Green Vegetation Index.
[t] Green Normalized Difference Vegetation Index.
[u] Logistic Regression.

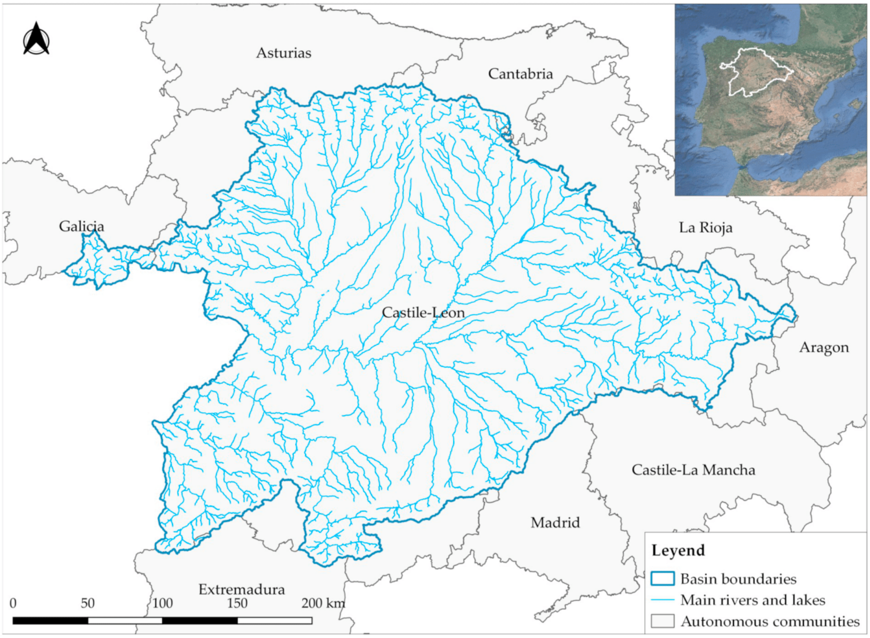


Fig. 1. The Duero Hydrographic Basin located in Spain.

flowering and onset of yellowing. To exploit this information, crop features extracted from multi-temporal NDVI metrics have been extensively used for crop mapping, achieving up to 90% OA values (Bontemps et al., 2015; Inglada et al., 2015; Lu and Weng, 2007; Matton et al., 2015; Peña et al., 2014; Pittman et al., 2010; Schultz et al., 2015; Valero et al., 2016; Wardlow and Egbert, 2008). However, the study of a very large area implies high spatial and temporal variability regarding climate and phenology, so crop characteristics occur in different time periods. In such cases, both zoning the analysis along the study area and gathering enough and representative ground-truth samples are needed.

In this work, 20,836 scenes from L8 (Level-1T) and S2 (Level-1C) were automatically downloaded and preprocessed (Section 2.3.1.) for the period between March 1st and October 31st 2017 with the aim of classifying the crops of the Duero river basin in 2017 attending multi-temporal variation of $NDVI_{TOA}$ values. To obtain the same spatial coherence between L8 and S2 NDVI values, input data was divided in 278 spatial regions (Tuplekeys) created within a local nested grid. 192 out of the 278 Tuplekeys covered the river basin in the storage Level Of Detail (LOD). As further explained in Section 2.3.2, this step was implemented due to L8 and S2 different spatial, temporal and radiometric resolutions (Table 2). Thus, completely integrating all input data in Tuplekeys solved the issue of pixels misalignment. Furthermore, several filtering criteria was applied so just the most representative NDVI scenes (8,671 out of 20,836) were used to perform the final uncalibrated pixel-based crop classification.

Also, as it is not the specific NDVI value in a pixel but the variation of this value through time and its comparison with several crop patterns in a study area what defines a crop classification, NDVI at the top of the atmosphere ($NDVI_{TOA}$) was analyzed, instead of at the bottom of the atmosphere ($NDVI_{BOA}$), avoiding atmospheric corrections and optimizing processing times (Eq. (1)).

$$NDVI_{TOA} = (NIR_{TOA} - R_{TOA})/(NIR_{TOA} + R_{TOA}) \quad (1)$$

Ranging $NDVI_{TOA}$ from -1 to $+1$, with higher values being representative of healthier crops (Rouse et al., 1973), and NIR_{TOA} and R_{TOA} the near-infrared and red reflectances at the top of the atmosphere, respectively.

2.2.2. Ground-truth reference samples

To ensure an accurate crop classification using remotely-sensed (RS) satellite data, a proper amount of reference samples must be provided for calibrating the algorithms and assessing their accuracy (Congalton, 1991). The quality and representativeness of ground-truth data can significantly influence the performance of the algorithms used and, consequently, the classification results (Chen et al., 2002). Field surveys, farmer's statements, aerial photographs, satellite images or land cover / land use (LCLU) maps are widely-used suppliers of ground-truth samples (Azar et al., 2017; Immitzer et al., 2016; Inglada et al., 2015; Lu and Weng, 2007; Ok et al., 2017; Peña et al., 2014; Schultz et al., 2015; Tatsumi et al., 2015; Ustuner et al., 2017).

The two main uses of the reference samples are: (i) calibrating the classifiers and (ii) evaluating the classification accuracy. Therefore, the calibration dataset supports the RS data and the classification algorithms to perform the final crop map (Delincé, 2017).

In this study, both summer field visits provided by fluvial guards of the river basin (from June to September 2017) and farmers' statements to the Common Agricultural Policy (n.d.) (CAP) of such year were used as reference data. 249 field visits determined the crop type, phenological stage and irrigation system established in the visit date. CAP information represented only irrigated plots and provided all farmers' declarations regarding crop type, surface and plot delimitation.

Table 2
Main characteristics of satellites and bands used. Adapted from Landsat Science Portal (n.d.) and The European Space Agency portal (n.d.).

Satellite platform	Landsat-8	Sentinel-2 (A & B)
Sensor	Operational Land Imager (OLI)	Multispectral Instrument (MSI)
Area covered by each scene	170 × 185 km	100 × 100 km
Spatial resolution of the bands used	30 m	10 m
Temporal resolution	16 days	5 days
Radiometric resolution	12 bits	12 bits
Bands used	Band 4 (Red: 630–680 nm) Band 5 (Near Infrared: 845–885 nm)	Band 4 (Red: 645–683 nm) Band 8 (Near Infrared: 762–907 nm)

Table 3
Number of reference samples used for the 2017 crop classification in the Duero river basin, both from field surveys made by the fluvial guards and from the farmer's statements to the Common Agricultural Policy (CAP).

Aggregated crop class	Individual crop class	Number of CAP statements	Number of plots visited
Spring crops	Wheat	8,141	3
	Barley	6,109	8
	Rye	275	–
	Rapeseed	791	2
	Green peas	802	1
	Oat	1,008	–
Summer crops	Sugar beet	2,055	54
	Potato	1,142	60
	Corn	7,567	57
Alfalfa and ray-grass	Alfalfa	2,821	38
	Ray-grass	279	–
Sunflower	Sunflower	2,730	22
Fallow	Fallow	2,780	1
Vineyard	Vineyard	249	3
Pastures	Pasture	94	–
Total		36,843	249

352,403 irrigated plots had been declared to the CAP in 2017 but, after a spatial analysis, those with an area of < 1 ha were deleted to avoid the border effect in small plots. Lastly, considering the labeled classified crop types, 36,843 CAP statements were used (Table 3).

As a novelty, the accuracy of the final crop classification was evaluated per each of the algorithms not only for the whole basin but also per each of the Tuplekeys. Thus, the spatial distribution of the overall accuracy (OA) along the basin was analyzed. Therefore, all available ground-truth data was exploited by using different reference samples for either calibration or validation. All field visits were used for determining the classification OA at the level of the whole basin due to their higher accuracy stating the type and stage of the crops in the visit date. On the other hand, 70% of the CAP statements were used for calibrating the algorithms while the other 30% were used for assessing OA per Tuplekey, compensating the low number of field surveys.

Regarding the crop types classified, 15 individual and 7 grouped classes were labeled, applying the classification algorithms twice. Table 3 shows the number of agricultural plots visited and the CAP statements for the selected individual and gathered crop classes.

2.3. Classification methodology

Obtaining a proper crop classification through the proposed methodology requires to follow 4 main consecutive steps to use jointly multi-temporal RS data from S2 and L8, as outlined in Fig. 2.

2.3.1. Data collection and pre-processing

This step involves the execution of two different processes: (i) downloading and pre-processing RS satellite data and (ii) gathering ground-truth data from the fluvial guards of the river basin and the farmers' statements to the CAP. After downloading L8 and S2 data, $NDVI_{TOA}$ images were generated for both RS sensors. Both United States Geological Survey (USGS) and European Space Agency (ESA) provide services for querying and downloading L8 Level 1T and S2 Level 1C products. These services could be used through Application Programming Interfaces (API). Thus, the developed approach made use of these interfaces, automatically querying the available products (NIR_{TOA} and R_{TOA} images) for the study area and time range of interest (March 1st – October 31st 2017), downloading and keeping them in a system catalogue and calculating $NDVI_{TOA}$ images using Eq. (1) (Piedelobo et al., 2018).

2.3.2. Satellite data integration

Once $NDVI_{TOA}$ images were generated from both satellite sensors, a proper data integration was required to perform a precise crop classification. Therefore, special spatial regions were automatically created for the study area. These spatial regions, called Tuplekeys, had a grid structure compatible with both L8 and S2 data (ANZLIC, 2012; Purss et al., 2015; Stumpf et al., 2018; Villa et al., 2016). The goal was processing multiple $NDVI_{TOA}$ layers from both satellite platforms optimizing the spatial coherence between them. Thus, the following issues regarding Earth Observation (EO) multi-temporality and multi-resolution are solved:

- Pixel misalignment between L8 and S2 images since pixel sizes of both imagery sets are not multiples. This leads to the impossibility of directly comparing radiometric values from different dates.
- Pixel non-alignment in the upper Level of Detail (LOD) of the resolution pyramid. This issue is due to the different spatial resolution of L8 (30 m) and S2 (10 m) images. The size of a given image was N by N where $N = 3^n$, giving the image pyramid a hierarchical structure composed of n levels of the same image of different resolutions. The bottom of the pyramid corresponded to the full resolution of the given image. Each set of 3 × 3 neighbor pixels was replaced by their average as the pixel value of the image at the next level. This process, that divided the image size by 3 on each dimension, was repeated n times until finally an image of only 1 pixel (average of the entire image) was generated as the top of the pyramid with a dimension of 10 × 10 m (finest spatial resolution of S2). Thus, appropriate alignment of the pixels in all LODs was mandatory to perform multi-resolution analysis.

The unique local nested grid solves the storing, processing and comparison between the raster input data from both satellite platforms. This methodology was applied to generate the Tuplekey regions, organizing different footprints, pixel sizes and pixel positions at all pyramid levels (ANZLIC, 2012; Purss et al., 2015; Stumpf et al., 2018; Villa et al., 2016).

To obtain a local nested grid for the Duero river basin, the first step was the creation of a nested grid that covered all the Iberian Peninsula and had the coarsest spatial resolution. The method consisted of placing a fine grid inside the coarse grid. Thus, the coarse grid covered the entire Iberian Peninsula while the fine grid preserved the detailed features of the plots of the study area. The following parameters defined the Tuplekey generation process:

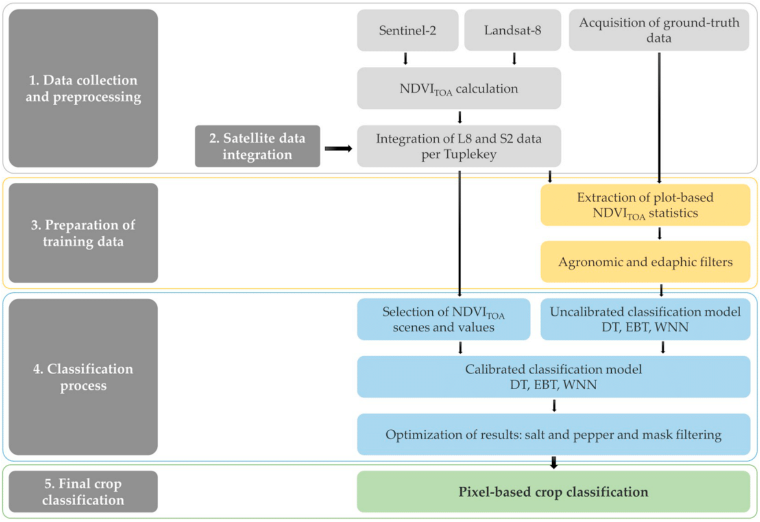


Fig. 2. Flowchart of the proposed methodology for crop classification.

- The coordinate reference system (CRS). In this case, UTM 30 WGS84.
- The coordinates of the upper left corner of the grid: Initial NW (North West) Origin longitude (DEG) and Initial NW (North West) Origin latitude (DEG). Coordinates of the grid cells at all pyramid levels remained as whole integer numbers, not decimal numbers.
- Region of Interest (ROI): the area of interest that covered the entire Iberian Peninsula was equal to 1,500,000.0 m in width.
- Ground Sample Distance (GSD) for the maximum LOD. It was defined as 10 m, which corresponded to the spatial resolution of S2.
- Interval of LODs. LOD 0 corresponded to the coarsest spatial resolution, which was defined as 7,290 m while LOD 6 corresponded to the finest spatial resolution, defined as 10 m. LOD 4 was chosen as the storage level to keep appropriate sized files.
- Recursive ratio factor in tiles. It was defined as 3 because L8 spatial resolution was 30 m and S2 was 10 m, so there was a direct proportion equal to 3 between them. Consequently, the nested grid in each higher resolution level must be divisible in 3 × 3 sequentially.
- The maximum raster file size. It corresponded to a L8 scene of 183,000.0 m of width.
- The final ROG (Region Of Grid). It was obtained by resizing the initial ROI, defined to cover the maximum initial distance entered (1,500,000.0 m), considering the inclusion of a scene of maximum size corresponding to a L8 scene (183,000.0 m).

Fig. 3 shows the developed local nested grid and Tuplekeys from LOD 0 (coarsest nested grid), which covered the entire Iberian Peninsula to LOD 4 (storage level), displaying just the 192 Tuplekeys that covered the river basin.

2.3.3. Preparation of training data

A plot-based approach was used to train the classification algorithms using $NDVI_{TOA}$ metrics (Azar et al., 2017; Immitzer et al., 2016; Inglada et al., 2015; Ok et al., 2017; Peña et al., 2014; Schultz et al., 2015; Tatsumi et al., 2015; Ustuner et al., 2017). Thus, both $NDVI_{TOA}$ average and standard deviation were calculated at the level of each plot of the reference samples. 25,790 CAP statements (70%) were used for this purpose. Since the approach generated a massive volume of information, several filters were applied to use just the most representative training data. This step ensured both a precise and efficient classification model.

1. Extraction of plot-based $NDVI_{TOA}$ statistics.
   Using both CAP data (plots geographic delimitation) and $NDVI_{TOA}$ images organized in the Tuplekey regions, the mean and standard deviation of $NDVI_{TOA}$ at a plot-based level was calculated. Considering the border effect when using RS data at this level, a 30 m buffer was applied inwardly before performing the metrics. Results were kept in two different files, one for L8 and one for S2 with the following information: identification of each plot, crop type and $NDVI_{TOA}$ statistics.
2. Agronomic and edaphic filters.
   The training dataset was filtered by agronomic and edaphic criteria so that only the most useful and representative data trained the classification algorithms. Therefore, when multiple images were available for the same region and week, just the maximum $NDVI_{TOA}$ value remained per plot since no significant change in the phenological stage of a crop occurs in less than a week. This filter's goal is decreasing the high volume of input data in the process. Moreover, picking the maximum $NDVI_{TOA}$ value ensured a less presence of clouds in the image since clouds have very low $NDVI_{TOA}$ values.
   In addition, to ensure both the agro-climatic and edaphic coherence of the training data, just 200 plots of each crop were selected for taking part in the calibration process. Selected plots were the closest to the centroid of each Tuplekey. Nevertheless, if there was a crop class represented by < 200 plots, the total amount would be considered. In this way, both the quantity and representativeness of the training data were assured throughout the basin.

2.3.4. Classification process

During this step, the training data prepared was used to calibrate the classification algorithms by a plot-based approach and per Tuplekey. The fact of both filtering the training dataset and calibrating the model per Tuplekey instead of for the entire basin made it possible

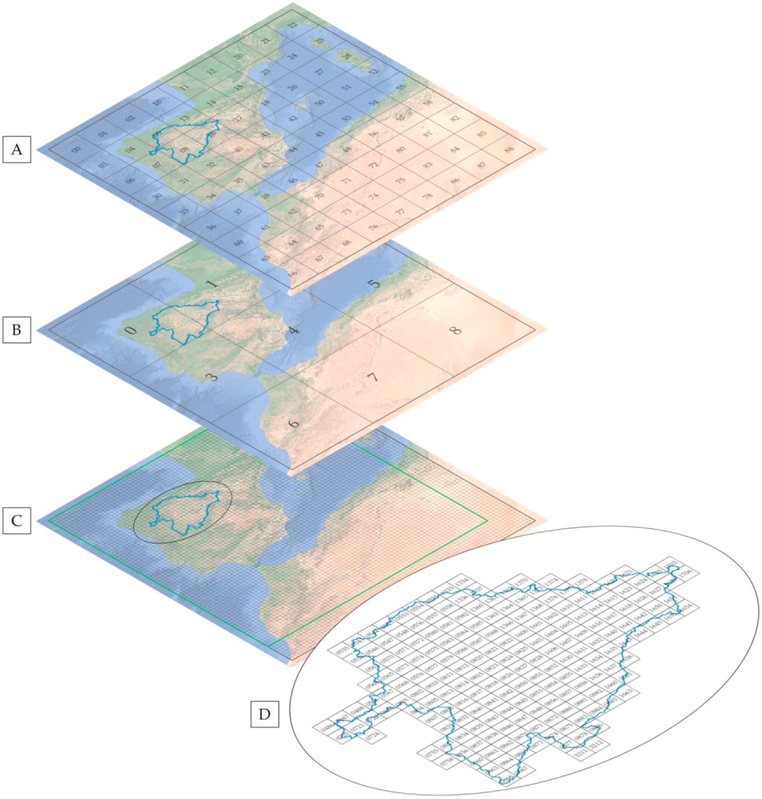


Fig. 3. Local nested grid in several LODs. **(a)** Local nested grid in LOD 2: each tile of the previous grid in LOD 1 was divided in 3 × 3. **(b)** Local nested grid in LOD 1: coarsest grid in LOD 0 with tiles divided in 3 × 3. **(c)** The coarsest nested grid that had LOD 0 and covered the entire Iberian Peninsula (in grey), the ROI (in green) and LOD 4 (little tiles in grey). **(d)** Zoom to the Duero basin to show the Tuplekeys in LOD 4 that cover the study area.

to differentiate the unique edaphic and agro-climate conditions of each region.

The classifiers chosen to be evaluated were Decision Trees (DT), Ensemble Bagged Trees (EBT) and Weighted Nearest Neighbor (WNN) since they show major guarantees in terms of speed and accuracy according to literature (Table 1). Table 4 describes the main characteristics of each method. The *ClassificationLearner* application of Matbal® was used with the aim of calibrating and validating the different algorithms.

The classification methodology goes through the following steps:

1 Selection of $NDVI_{TOA}$ scenes

To simplify the final classification process, S2 over L8 $NDVI_{TOA}$ scenes were selected when both were available for the same Tuplekey and date due to its better resolution.

2 Cloud cover filter

As clouds show very low $NDVI_{TOA}$, only scenes with an average value > 0.20 were used.

3 Classifiers calibration

The selected classifiers must learn from the prepared training data (70% of CAP plots). The plot-based calibration process was performed

Table 4
Algorithms evaluated for crop classification.

Method	Main characteristics
Decision Trees (DT)	Different number of leaves and maximum number of splits, up to 100
Ensemble Bagged Trees (EBT)	Random forest ensemble method with decision trees
Weighted Nearest Neighbor (WNN)	Distance weight. The number of neighbors was set to 10

per Tuplekey and classification algorithms learnt from the $NDVI_{TOA}$ signatures of the training data, considering all the plot-based statistics extracted during the previous step (Section 2.3.3).

4 Crops classified

Regarding the number of crops classified, 15 individual classes (alfalfa, corn, sugar beet, potato, sunflower, barley, wheat, fallow, rapeseed, green peas, vineyard, ray-grass, rye, oats and pastures) and 7 grouped classes (spring crop, summer crop, alfalfa and ray-grass, sunflower, fallow, vineyard and pastures) were labeled. Gathered classes were grouped attending the seasonality of the individual crops and their growing stages as their NDVI signatures are quite similar. Therefore, classification algorithms were applied two times: one considering all individual crop classes and the second one considering just the gathered classes.

5 Optimization of results

Finally, both the salt and pepper denoising approach and masks filtering artificial raw elements and forest areas were applied. Regarding the filtering masks, SIGPAC (Geographic Information System for Agricultural Plots, n.d.) land uses per cadastral parcel were the source of information. Finally, the salt and pepper denoising was applied to avoid the mixed-crop classification of plots (Basukala et al., 2017; Belgiu and Csillik, 2018).

2.3.5. Final crop classification: accuracy assessment

In this case study, classification accuracy was determined per classifier: (i) globally for the whole basin and (ii) per Tuplekey, so a spatial analysis of the OA could also be performed. Thus, an evaluation on how the number of images used per Tuplekey affects the final pixel-based classification was also carried out. Moreover, OA was determined considering: (i) individualized crop classes and (ii) gathered crop classes.

The confusion matrix allowed the comparison between reference data and final crop classes. Field surveys performed by the Duero fluvial guards in 2017 summer period were considered for assessing the OA for the whole basin. However, due to the lack of field samples, 30% of CAP statements were considered for assessing the classification accuracy per Tuplekey.

Overall, user's and producer's accuracies (OA, UA and PA) were calculated to assess the accuracy per classifier. In addition, per-class accuracy was evaluated regarding misclassified crops, both for individual and gathered crop classes, calculating omission and commission errors (OE and CE) (Congalton, 1991).

3. Results

3.1. Classification map for individual crop classes

This classification map offered a high overall accuracy (OA) when considering the 15 individual crop classes (alfalfa, corn, sugar beet, potato, sunflower, barley, wheat, fallow, rapeseed, green peas, vineyard, ray-grass, rye, oats and pastures) for all three classifiers and considering the whole basin. Ensemble Bagged Trees (EBT) classifier provided the best result with and OA of 87%, being Decision Trees (DT) and Weighted Nearest Neighbor (WNN) classifiers very close with OAs of 81% and 80%, respectively. Fig. 4 shows the final pixel-based crop classification map in the Duero river basin for individual crop classes using EBT and Table 5 its confusion matrix, as this classifier obtained the highest accuracy.

The following significant misclassified cases were obtained with WNN: (i) potato as corn 6 times and as sunflower 4 times, (ii) alfalfa as sugar beet 4 times and (iii) sugar beet as corn 4 times. On the other hand, with DT: (i) corn was confused with potato 4 times, (ii) sugar beet with alfalfa 3 times, (iii) alfalfa with pasture 3 times and (iv) sunflower with corn 4 times. However, other 25 misclassified crops were obtained when using DT, even not exceeding 2 times. As for EBT, only one significant misclassification occurred, potato confused with corn 4 times, among other 20 confusion cases, but not exceeding 2 times. Thus, EBT got less significantly confused crops than WNN and DT, which explains its better OA. These confusion cases are explained by the high similarity between their growing cycles. As Table 6 shows, potato and corn were the majorly confused classes due to their likeliness initial and late growing stages.

As for OAs per Tuplekey, WNN ranged 54–58% to 74–78% while global OA was 80% and DT presented the lowest values, ranging 42–46% to 62–66%, while global OA was 81%. The highest OAs per Tuplekey were again obtained when using EBT classifier, ranging mainly 70–74% and 74–78%, but still not reaching its global OA of 87%. Lower OAs were obtained per Tuplekey than for the whole basin due to using different validation data in each case. 30% of CAP statements were considered for estimating OA per Tuplekey instead of the field surveys due to the lack of these ones.

In addition, similar OAs were observed between adjacent Tuplekeys, remaining three spatial regions in the center of the basin as the lowest OA for all three classifiers (Fig. 5). The total number of $NDVI_{TOA}$ images used for the final crop classification was also calculated per Tuplekey, finding out that the lower number of images used, the lower OA was obtained.

Regarding the execution time needed for the classification process, EBT had the longest processing time, lasting 16 h and 8 min. On the other hand, DT classifier, slightly more accurate than WNN, needed only 2 h and a half, while WNN lasted almost twice that time, 5 h and 22 min. The developed approach was performed in a commercial computer with an Intel®CoreTM i9 7900× CPU (3.30 GHz), 64 bits and 64 Mb of RAM.

3.1.1. Per-class accuracy

Table 7 shows commission and omission errors (CE and OE) per class and classifier considering individual crop classes. Ray-grass, rye, oat and pasture showed both a CE and OE equal to 100% due to the lack of field surveys representing these crop classes. Moreover, other crops, i.e. alfalfa and barley, were misclassified as ray-grass and rye. Apart from them, the worst classified crop class was wheat, with a CE of 67% and OE ranging 75–86% for all three classifiers.

On the other hand, green pea was the only individual crop class with both a CE and OE equal to 0% for the three classifiers. Fallow also showed a CE of 0% for all the classifiers, but OE was just 0% when using DT while significantly high, 50 and 67% when using EBT and WNN, respectively.

EBT showed the lowest CE and OE among all three classifiers for alfalfa, corn, sugar beet and potato. Regarding DT, sunflower presented the lowest CE and OE when compared to the other classifiers. On the other hand, WNN showed higher CE and OE per crop class than the other algorithms. Therefore, it could be concluded that EBT performed a better classification for alfalfa, corn, sugar beet and potato and DT for fallow and sunflower while green pea is well classified using either of the classifiers.

3.2. Classification map for grouped crop classes

This classification map also offered high OAs when considering 7 grouped crop classes (spring crop, summer crop, alfalfa and ray-grass, sunflower, fallow, vineyard and pastures) for all three classifiers. EBT provided again the highest OA for the whole basin, 92%, followed in this case by WNN and DT, with OAs of 89% and 88%, respectively. Thus, an improvement of the OAs could be noticed for all three classifiers when considering gathered instead of individual crop classes (92% instead of 87% for EBT, 89% instead of 80% for WNN and 88% instead of 81% for DT). This fact was due to gather some individual

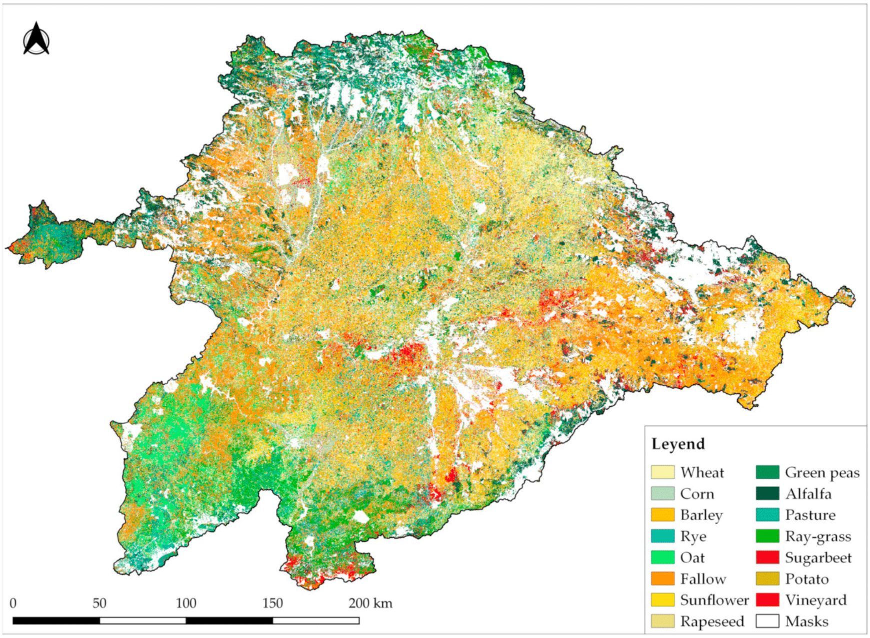


Fig. 4. 2017 final per-pixel crop classification performed with EBT classifier in the Duero river basin considering individual crop classes.

crop classes with similar growing cycles in the same class, decreasing the amount of misclassification cases. Final pixel-based crop classification in the Duero river basin and confusion matrix when using EBT and considering grouped crop classes are shown in Fig. 6 and Table 8, as the most accurate results.

WNN confusion matrix showed the following misclassified crops: (i) alfalfa and ray-grass classified as summer crop 6 times and as spring crop 3 times, (ii) summer crop confused with spring crop 4 times and with sunflower 3 times and (iii) sunflower misclassified as summer crop 3 times. Regarding DT classifier, the most significant confusion classes were: (i) sunflower classified as vineyard 8 times and as summer crop 4 times, (ii) summer crop classified as alfalfa and ray-grass 6 times and (iii) alfalfa and ray-grass confused with spring crop 3 times. Finally, the most noteworthy misclassification classes obtained with EBT were: (i) sunflower classified as summer crop 4 times and (ii) summer crop confused with spring crop 3 times and with alfalfa and ray-grass other 3 times. The growing stages showed again a high likeliness between the confused grouped classes (Table 9). Nevertheless, the most important remark was the decreased number of misclassified crops when classifying grouped instead of individual crop classes.

When getting OA per Tuplekey and hence its spatial distribution along the basin, higher and more homogeneous OA values could be noticed when crops were gathered instead of individualized. However, the three Tuplekeys with the lowest OA remained in the middle of the basin whether considering grouped or separated crop classes and it was directly related with the number of $NDVI_{TOA}$ images used. Spatial distribution of OAs per Tuplekey showed a significance likeliness between EBT and WNN classifiers, ranging mainly 86–90% to 90–94%, like their global OAs of 92 and 89% when assessing the accuracy for the whole basin. DT showed again the lowest values, ranging 42–46% to 62–66%, while its global OA was 88% (Fig. 7).

As for processing times when considering gathered crop classes, EBT, the most accurate classifier, showed again the longest processing time, lasting 16 h. On the other hand, DT needed only 2 h and a half, while WNN lasted 5 h. Therefore, executing processes were slightly quicker when crop classes were grouped instead of separated, but quite similar.

3.2.1. *Per-class accuracy*

Table 10 shows commission and omission errors (CE and OE) per class and classifier considering grouped crop classes. Pasture was the only class showing both a CE and OE equal to 100% due to the lack of field surveys representing it. As for the other crop classes, errors varied significantly, reaching 73%.

Comparing CE per classifier, fallow was the best classified crop, with a CE of 0% using either of the algorithms. EBT showed better results classifying summer crop and alfalfa and ray-grass (4 and 11%) and DT for vineyard (0%). As for OE, EBT generally presented the lowest values, especially for both fallow and vineyard, with an OE of 0%.

Therefore, for grouped crop classification, EBT showed the best results for classifying sunflower, summer crop and alfalfa and ray-grass; both EBT and DT classified perfectly fallow; while WNN showed the worst results.

3.3. *Mixed pixel-based classification in the same plot*

Mixed pixels' issue consisted in pixels that, even belonged to the same plot, were classified as different crop types. This problem took place even after applying the salt and pepper denoising approach and for either of the three classifiers. However, it significance depended on the classification algorithm used.

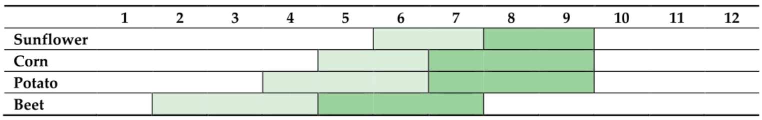
Table 5
Confusion matrix obtained with EBT classifier for the 2017 crop classification in the Duero river basin considering individual crop classes and field surveys performed by fluvial guards in 2017 summer period. Both UA and PA are shown in %.

	A[a]	**C**[b]	**SB**[c]	**PO**[d]	**S**[e]	**B**[f]	**W**[g]	**F**[h]	**RA**[i]	**GP**[j]	**V**[k]	**RG**[l]	**R**[m]	**O**[n]	**P**[o]	**Total**	**UA**[q]
A[a]	**35**	0	1	0	0	0	0	0	0	0	0	0	0	0	0	**36**	97
C[b]	0	**53**	2	4	2	0	0	0	0	0	0	0	0	0	0	**61**	87
SB[c]	0	0	**48**	2	0	0	0	0	0	0	0	0	0	0	0	**50**	96
PO[d]	0	2	2	**53**	1	1	0	0	0	0	0	0	0	0	0	**59**	90
S[e]	1	2	0	0	**18**	0	1	0	0	0	0	0	0	0	0	**22**	82
B[f]	0	0	1	1	0	**5**	1	0	0	0	0	0	0	0	0	**8**	63
W[g]	1	0	0	0	0	2	**1**	0	1	0	0	0	0	0	0	**5**	20
F[h]	0	0	0	0	0	0	0	**1**	0	0	1	0	0	0	0	**2**	50
RA[i]	0	0	0	0	1	0	0	0	**1**	0	0	0	0	0	0	**2**	50
GP[j]	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	**1**	100
V[k]	0	0	0	0	0	0	0	0	0	0	**2**	0	0	0	0	**2**	100
RG[l]	0	0	0	0	0	0	0	0	0	0	0	**0**	0	0	0	**0**	0
R[m]	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0	0	**0**	0
O[n]	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0	**0**	0
P[o]	1	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	**1**	0
Total	**38**	**57**	**54**	**60**	**22**	**8**	**3**	**1**	**2**	**1**	**3**	**0**	**0**	**0**	**0**	**249**	
PA[p]	92	93	89	88	82	63	33	100	50	100	67	0	0	0	0		

Bold indicates (1) the main diagonal, (2) total number of parcels identified with the same crop type as for each line and column, (3) individual crop classes in the first column and in the first line.

[a] Alfalfa.
[b] Corn.
[c] Sugar beet.
[d] Potato.
[e] Sunflower.
[f] Barley.
[g] Wheat.
[h] Fallow.
[i] Rapeseed.
[j] Green peas.
[k] Vineyard.
[l] Ray-grass.
[m] Rye.
[n] Oat.
[o] Pasture.
[p] Producer's accuracy.
[q] User's accuracy.

Table 6
Misclassified individual crop classes with similar phenological cycles. Numbers 1–12 mean the month of the year, light green "Initial and development stage" and darker green "Mid and late stage". Growing stages of the different crop classes were adapted from FAO (Food and Agriculture Organization of the United Nations). Alfalfa and pasture are not shown as they have pluriannual cycles.



DT showed the quickest execution time but also the most noteworthy appearance of mixed pixels, followed by WNN. On the other hand, EBT, which presented the highest OA for both individual and grouped crop classes and for the whole basin or per Tuplekey, showed the lowest rate of mixed pixels at a plot level.

Fig. 8 shows the mixed pixels' issue per classifier for the 210th plot of the field visits performed by the Duero basin fluvial guards. According to the field survey, the crop was a sugar beet. However, it was labeled as sugar beet and potato, both as majoritarian classes, using WNN, and as sugar beet, potato, wheat and pasture using DT classifier. Thus, DT did not only classify two extra classes but also obtained scattered pixels, which made it difficult to distinguish the majoritarian crop class in the plot.

On the other hand, EBT classifier labeled the plot as sugar beet and alfalfa, but it was easier to distinct the majoritarian crop class. Therefore, a plot-based estimation of the majoritarian crop class must be done to solve this issue.

4. Discussion

The developed pixel-based classification approach was tested for performing the 2017 crop classification at the large area occupied by the Duero river basin in Spain, 78,859 km^2. Crop mapping at this kind of scale and using high resolution imagery does not exist in the literature, finding 17,000 km^2 as the largest area studied in previous research experiences (Inglada et al., 2015). The main challenge when performing a crop classification in large study areas remain in the highly heterogeneous climates, landscapes and phenology, so just one calibrated classification model was not enough (Eggen et al., 2016).

The presented methodology achieved almost perfect classification

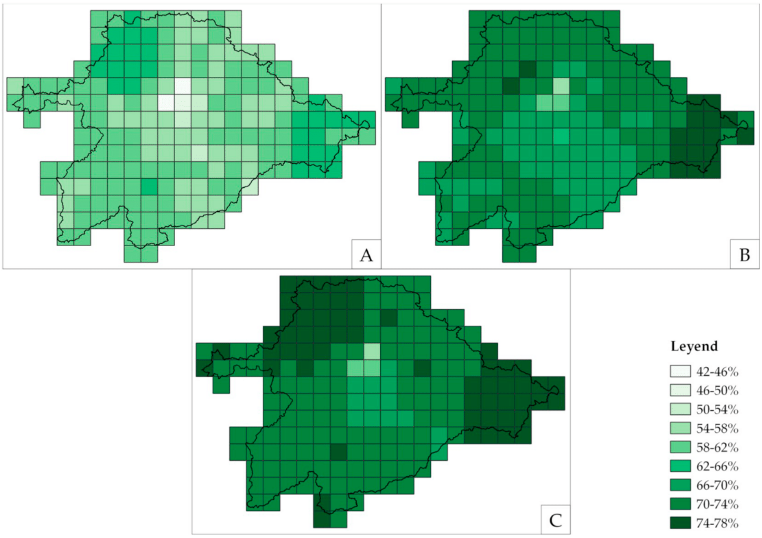


Fig. 5. Overall accuracy (OA) per each of the Tuplekeys when classifying individual crop classes and considering 30% of 2017 farmers' statements to the CAP as validation data. **(a)** Using Decision Trees (DT). **(b)** Using Weighted Nearest Neighbor (WNN). **(c)** Using Ensemble Bagged Trees (EBT).

Table 7
Commission and omission errors per class and classifier for the 2017 crop classification in the Duero river basin considering individual crop classes. Results are organized from the lowest to the highest CE obtained by EBT as the most accurate classifier. Both CE and OE are shown in % for each of the classifiers.

Individual crop classes	Commission error			Omission error		
	DT	WNN	EBT	DT	WNN	EBT
Green peas	0	0	0	0	0	0
Fallow	0	0	0	0	67	50
Corn	16	9	7	11	20	13
Alfalfa	18	18	8	11	6	3
Sugar beet	19	20	11	8	14	4
Potato	14	20	12	32	11	10
Sunflower	15	18	18	12	31	18
Vineyard	0	67	33	25	0	0
Barley	63	63	38	50	25	38
Rapeseed	50	50	50	0	67	50
Wheat	67	67	67	75	86	80
Ray-grass	100	100	100	100	100	100
Rye	100	100	100	100	100	100
Oat	100	100	100	100	100	100
Pasture	100	100	100	100	100	100

results by the effective integration of remotely-sensed data from two different open-source satellite platforms, Landsat-8 (L8) and Sentinel-2 (S2) A and B. These satellites offered two datasets with different spatial and temporal resolutions (30 and 10 m and 16 and 5 days, respectively) and hence its combined use increased both the amount and quality of the input data.

20,836 images from L8 (Level-1T) and S2 (Level-1C) were automatically downloaded and preprocessed in the period of March 1st – October 31st 2017 with the aim of obtaining a set of multi-temporal $NDVI_{TOA}$ images. The developed approach was based on integrating S2 and L8 $NDVI_{TOA}$ raster layers in special spatial regions (Tuplekeys) within a local nested grid that covered the whole basin. This novelty allowed to feed the classification process with a completely coherent and consistent database, organizing image footprints, pixel sizes and pixel positions at all pyramid levels (ANZLIC, 2012; Purss et al., 2015; Stumpf et al., 2018; Villa et al., 2016). Therefore, input data was divided in 278 Tuplekeys and 192 covered the river basin in the storage Level Of Detail (LOD).

However, the main goal was creating not only an accurate but efficient approach for crop classification of large areas. Thus, several filters based on agronomic and edaphic criteria were applied so just the most representative $NDVI_{TOA}$ images (8,671 out of 20,836) were used to perform the final calibrated pixel-based crop classification.

The three most accurate and efficient machine learning classifiers according to the literature (Table 1) were both tested and evaluated. According to the results, Ensemble Bagged Trees (EBT) showed the best performance, both when considering individual and gathered crop classes, reaching overall accuracies (OAs) of 87% and 92%, respectively, which reaffirm previous experiences. However, it also showed the longest executing time, 16 h.

Decision Trees (DT) was slightly more accurate than Weighted Nearest Neighbor (WNN), 81% and 80%, classifying individual crop classes, but less, 88% and 89%, considering aggregated crop classes. Nevertheless, DT has been widely used for crop classification, even not being the most accurate classifier since it is easily trainable and hence provides the quickest processing (Choodarathnakara et al., 2012).

OA was also assessed per Tuplekey using 30% of 2017 farmers' statements to the CAP, as well as the total number of $NDVI_{TOA}$ images used, finding out that low OA values were directly related with the quantity of worth classifying images filtered per Tuplekey. Generally, OA rates per Tuplekey were lower than the generic OA calculated for the whole basin for either of the classifiers due to the quantity of reference data, CAP declarations instead of field surveys.

Regarding per-class commission and omission errors (CE and OE), high rates were mainly associated with a lack of reference data from the field surveys. Thus, ray-grass, rye, oat and pasture for individual crop classification and just pasture for aggregated crop classification

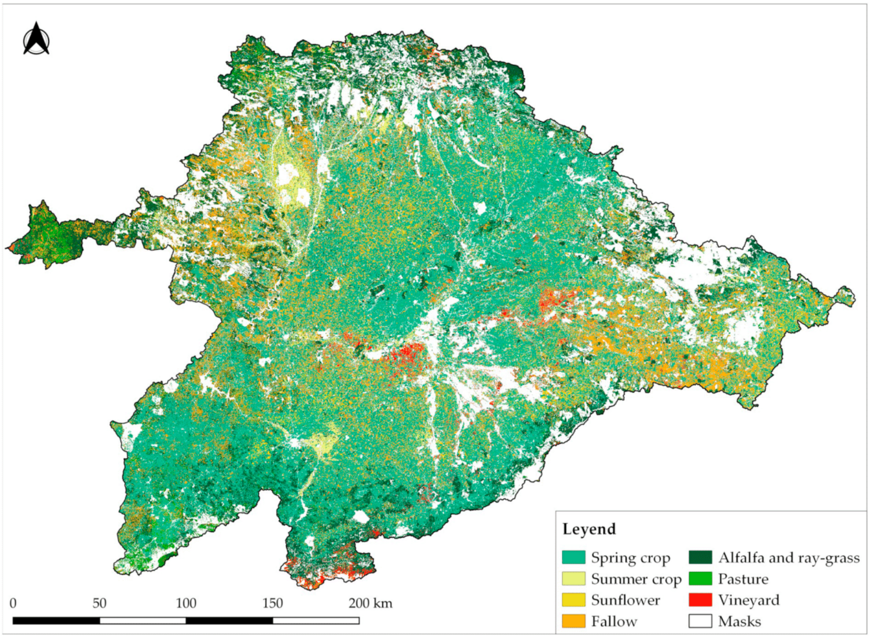


Fig. 6. 2017 final per-pixel crop classification performed with EBT classifier in the Duero river basin considering grouped crop classes.

Table 8
Confusion matrix obtained with EBT classifier for the 2017 crop classification in the Duero river basin considering grouped crop classes and field surveys performed by fluvial guards in 2017 summer period. Both UA and PA are shown in %.

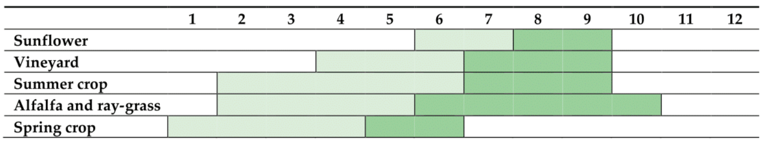
	Spring crop	**Summer crop**	**Alfalfa and ray-grass**	**Sunflower**	**Fallow**	**Vineyard**	**Pastures**	**Total**	**UA**[b]
Spring crop	**12**	3	2	1	0	0	0	**18**	67
Summer crop	2	**164**	2	4	0	0	0	**172**	95
Alfalfa and ray-grass	0	3	**34**	0	0	0	0	**37**	92
Sunflower	0	1	0	**17**	0	2	0	**20**	85
Fallow	0	0	0	0	**1**	0	0	**1**	100
Vineyard	0	0	0	0	0	**1**	0	**1**	100
Pasture	0	0	0	0	0	0	**0**	**0**	0
Total	**14**	**171**	**38**	**22**	**1**	**3**	**0**	**249**	
PA[a]	86	96	89	77	100	33	0		

Bold indicates (1) the main diagonal, (2) total number of parcels identified with the same crop type as for each line and column, (3) gathered crop classes in the first column and first line.

[a] Producer's accuracy.

[b] User's accuracy.

Table 9
Misclassified grouped crop classes with similar phenological cycles. Numbers 1–12 mean the month of the year, light green "Initial and development stage" and darker green "Mid and late stage". Growing stages of the different crop classes were adapted from FAO (Food and Agriculture Organization of the United Nations).



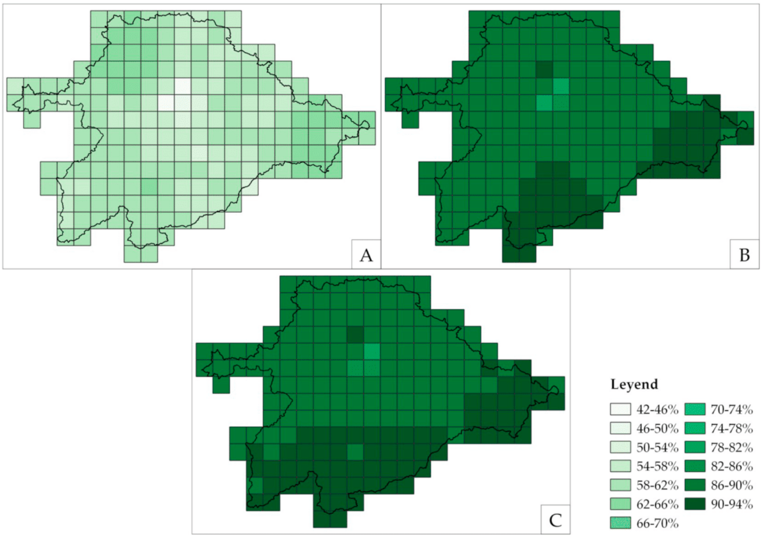


Fig. 7. Overall accuracy (OA) per each of the Tuplekeys when classifying grouped crop classes and considering 30% of 2017 farmers' statements to the CAP as validation data. **(a)** Using Decision Trees (DT). **(b)** Using Weighted Nearest Neighbor (WNN). **(c)** Using Ensemble Bagged Trees (EBT).

Table 10
Commission and omission errors per class and classifier for the 2017 crop classification in the Duero river basin considering grouped crop classes. Results are organized from the lowest to the highest CE obtained by EBT as the most accurate classifier. Both CE and OE are shown in % for each of the classifiers.

Grouped crop classes	Commission error			Omission error		
	DT	WNN	EBT	DT	WNN	EBT
Fallow	0	0	0	0	50	0
Summer crop	6	5	4	4	6	5
Alfalfa and ray-grass	16	24	11	16	6	8
Spring crop	14	14	14	29	43	33
Sunflower	55	23	23	17	23	15
Vineyard	0	67	67	73	0	0
Pasture	100	100	100	100	100	100

obtained both CE and OE of 100%, followed by wheat and vineyard, respectively. Therefore, using a larger and representative ground-truth dataset would allow to improve the crop classification (Lu and Weng, 2007). Defining several monitoring plots that represent the most significant crop types in the basin, as well as developing a methodology for assessing the crop type and stage, could be the solution to this issue.

The presence of mixed pixels was also recognized as an issue that affected the discrimination of the majoritarian crop class in a plot and hence OA per classifier. This problem was most significant using DT classifier, which also showed lower OAs, but the fastest processing. Mixed pixels are a very common issue when performing crop mapping, regardless the sensor resolution and the processing time needed (Basukala et al., 2017; Belgiu and Csillik, 2018; Choodarathnakara et al., 2012; Hsieh et al., 2012). Different approaches have been developed in this matter, i.e. using higher spatial resolution images to enhance the input datasets (Lu and Weng, 2007), but depending on non-freely available data. Another solution could be using soft classification methods based on fuzzy logic, so each pixel would belong to more than one crop class, having membership grades for each class (Choodarathnakara et al., 2012; Murmu and Biswas, 2015).

5. Conclusions

The main purposes of the presented study were: (i) to assess the

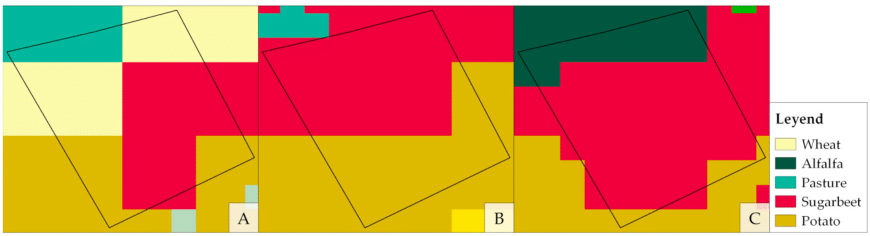


Fig. 8. Pixel-based crop classification for the 210th plot of the field visits performed by the Duero basin fluvial guards in 2017 summer period from the quickest to the slowest classifier. **(a)** Using Decision Trees (DT). **(b)** Using Weighted Nearest Neighbor (WNN). **(c)** Using Ensemble Bagged Trees (EBT).

accuracy when performing a cropland map in the Duero river basin using the three most accurate supervised classification algorithms according to the literature, (ii) to evaluate the integrate use of freely available multi-temporal remote sensing data from S2 and L8 satellite platforms since they have different spatial and temporal resolutions and (iii) to evaluate the approach outputs and efficiency considering both a long period of time and a large study area, and hence a huge quantity of information to be processed. Therefore, the developed classification methodology was capable to:

- Filter the available NDVI dataset attending both agronomic and edaphic criteria, improving the efficiency and therefore computation timing of the classification process since it did not consider redundant input data.
- Integrate the use of L8 and S2 NDVI data in a large study area by automatically creating special spatial regions called Tuplekeys that permitted its jointly used on a coherent way, organizing footprints and pixel sizes and positions at all levels of detail (LOD), increasing the available spatial and temporal resolution of the input data per Tuplekey.
- Test and evaluate the three most accurate supervised classification algorithms: Ensemble Bagged Trees (EBT), Decision Trees (DT) and Weighted Nearest Neighbor (WNN) both for individual and gathered crop classes.
- Obtain not only a generic OA value for the whole basin, but also its spatial distribution along the basin, calculating the accuracy per Tuplekey. Field surveys taken by the fluvial guards of the river basin during the summer of 2017 were used when calculating the classification accuracy for the whole basin. On the other hand, 30% of 2017 CAP statements were used when performing OA per Tuplekey due to the lack of field visits.
- Conclude that EBT classifier provided the best classification results both when considering individual and grouped crop classes, achieving the highest OA both globally and spatially distributed along the basin.
- Obtain 2017 crop classification in the Duero basin, covering almost 80,000 ha, with an OA of 87% and 92% with EBT classifier for individual and grouped crop classes, respectively, in just 16 h of computing time with a commercial computer, which proved the high efficiency and accuracy of the proposed methodology.

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Author contributions

Conceptualization, M.A.M. and D.G.A.; Methodology, D.H.L., R.B., M.A.M., L.P. and S.d.P.; Software, D.H.L and M.A.M.; Validation, L.P., S.d.P. and A.C.; Formal Analysis, L.P., S.d.P. and R.B.; Investigation, L.P., S.d.P., D.H.L., R.B., M.A.M., A.C. and D.G.A.; Resources, D.H.L., M.A.M. and D.G.A.; Data Curation, L.P., S.d.P., D.H.L., R.B. and M.A.M.; Writing-Original Draft Preparation, L.P., S.d.P., A.C., M.A.M. and D.G.A.; Writing-Review & Editing, L.P., S.d.P. and M.A.M.; Visualization, M.A.M. and D.G.A.; Supervision, M.A.M. and D.G.A.; Project Administration, D.G.A.; Funding Acquisition, D.G.A.

Conflicts of interest

The authors declare no conflicts of interest.

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Paper IV: Assessment of Green Infrastructure in Riparian Zones Using Copernicus Programme

remote sensing

MDPI

Article

Assessment of Green Infrastructure in Riparian Zones Using Copernicus Programme

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Abstract: This article presents an approach to identify Green Infrastructure (GI), its benefits and condition. This information enables environmental agencies to prioritise conservation, management and restoration strategies accordingly. The study focuses on riparian areas due to their potential to supply Ecosystem Services (ES), such as water quality, biodiversity, soil protection and flood or drought risk reduction. Natural Water Retention Measures (NWRM) related to agriculture and forestry are the type of GI considered specifically within these riparian areas. The approach is based on ES condition indicators, defined by the European Environment Agency (EEA) to support the policy targets of the 2020 Biodiversity Strategy. Indicators that can be assessed through remote sensing techniques are used, namely: capacity to provide ecosystem services, proximity to protected areas, greening response and water stress. Specifically, the approach uses and evaluates the potential of freely available products from the Copernicus Land Monitoring Service (CLMS) to monitor GI. Moreover, vegetation and water indices are calculated using data from the Sentinel-2 MSI Level-2A scenes and integrated in the analysis. The approach has been tested in the Italian Po river basin in 2018. Firstly, agriculture and forest NWRM were identified in the riparian areas of the river network. Secondly, the Riparian Zones products from the CLMS local component and the satellite-based indices were linked to the aforementioned ES condition indicators. This led to the development of a pixel-based model that evaluates the identified GI according to: (i) its disposition to provide riparian regulative ES and (ii) its condition in the analysed year. Finally, the model was used to prioritise GI for conservation or restoration initiatives, based on its potential to deliver ES and current condition.

Keywords: green infrastructure; riparian zone; natural water retention measure; ecosystem service; Copernicus; Sentinel-2; vegetation index; water index; downstream service

1. Introduction

In the view of human-induced climate change, ecosystem-based measures for disaster risk reduction (Eco-DRR) and climate change adaptation (CCA) have gained increasing attention [1]. Eco-DRR has been defined as "the sustainable management, conservation and restoration of ecosystems to reduce disaster risk, with the aim to achieve sustainable and resilient development" [2]. Eco-DRR is based on the concept that healthy, diverse and well-managed ecosystems increase the resilience of human societies and the environment to climate change impacts [3].

Taking into account ecosystem management in DRR, as well as within CCA strategies and policies, helps to convert the feedback loop existing between climate change impacts, ecosystem degradation and increased disaster risk [4]. In this context, the possible impacts of climate change on water quantity and quality, agriculture productivity, food security or greenhouse gas emissions have been a major concern [5].

The European Environment Agency (EEA) has the main role in analysing trends and vulnerabilities to assess the progress towards agreed targets and future actions against possible scenarios, both for each Member State of the European Union (MS) and the whole EU [6,7]. Therefore, the EEA has required systematic knowledge that links policy actions to economic, environmental and social trends. This can support the development of relevant, timely, robust and accessible information that helps policy makers and public users to act accordingly [8]. Thus, connecting existing knowledge to wider and deeper analyses, taking advantage of the latest freely available technologies, is a key step for getting efficient, accurate and near-real-time information that can support decisions regarding Eco-DRR and CCA [9].

Consequently, Green Infrastructure (GI) has been appearing more frequently as an effective nature-based spatial planning tool [7]. However, the concept of GI is still under discussion and hence has such a wide range of applications [10]. Thus, despite its increasing relevance in several policy areas, no universally accepted definition exists yet [11]. At a European scale, GI is defined as a concept addressing the connectivity of bionetworks, their protection and provision of ecosystem services (ES), while also contributing to climate change mitigation and adaptation [12–14].

GI operates at different scales and can support several ES. ES are classified as (i) provisioning services, supplying natural resources (e.g., fresh water); (ii) regulatory and maintenance (e.g., climate or flood regulation) or (iii) cultural (e.g., educational or recreational) [15]. In contrast with grey infrastructure (GrI), which usually has a single objective, GI is multifunctional and can thus promote win-win solutions to deliver benefits to several users and stakeholders [16,17]. For instance, floodplains are an important element of river systems to filter and store water, assure natural flood and drought protection [18], sustain biological diversity and provide recreational opportunities [19]. However, around 70–90% of Europe's floodplain area is ecologically degraded [20].

On the contrary, GrI is typically a component of a centralized approach to manage natural related hazards, specifically in the water management sector. It is thus a human-engineered infrastructure, such as levees, reservoirs and water or wastewater treatment plants [17].

However, GI and GrI shall not always be considered as fully replacing the other (e.g., they can complement each other in hybrid approaches) and GI cost-effectiveness is still under discussion: e.g., the US Centre for Sustainable Economy developed the standard Green vs. Gray Analysis (GCA) methodology [21] and the UK Natural Economy Northwest Programme developed the GI Valuation Toolkit [22]; but the published benchmark approach at global scale still needs to be refined at different local scales [23,24].

GI can be divided in several categories: (i) protected areas included in the Natura 2000 network, as defined by the Habitats [25] and Birds Directives [26] and by the 2020 Biodiversity Strategy [27]; (ii) restoration zones; (iii) sustainable use areas (e.g., biosphere reserves); (iv) green urban features; (v) natural and artificial connectivity features (e.g., hedgerows or riparian river vegetation) or (vi) multifunctional zones providing several services, such as access, recreation and biodiversity [14].

Furthermore, GI can include both natural and anthropogenic features, exist both in urban and rural settings and include "blue" spaces, like ponds and stream networks [17]. However, to be considered as a GI component, all its elements need to be part of a larger habitat, green area or network that serves a wider function and that, ideally, has been developed, maintained and enhanced through coordinated interventions [11,12].

Adequately mapping and assessing GI has become a significant task, especially due to its contribution to the management of extreme events, such as floods, droughts or water stress [28–30]. Developing suitable tools to perform this task would ease the mitigation of current and future risks related to climate change, land cover/land use changes and fluctuations of socio-economic conditions [31].

As pointed out by the European Commission (EC) [13], public authorities have used GrI as a substitute of natural solutions to prevent the degradation of key ecosystem services. GI is instead a successfully tested measure to also provide economic, social and ecological benefits to humans [17].

Therefore, GI's potential as a policy measure to improve the resilience of ecosystems and, as a consequence, of the anthropic structures and activities depending on them and on the ES they deliver, has been increasingly acknowledged by policymakers over the past decades [12,32]. In 2011, the 2020 Biodiversity Strategy [27] explicitly stated the importance of incorporating GI into spatial planning in order to achieve its Target 2 of maintaining and enhancing ES and recovering at least 15% of the degraded ecosystems across Europe.

Later on, the EC formulated a specific strategy on GI [13], aiming to promote it among stakeholders, encouraging investments in, and the development of, trans-European GI networks. The strategy recognized the need to incorporate GI into key policies, such as: (i) the EU Strategy on Adaptation to Climate Change [33]; (ii) upgrading the Natura 2000 Network [25–27]; (iii) the European Forests Strategy [34]; (iv) the Common Agricultural Policy (CAP) objectives [35] or (v) water-related policies, such as the Water Framework [36] or the Floods Directives [37], among others.

Developing new GI and restoring damaged ecosystems that connect natural core areas, reducing bionetwork fragmentation, can tackle both ecosystems' condition and human well-being [38]. Action 5 of the 2020 Biodiversity Strategy [27] called MS to map and assess the condition and pressures on ecosystems and their services in their national territory with the assistance of the EC. The technical report of the 2018 Mapping and Assessment of Ecosystems and their Services (MAES) Initiative [39] presented indeed a core set of suitable ES condition indicators. The set of indicators can act as a basis tool for identifying and prioritising areas for ecosystem restoration and deployment of GI (Target 2 of the 2020 Biodiversity Strategy) [17,19,20,27].

The overall objective of the presented initiatives and strategies is hence to promote GI in Europe to improve the connectivity of Natura 2000 sites [25–27] within and across national borders, linking biodiversity-rich areas where investments for ecosystem protection and restoration are prioritised, so as to enhance the delivery of essential ES throughout the EU territory [27,39]. Specifically, 2018 MAES report [39] states that "the condition indicators for ecosystem attributes are based on the spatial coverage, the configuration and the state of the green space and vegetation. Special attention goes to the share of protected area inside the boundaries. This can be measured by intersecting the area of Natura 2000 sites or of other protected areas". The proximity to protected areas constitutes indeed a significant indicator to assess GI due to its structural continuity and functional connectivity of semi-natural vegetation, providing favourable corridors for species dispersal and for the improvement of fragmented landscapes [13].

The aim of the presented research is to find a way to: (i) identify GI using Copernicus and Earth Observation, (ii) assess its capacity to deliver benefits to humans, (iii) analyse its condition and (iv) rank its conservation priority accordingly. The case study selected to test the approach is the Po river basin, located in Northern Italy. It is the largest water catchment and a focal point for the economy of the country, with more than 40% of national gross domestic product (GDP) and 35% of agricultural production, which makes climate change effects a major concern [40,41].

The study focuses on riparian areas, which represent transitional areas occurring between land and freshwater ecosystems, characterised by distinctive hydrology, soil and biotic conditions and strongly influenced by the watercourse [42]. Thus, these areas can efficiently serve a wide range of functions related to water quality, flow moderation, soil erosion and biodiversity conservation [16,18–20,28,30,42]. The protection of riparian areas is therefore significant for ES conservation [43,44].

Within these areas, the study focuses on Natural Water Retention Measures (NWRM), which are defined as "multi-functional measures that aim to protect and manage water resources and address water-related challenges by restoring or maintaining ecosystems as well as natural features and characteristics of water bodies using natural means and processes" [42]. Specifically, the analysis focuses on agriculture and forestry types of NWRM and on regulative ES due to the role of NWRM in regulating extreme events, such as floods or droughts, by storing or slowing runoff, increasing evapotranspiration, increasing groundwater recharge or increasing soil water retention [19,42,43].

Lack of recent field data and current availability of open-source satellite-based reliable data with high spatial, temporal and radiometric resolutions makes remote sensing a suitable tool to monitor GI in the case study. Especially due to the full, open and free European Copernicus Land Monitoring Service (CLMS) [45] and after the launch of Sentinel-2 (S2) B in March 2017, increasing its revisit time to just five days [46]. Specifically, the Riparian Zones products from the CLMS local component were used since they provide detailed data on these areas' land cover/land use class and disposition to deliver riparian ES [47,48]. Moreover, S2 data has been used due to its high spatial resolution to overcome this weakness of the bio-geophysical indices offered in the CLMS [49]. The goal was to determine and evaluate ES condition indicators specified in the reviewed frameworks, such as the greening response and water stress [39], using indices that can be related to vegetation biophysical characteristics, like the Normalized Difference Vegetation Index (NDVI) [50–53].

The approach is an improvement of the current Riparian Zones products [47]. The integration with other datasets (Natura 2000), high-resolution satellite data (S2) and previous research that outlines user requirements [54–56] and sets ES condition indicators [39,57–65], allows the identification of NWRM within the riparian system of a river network and the assessment of their current condition. Furthermore, it overcomes specific limitations mentioned by decision-makers, such as data availability, scalability and possibility to monitor over time [55]. Specifically, it can ease MS tasks [27] by quickly identifying and assessing GI condition and supporting the corresponding management or restoration plans [31].

The article is organized as follows: after introducing the concept of GI and presenting the current policies and initiatives on its deployment and appropriate conservation, Section 2 describes the case study, the input data used and the steps followed for the integration and analysis of the Copernicus products. Section 3 shows illustrations of the identified and assessed GI in the modelled area. Section 4 discusses the results of the analysis, data gaps and future challenges, especially regarding CLMS potential to map and assess GI and, finally, Section 5 summarizes the conclusions derived.

2. Materials and Methods

2.1. Case Study: Po River Basin

Po is the largest Italian basin, covering an area of 74,000 km^2; 70,000 km^2 in Italy and 4000 km^2 in Switzerland and France. The related river network has a total length of about 6750 km, corresponding 650 km to the main river. The area consists of two regions: Upper Po (75%), characterised by mountainous streams from the Alps [66], and Po Valley (25%) with flat and wide plains [67] (Figure 1).

The hydrological network is therefore characterised by a mixed discharge regime: part Alpine with spring and summer floods and winter droughts and part Apennine with spring and autumn floods and summer droughts [68,69]. The highest streamflow peaks can be observed both in spring and autumn due to precipitation and snow melting, while the Maritime and Liguria Alpine areas are characterised by lower specific discharge and higher evapotranspiration that limits river flow [70,71].

The basin is a strategic area for the Italian economy, produces 40% of gross domestic product (GDP) and has a population of over 16 million [40]. Despite high urbanization, agriculture plays a dominant role in the basin [40,72]. Water uses concern industrial activities, agricultural productions, livestock and inland navigation and, consequently, water extreme events can provoke serious economic damages [41,68].

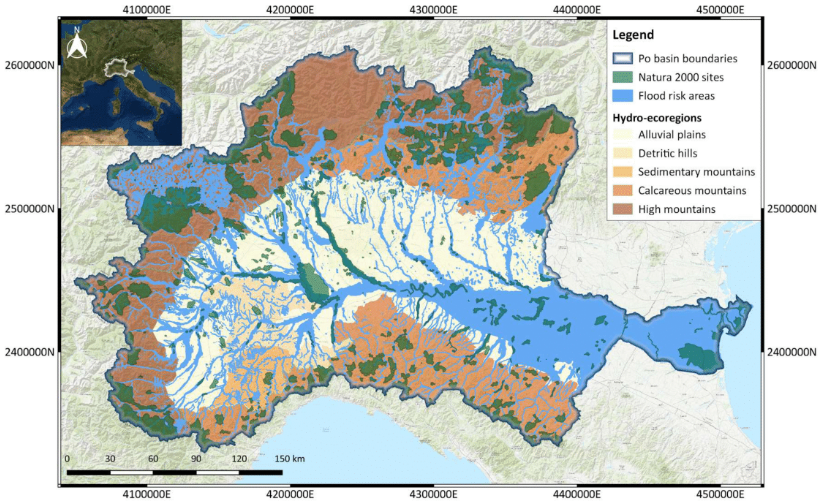

Figure 1. Po hydrographic basin location in Italy: basin boundaries, hydro-ecoregions [73], flood risk area [74] and Natura 2000 sites [75].

Previous scientific research analysed the difference in precipitation, temperature and daily flux of Po river by comparing forecast data (2021–2050) and recorded data (1982–2011). The comparison showed a significant decrease in annual average water availability and a higher frequency and intensity of extreme events [40,41,72]. This makes the region interesting to study GI as a nature-based solution for mitigating water stress effects [70].

Floods and droughts affect the river basin more intensely in its delta area due to higher pressure on water resources [68,72] (Figure 1). Also, Po delta is the largest wetland in Italy and over a third of its surface is protected under the Birds Directive [26] (Figure 1). Therefore, it was selected as the study area to analyse GI condition using data from the Sentinel-2 satellite platform [46].

2.2. Materials

2.2.1. Copernicus Land Monitoring Service: Riparian Zones and Corine Land Cover

CLMS local component focuses on different hotspots, i.e., areas that are prone to specific environmental challenges [49]. The Riparian Zones (RZ) is a local CLMS product that supports the objectives of European legal acts and policy initiatives, such as the Biodiversity Strategy to 2020 [27], the Habitats [25] and Birds Directives [26], the Water Framework [36] and the Floods Directives [37].

RZ consists of three products: Delineation of Riparian Zones (DRZ), Land Cover/Land Use (RZ LC/LU) and Green Linear Elements (GLE) [47]. Moreover, the DRZ product consists of three components [48] of which the Delineation of Potential Riparian Zones (DRZP) was used. DRZP is derived from weighing hydrological and geomorphological parameters, among other input data (Table 1), to express the likelihood of an area to host riparian features and hence to provide riparian-related benefits.

RZ LC/LU and DRZP (Figure 2) are the main input data used in the approach to identify GI and its potential to provide riparian-related ES respectively, since they provide very detailed information of the riparian environment (LC/LU classes and its characteristics) along large and medium-sized river streams (Table 1).

Table 1. Main characteristics of the Riparian Zones' (RZ) products from the Copernicus Land Monitoring Service (CLMS) local component used in the approach [47].

Product	Delineation of Potential Riparian Zones	Riparian Zones Land Cover/Land Use
Product short name	DRZP	RZ LC/LU
Product definition	Spatial model which indicates the capacity to host riparian features.	Detailed LC/LU dataset for areas along a buffer zone of selected rivers (Strahler level 3 to 8).
Input data	(1) EU-DEM1 [1] (2) Water masks [2] (3) JRC FHRM [3] (4) HWSD [4]	(1) DRZA [5] (2) Satellite Imagery [6] (3) Corine Land Cover 2006/2012 (4) Urban Atlas 2006/2012 (5) Imperviousness degree and tree cover density [7] (6) National orthophoto web map services, Google Earth Pro and Bing Maps (7) Numerous additional references and in-situ data sources
Geometric resolution or equivalent scale	Raster: 25 m Vector: 1:50.000	1:10.000
Minimum Mapping Unit	Raster: 625 m^2 pixel-based Vector: 50 ha	0.5 ha
Minimum Mapping Width		10 m
Coordinate Reference System	ETRS89/LAEA Europe EPSG: 3035	ETRS89/LAEA Europe EPSG: 3035
Temporal reference	2010–2014	2010–2014
Accuracy	Not-yet-assessed (just by experts)	≥85%
Responsible	European Environment Agency (EEA)	European Environment Agency (EEA)

[1] European Digital Elevation Model, 25 m spatial resolution. [2] Water masks from the Riparian Zones Land Cover/Land Use, EU-Hydro 2006, Open Street Map and mask from CORE_03 data for riparian zones gap filling. [3] Flood Hazard Risk Maps by the Joint Research Centre at 20, 50, 100, 200 and 500 years of returned period, 100 m spatial resolution. [4] Harmonized World Soil Database. [5] Delineation of Actual Riparian Zones. [6] Remote sensing satellite data from 1.5 m SPOT-6, 2.0 m Pleiades and 2.5 m SPOT-5. [7] Pan-European high-resolution layers from Copernicus initial operations.

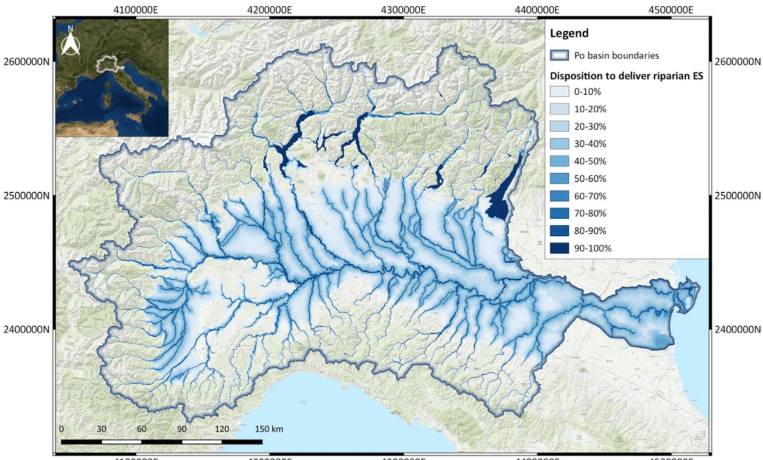

Figure 2. Disposition to provide regulative ecosystem services (ES) in the Po river basin area, obtained using the Delineation of Potential Riparian Zones (DRZP) product from the CLMS local component [48].

Corine Land Cover (CLC) consists of an inventory of land covers classified in 44 overall classes. It is a pan-European product initiated in 1985 (reference year 1990) and updated every 6 years. The RZ LC/LU product was performed using CLC 2006/2012, among other inputs (Table 1). Thus, CLC 2018 and Corine Land Cover Change (CLCC) 2012/2018 [76] (Table 2) were used for an internal cross-check validation approach of the main input data. The goal was updating the LC/LU classes, avoiding false positives in GI identification due to LC/LU changes between 2012 and 2018, before performing the subsequent spatial and temporal analyses on the vegetation condition. Afterwards, the misclassified GI was photo-interpreted using recent Sentinel-2 satellite images.

Table 2. Main characteristics of the Corine Land Cover (CLC) 2018 and Corine Land Cover Change (CLCC) 2012/2018 [76].

Product	CLC 2018 and CLCC 2012/2018
Satellite data	Sentinel-2 (S2) (and Landsat-8 for gap filling)
Time consistency	2017–2018 (CLC) and 2012–2018 (CLCC)
Geometric accuracy	≤10 m (S2)
Minimum Mapping Unit/Width	25 ha/100 m
Coordinate Reference System	ETRS89/LAEA Europe EPSG: 3035
Change mapping (CLCC)	Boundary displacement min. 100 m All changes ≥5 ha are mapped
Thematic accuracy	≥85%

2.2.2. Ancillary Data: Hydro-Ecoregions, Flood Hazard Risk Maps and Natura 2000 Network

The DRZP layer is not validated yet (by September 2019) due to lack of reference data and characteristics of riparian zones in sufficient detail [48]. To assure that the layer was suitably characterizing riparian areas in the case study area, it was cross-checked with available local ancillary data, i.e., products offered by the Emilia-Romagna region in an open-source catalogue: the hydro-ecoregions (HERs) [73] and the 2013 Flood Hazard Risk Maps (FHRM) [74].

Po HERs have been defined according to the implementation of the Water Framework Directive [36]. Each area is characterized based on: (i) the lithological structure and properties of the rocks (hardness, permeability and influence of water chemistry); (ii) relief (altitude and slope) and (iii) climate, depending on the precipitation and temperature (yearly average and seasonal variation) [73]. On the other hand, the FHRM are defined according to the Floods Directive [37] and delimitate hazard risk areas depending on: (i) scenarios of low, medium or high probability of flood; (ii) return period and (iii) information associated to all the exposed elements [74].

Firstly, these vector and alpha-numeric datasets were interpreted with respect to the aquatic ecosystem functioning and its benefits for the water balance. Subsequently, the outcome was compared with the DRZP buffers and percentage ranges. The correlation is visible in Figures 1 and 2.

The Natura 2000 network, obtained from the same catalogue, defines rich habitats that play a significant role as natural corridors within the wider landscape [75]. It was used to determine its distance to the identified GI. The goal was increasing the conservation priority accordingly [39].

2.2.3. Sentinel-2 Multispectral Imagery

The presented work used also Sentinel-2 (S2) satellite data because it can monitor large surfaces with high spatial, temporal and radiometric resolutions. This may explain its worldwide use as input data for land cover/land use monitoring and decision-making applications [50,51]. Table 3 shows the main characteristics of the optical sensor on-board S2 (the Multispectral Instrument–MSI) and the band set used.

Table 3. Main characteristics of the Sentinel-2 (S2) Multispectral Instrument (MSI) sensor and bands used [77].

Satellite Platform	Sentinel-2 (A & B)
Spatial resolution	10 m [1] and 20 m [2]
Temporal resolution	5 days [3]
Time consistency	2015-to date
Radiometric resolution	12 bits
Band set used	Band 2 (Blue): 0.490 µm Band 4 (Red): 0.665 µm Band 8 (NIR): 0.842 µm Band 11 ($SWIR_1$): 1.610 µm

[1] Visible and Near-Infrared bands. [2] Short-Wave Infra-Red bands. [3] 10 days using one satellite, 5 days using two.

Just 4 bands were needed to calculate the biophysical variables applied to assess GI condition in terms of its vegetative health stage and water content [52]. Vegetation indices are calculated using the spectral bands that capture the Red and Near-Infrared (NIR) reflectance, as this part of the electromagnetic spectrum shows a higher sensitiveness to the leaf chlorophyll content [78,79]. On the other hand, leaf water content largely controls the spectral reflectance in the Short-Wave Infrared (SWIR) interval of the electromagnetic spectrum [80].

2.3. Methodology

The proposed steps to identify the existing NWRM and estimate its disposition and condition for delivering riparian regulative ES (Figure 3) are based on the benchmarks developed for mapping and assessing ecosystems and their services [39,57–65]. This is mainly required by the EEA to fulfil the targets of the 2020 Biodiversity Strategy in this regard [27].

2.3.1. Input Data Acquisition

Specifically, the Delimitation Units DU018A and DU005A, that catch the study area, were downloaded from the Delineation of Potential Riparian Zones (DRZP) and the Riparian Zones Land Cover/Land Use (RZ LC/LU) products in the local CLMS. Then, they were clipped using the basin boundaries.

As for the satellite data used, Sentinel-2 Level 1C (S2 L1C) scenes of the tile T32TQQ that covers Po delta were acquired from the French Sentinel collaborative ground segment PEPS-CNES [81], an operating platform mirroring all Sentinel products provided by the European Space Agency (ESA). Just one S2 tile was analysed in order to observe an area in which the climate conditions, phenology types and development trends could be considered almost the same [51]. 36 scenes for the period of 1st January–30th October 2018, with a cloud cover below 50%, were downloaded and pre-processed. This year was selected to perform an intra-annual assessment of the variability in the phenological trend of the selected GI. Also, it was selected since the scenes were less affected by atmospheric effects and cloud cover.

2.3.2. Pre-Processing

To assure that the main input Copernicus products were suitably characterizing the riparian areas in the case study area in the analysed year, they were cross-checked with auxiliary data, i.e., available local ancillary data and the updated version of CLC 2018. This way, the analysis was based on LC/LU datasets and satellite images of the same period.

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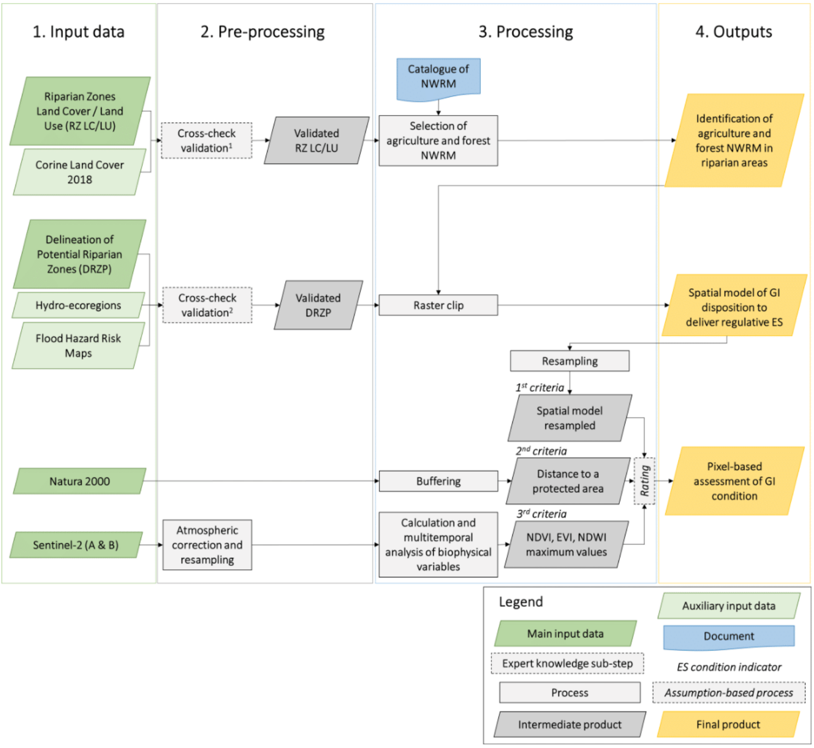

Figure 3. Flowchart of the proposed methodology to identify Natural Water Retention Measures (NWRM) in riparian areas of a river network, its disposition to provide regulative ES and its condition (input data explained in Section 2.2). [1] Comparison between the land cover/land use classes assigned to the identified GI due to the launch of an updated version of Corine Land Cover in 2018. [2] Due to lack of reference data on riparian characteristics in a sufficient level of detail, the authors checked the correlation between the DRZP layer's modelled area in the case study and regional products.

The Maccs-Atcor Joint Algorithm (MAJA) [82] was used right after acquiring the S2 L1C scenes from the PEPS-CNES segment [81]. The selection of this atmospheric correction algorithm was based on its unique method for detecting clouds and shadows using multi-temporal series of data input instead of a single image [82]. This improves the correction of atmospheric, shadows and even slope effects in comparison with SNAP or Sen2Cor-derived S2 L2A [83], which could affect the vegetation and water indices that are calculated afterwards. Thus, time series of the T32TQQ tile were processed together since it did not represent a massive quantity of data.

Afterwards, 7 scenes were selected, one per month from March to September 2018 (Table 4). This selection was made due to their lower cloud cover and hence fewer missing values. Also, since this period of the year catches the most prominent stage of the vegetation development cycle (according to the growing stages specified by the Food and Agriculture Organization of the United Nations, FAO [50,51]). Thus, this period catches the highest values of the analysed bio-geophysical indices if the detected GI is being adequately maintained [78–80].

Table 4. Scenes used of the T32TQQ tile, caught by the S2 MSI sensor, to test the approach; downloaded and pre-processed on the PEPS-CNES collaborative ground segment [81].

Satellite Platform	Date	Cloud Coverage (%)
S2A	30 March 2018	45
S2A	19 April 2018	5
S2A	19 May 2018	31
S2A	28 June 2018	18
S2A	18 July 2018	0
S2A	17 August 2018	2
S2A	26 September 2018	5

Lastly, band 11 ($SWIR_1$) was resampled from 20 to 10 m using the Semi-Automatic Classification Plugin 6.2.5 [84] in QGIS 3.2.1 in order to calculate the indices with the finest spatial resolution.

2.3.3. Processing and Outputs

A significant phase of the research was finding attributes that allowed to: (i) spatially identify GI sites that serve for water retention (1st output), (ii) recognize their role in the river riparian system (2nd output) and (iii) assign them an importance based on their conservation condition (3rd output) (Table 5). With this aim, assumptions were made by: (i) selecting the common criteria used by the consulted approaches on indicators to detect ecosystems' condition [39,57–65] (1st column) and (ii) linking it to the suitable Copernicus products [47], available ancillary data [75] or the most successfully used bio-geophysical indices to monitor vegetative surfaces [52,78–80] (2nd column).

Table 5. Criteria selected and indicators used to identify riparian NWRM and assess their disposition to deliver regulative ES and their current condition.

Criteria [39,57–65]	Indicators Used	Output Delivered
Capacity to provide ecosystem services	Riparian Zones products [47] from the Copernicus local component: - Identification of agriculture and forest riparian GI [1] according to MAES level 4 LC/LU classes [2]. - Disposition to deliver riparian ES according to the DRZP [3] product. Natural Water Retention Measures catalogue from DG-ENV [42].	1. Identification of agriculture and forest NWRM in riparian areas 2. Spatial model of GI disposition to deliver regulative ES
Membership in Natura 2000 network	Buffers of Natura 2000 areas [75] to calculate the distance to detected GI.	3. Pixel-based assessment of GI condition [5]
Indicators of the ecosystem's functional attributes: greening response and water stress	Bio-geophysical indices calculated using Sentinel-2 (S2) [4]: - NDVI: vegetation vigorousness [78]. - EVI: more sensitive than NDVI in heavily vegetated sites [79]. - NDWI: vegetation water stress [80].	

[1] Green Infrastructure. [2] Mapping and Assessment of Ecosystems and their Services (MAES) level 4 of Land Cover/Land Use classes, consulted in the RZ LC/LU Copernicus local product. [3] Delineation of Potential Riparian Zones product from the Copernicus local component [48]. [4] Being NDVI, the Normalized Difference Vegetation Index; EVI, the Enhanced Vegetation Index and NDWI, the Normalized Difference Water Index. [5] Using the indicators stated together with output 2.

Identification of Agriculture and Forest NWRM in Riparian Areas

The proposed approach focused first on detecting vegetation and forestry GI sites in the riparian areas of Po river basin. More specifically, nature-based measures for water retention (NWRM). The RZ LC/LU product is the main input used [47]. As it follows the MAES nomenclature (levels 1 to 4) for defining the LC/LU classes, level 4 was consulted due to its higher level of detail.

These LC/LU classes were linked to the type of agriculture and forest NWRM using the catalogues developed by the European Commission Directorate-General Department for Environment Policies (DG-ENV) [42] (Table 6). An area of 4040 km^2 of agriculture and forest NWRM was detected in the riparian areas of Po river basin, finding a significant appearance of forest riparian buffers (66%), followed by meadows and pastures (20%).

Table 6. Types of agriculture and forest GI for natural water retention (NWRM) identified in the riparian areas of Po river basin and corresponding area extent.

MAES Level 4 LC/LU Classes [1] [47]	Green Infrastructure [42]	Area (km^2)
Pastures Managed grasslands without trees and scrubs with a Tree Cover Density (TCD) of less than 30% and over or equal 30% Dry, mesic and alpine and subalpine grasslands without trees with a TCD of less than 30% Herbaceous vegetation Heathlands and moorlands Sparsely vegetated areas	**Meadows and pastures**	775.68
Transitional woodland and scrub Lines of trees and scrub	**Buffer strips and hedges**	94.10
Annual crops associated with permanent crops Complex cultivation patterns	**Crop rotation Strip cropping along contours Intercropping [2]**	91.46
Land principally occupied by agriculture with significant areas of natural vegetation Agro-forestry with a TCD over 30% and less than 30% Dry, mesic and alpine and subalpine grasslands with trees with a TCD over or equal 30%	**Green cover**	224.07
Riparian and fluvial broadleaved, coniferous and mixed forest with a TCD over 80%, 50–80%, 30–50% and 10–30% Broadleaved, coniferous and mixed forest swamp with a TCD over 80%, 50–80%, 30–50% and 10–30%	**Forest riparian buffers**	2688.64
Riverbanks	**Riverbanks**	133.92
Forest Other natural and semi-natural broadleaved, coniferous and mixed forest with a TCD over 80%, 50–80%, 30–50% and 10–30% Broadleaved evergreen forest with a TCD over 80%, 50–80%, 30–50% and 10–30% Highly artificial broadleaved, coniferous and mixed plantations with a TCD over 80%, 50–80%, 30–50% and 10–30% Other scrub land Sclerophyllous vegetation	**Continuous cover forestry**	32.26

[1] Mapping and Assessment of Ecosystems and their Services (MAES) level 4 of Land Cover/Land Use classes, consulted in the RZ LC/LU Copernicus local product. [2] These GI types have been gathered in the delivered spatial models as crop rotation.

After that, spatial operations were carried out in a model using ArcGIS 10.2 raster calculator algorithms (Figure 3).

Spatial Model of GI Disposition to Deliver Regulative ES

Clipping the identified NWRM (1st output) by the DRZP model [47] allows to detect the disposition of each site to deliver the associated regulative ES in the riparian system [42]. This disposition can be expressed by weighing different hydrological and geomorphological parameters that affect the appropriate functioning of riparian ecosystems, especially during extreme events, such as floods or droughts [28,30,42,72–74], and that the DRZP product takes into account (Table 1): (i) distance to water bodies, (ii) slope, (iii) flood hazard risk areas and their return period and (iv) soil type (i.e., erosion and permeability features) [47,48].

As a result, a spatial model of the identified agriculture and forest GI shows its disposition to deliver NWRM-related regulative ES (2nd output), measured from 0% to 100% and with a spatial resolution (SR) of 100 m due to the SR of the Copernicus product [47].

Pixel-based Assessment of GI Condition

- Buffering of the Natura 2000 network

The Natura 2000 areas of the river basin [75] were buffered every 10 m until 100 m [39,85]. Then, the identified GI was classified according to 10 distance ranges. This parameter was used to prioritise adequate management and conservation of those GI sites that belong or are close to Natura 2000 areas due to their contribution to the ecosystem's appropriate functioning, being hence significantly vulnerable items to changing climate consequences [39,57–65].

- Calculation and multitemporal analysis of biophysical variables

Vegetation and water indices were calculated for the period of March–September 2018 using the spectral bands from the 7 selected S2 images, once corrected from the atmospheric effect and resampled. Also, a filter of GI with a surface of less than 0.1 ha was applied due to S2 spatial resolution.

Several indices were analysed complementarily to obtain a more accurate and reliable characterization of the environment [52]. These spectral indices (Table 5) were selected for being the most significantly used in vegetation and forestry studies, achieving representative and accurate results in previous experiences [52,86,87].

The Normalized Difference Vegetation Index (NDVI), as well as the Enhanced Vegetation Index (EVI), have been the most successful in studying the development stage, healthiness and vigorousness of vegetation [50,51,86]. On the other hand, the Normalized Difference Water Index (NDWI), also called Normalized Difference Moisture Index (NDMI) in some studies, has been used to detect wetness and water content in vegetation [87].

NDVI is calculated using the reflectance from the Red channel (R) and the Near-Infrared (NIR) (Equation (1)) [78]. EVI was selected since it complements the information derived from NDVI, being more sensitive to differences in heavily vegetated areas and less affected by atmospheric noise [79,86]. It is calculated similarly to NDVI, but also considering the reflectance in the Blue channel (B) (Equation (2)) [79].

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{R}}{\mathrm{NIR} + \mathrm{R}}, \tag{1}$$

$$\mathrm{EVI} = 2.5\frac{\mathrm{NIR} - \mathrm{R}}{\mathrm{NIR} + (6\,\mathrm{R} - 7.5\,\mathrm{B}) + 1}, \tag{2}$$

However, vegetation indices have a limited capability for retrieving vegetation water content due to uniquely providing information on vegetation greenness (chlorophyll), which is not directly nor uniformly related to the quantity of water in vegetation [80,87]. Thus, NDWI was also calculated.

This index is defined using NIR and SWIR reflectance (Equation (3)) and, as NDVI and EVI, shows values in the range of −1 to +1, with higher values corresponding to higher leaf water content and vegetation cover [80]. The main reason for choosing this index was the easier observable monitoring of vegetative and forestry stages when observing their reflectance in the SWIR bands, as well as to identify water stress [52,87].

$$\mathrm{NDWI} = \frac{\mathrm{NIR} - \mathrm{SWIR}_1}{\mathrm{NIR} + \mathrm{SWIR}_1}, \tag{3}$$

Finally, a statistical analysis was performed to evaluate the yearly maximum value (and hence the healthiest and most vigorous vegetation stage) per index, pixel and GI type. This is since each vegetation surface displays its specific multitemporal variation of biophysical characteristics. Thus, each surface is defined according to a specific variation pattern during its annual development cycle [50,51].

- Rating of the ES condition indicators

The value of the indicators selected to assess GI condition (3rd output) was weighed using the following expressions as assumptions based on the existing theoretical approaches (Table 5) to allow their interpretation through a remote-sensing based approach:

Capacity to provide ecosystem services	$D_i = D/10;\ [0, 10],$	(4)
Membership in Natura 2000 network	$N_i = N/10; [0, 10],$	(5)
	$V_i = NDVI(BOA)_{maxi} \cdot 10; [0, 10],$	(6)
Greenness response and water stress	$E_i = EVI(BOA)_{maxi} \cdot 10; [0, 10],$	(7)
	$W_i = NDWI(BOA)_{maxi} \cdot 10; [0, 10],$	(8)

Representing *i*, the data extracted per pixel (10 × 10 m); *D*, the disposition to deliver the associated regulative ES, resampled to 10 m SR and expressed in percentages; *N*, the distance range from a GI to the Natura 2000 network; $NDVI(BOA)_{maxi}$, $EVI(BOA)_{maxi}$ and $NDWI(BOA)_{maxi}$, the maximum value per pixel for the analysed period (March–September 2018) of the bio-geophysical indices. All the indicators were analysed as integers and expressed in values from 0 to 10. Moreover, if in a pixel no data existed for a parameter, a null value was assigned to that indicator.

The conservation condition, *C*, (Equation (9)) was obtained per-pixel and per type of NWRM ($\forall j$). Then, it was dissolved to obtain one single modelled area indicating GI condition in the case study. The condition index was obtained summing the selected indicators, equally scaled, to allow the easy integration of new condition indicators in future assessments. All the evaluated parameters were considered equally significant since the consulted literature did not mention any distinction of priorities in that regard.

$$\text{Conservation condition, } C_i = D_i + N_i + V_i + E_i + W_i;\ \forall j,\ [0,\ 50], \quad (9)$$

Finally, the integer values obtained with Equation (9), from 0 to 50, with higher values representing a better condition, were translated into a ramp colour legend. This eases the interpretation of the spatial model, quickly locating GI playing a major role in the delivery of ES but that, given their compromised condition, would require management interventions.

The developed model assesses GI actual status based on the maximum value of the vegetation and water indices achieved per type of GI in its intra-annual development trend, among other condition indicators. Neither intra-seasonal nor inter-annual changes are assessed.

3. Results

Appropriately assessing ecosystems' condition must concern individual ecosystems, but also their territorial context [12,27,39]. Thus, the assumptions made and indicators used in the approach, based on the frameworks developed to map and assess ecosystems' conditions and their services (Table 5), include: (i) disposition of the identified NWRM to provide regulative ES in the riparian system, (ii) proximity to protected areas included in Natura 2000 and (iii) remotely-sensed greenness and water stress response as means of the ecosystem's functional attributes.

Figure 4 shows the inputs used (1st and 2nd columns) and outputs delivered (3rd column) for the same area extent. The area is part of the Po delta. It mainly consists of lines of trees and scrub, natural and semi-natural broadleaved forests and alpine and sub-alpine natural grassland (Figure 4a). According to the NWRM catalogue [42], these LC/LU classes were translated into "green cover", "forest riparian buffers" and "buffer strips and hedges" (Table 6) (Figure 4g). Those NWRM located closer to the river streams present a higher disposition to deliver regulative ES (Figure 4h), based on the DRZP dataset (Figure 4b), and a higher proximity to protected areas in Natura 2000 (Figure 4c). These two condition indicators and the analysis of biophysical variables (2nd column of Figure 4) allowed to detect GI in moderate condition (Figure 4i).

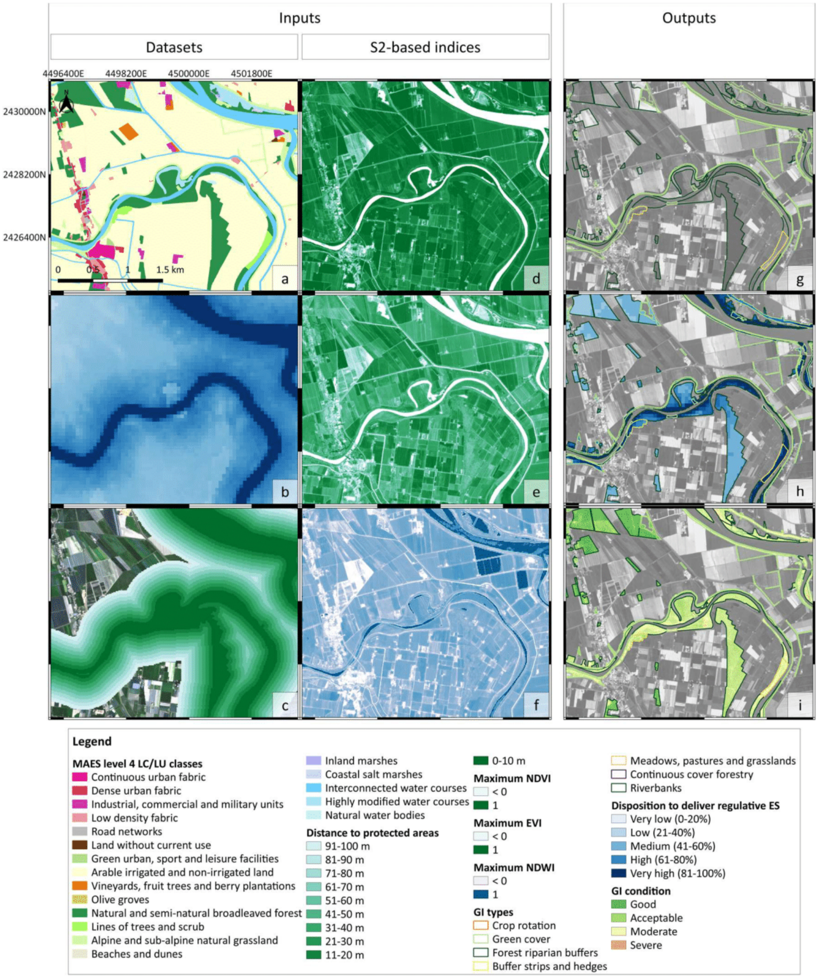

Figure 4. Riparian NWRM in an area of Po delta: (**a**) MAES level 4 LC/LU classes (from RZ LC/LU). (**b**) Disposition to deliver riparian ES (from DRZP). (**c**) Distance to protected areas in Natura 2000. (**d**) Maximum NDVI in 2018. (**e**) Maximum EVI in 2018. (**f**) Maximum NDWI in 2018. (**g**) 1st output: Identification of agriculture and forest NWRM in riparian areas. (**h**) 2nd output: Spatial model of GI disposition to deliver regulative ES. (**i**) 3rd output: Pixel-based assessment of GI condition.

3.1. Spatial Model of GI Disposition to Deliver Regulative ES

A spatial model weighing the capacity of the identified GI to deliver NWRM-related ES, such as protection against flood events, was obtained for the entire river basin. This disposition is measured in percentages from 0% to 100% and translated into a colour ramp from light to dark blue, following the labels of very low, low, medium, high and very high capacity to ease its interpretation (Figure 5).

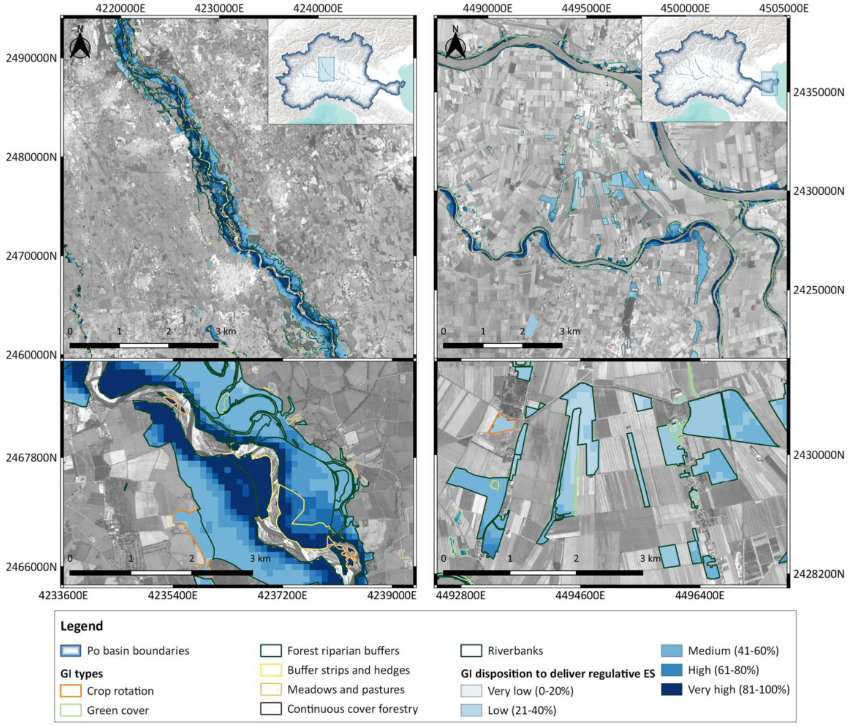

Figure 5. Spatial model representing the disposition of the identified agriculture and forest NWRM for providing the associated regulative ES in the river network of Po basin: Po hills in the central part of the basin (**left**) and Po delta (**right**).

The highest capacity to deliver the related regulative ES was found in NWRM located closer to the river flows (dark blue). Moreover, the riparian buffers located closer to the river courses were wider in the central part of the basin than in the delta area (Figure 5).

3.2. Pixel-Based Assessment of GI Condition

A model representing riparian GI condition in 2018 was obtained in Po delta (Figure 6). GI condition is illustrated according to a colour ramp from green to red, following the labels of good, acceptable, moderate, severe or critical, depending on the indicators' values (Table 5), assessed through Equations (4)–(9).

The assessment model delivered might serve as an early warning tool for that GI holding a major ecological role (highly weighed capacity to deliver regulative ES and proximity to Natura 2000 sites), but not suitably conserved (showing low vegetation healthiness and exposure to water pressures according to the bio-geophysical indices' values).

Figure 6 shows the identified riparian GI condition in two different areas of Po delta: (i) GI buffers closer to the river flow (left), mainly identified as "forest riparian buffers" and "green cover" (Table 6), and (ii) fields located between river flows (right), identified as "forest riparian buffers" and "crop rotation" (Table 6), whose disposition to deliver regulative ES is shown in Figure 5 (right).

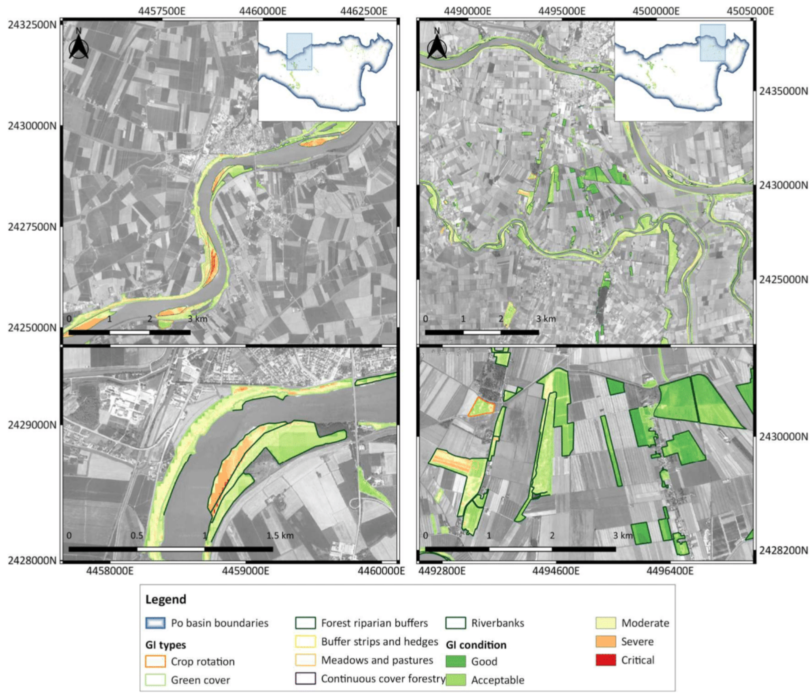

Figure 6. Assessment of the condition of the identified GI sites in the riparian areas of Po delta in 2018: GI buffers next to a river flow (**left**) and complex agricultural patterns (**right**).

The developed model allows to find GI in severe and critical conditions (orange to red colours) in both locations. In the first case, it corresponds to areas that suffer from water stress events (floods and droughts) due to influence of the river flow and, in the second, to stressed vegetation. These results are estimated from very low values of the bio-geophysical indices (which characterise bare soil and water masses) combined with a high capacity of the NWRM to deliver regulative ES and the proximity to, or inclusion in, protected habitats.

3.3. Results Per GI Class

3.3.1. Disposition to Deliver Regulative ES

The capacity to provide regulative ES (Figure 5) was evaluated in an area of 3077 km^2 of the detected NWRM in Po basin, of which over 40% presented high or very high ranges (Figure 7).

"Forest riparian buffers" represented the greater GI area showing a very high disposition to deliver regulative ES, followed by "meadows and pastures" (Figure 8). This outcome could be expected since these classes represent the major riparian GI surface in the basin. However, it seems remarkable that nearly all the surface occupied by natural "riverbanks" presented a very high disposition to deliver regulative ES. This fact might be related to their proximity to the river streams and hence their important role in flood scenarios.

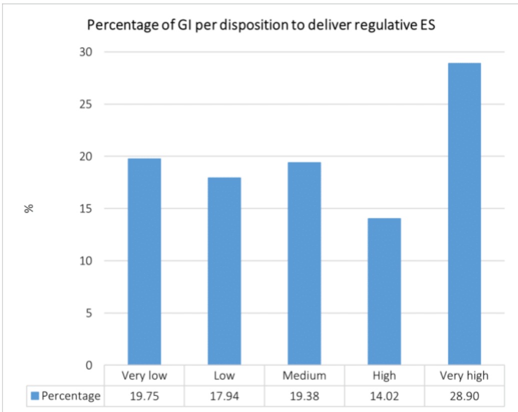

Figure 7. Percentage of GI per disposition to deliver regulative ES.

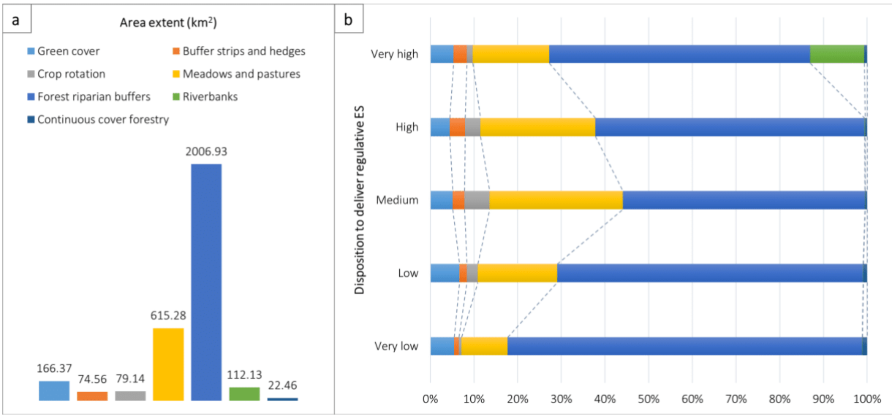

Figure 8. Assessment of GI disposition to deliver regulative ES in Po basin: (**a**) Area extent of each GI type that could be assessed using the DRZP Copernicus product. (**b**) Distribution of GI capacity to provide regulative ES depending on the type.

3.3.2. Condition Assessment in 2018 in Po Delta

The current condition was assessed (Figure 6) in an area of 102.5 km^2, which represents the agriculture and forest riparian NWRM in the Po delta. Over 80% was evaluated as presenting either an acceptable or moderate condition in 2018 following the presented approach, 5% showed a good condition and about 12% presented a severe or critical status (Figure 9).

"Crop rotation" stood out as the riparian NWRM most affected by a critical condition, followed by "forest riparian buffers" and natural "riverbanks" (Figure 10). This might be due to high exposure to vegetation stress and water pressures, but it must be considered that natural "riverbanks" also represented a very high capacity to deliver regulative ES (Figure 8). Therefore, this GI should be managed accordingly. Also, "green cover" was the main GI facing a severe condition (Figure 10).

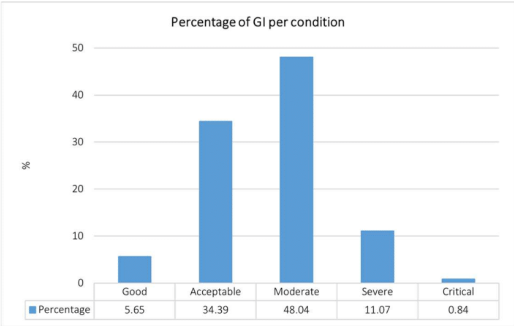

Figure 9. Percentage of GI per condition in 2018 in Po delta.

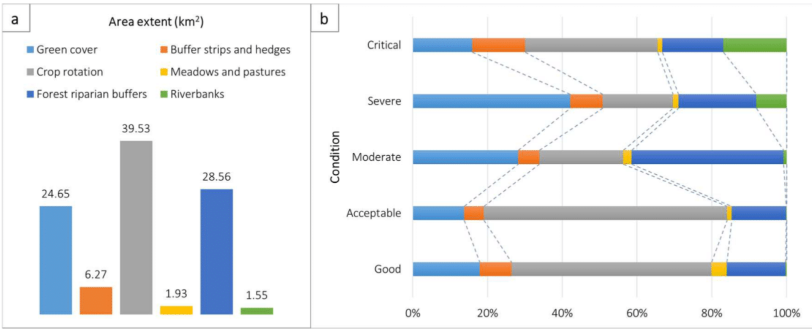

Figure 10. Assessment of GI condition in Po delta: (**a**) Area extent of each GI type. (**b**) Distribution of GI condition in 2018 depending on the type.

On the other hand, a high percentage of agricultural fields holding crop rotation, intercropping or other complex crop patterns (gathered as a sole GI class named "crop rotation") (Table 6) showed a good or acceptable condition (Figure 10). As for the GI class "continuous cover forestry", it was the only one not found in Po delta, which could be assumed since it did not represent a significant area in the basin.

4. Discussion

Decision-makers have mentioned the need for a practical tool that shows values or thresholds characterizing ES supply and condition, facilitating the accomplishment of policy objectives [88,89]. The presented approach can serve as a baseline, helping in understanding the indicator frameworks [55]. It specifically focuses on easing the tasks of Member States (MS) on the Mapping and Assessment of Ecosystems and their Services (MAES) (Action 5 of the 2020 Biodiversity Strategy [27]).

With the aim to overcome previous tools' weaknesses on scalability, data availability and possibility to monitor over time [55,58,89,90], the theoretical indicator frameworks [39,57–65] are linked to the freely-available sources of remotely-sensed data that are suitable to monitor them (Table 5): (i) products offered in the Copernicus Land Monitoring Service (CLMS) [49] and (ii) satellite-based bio-geophysical indices to monitor vegetated surfaces [52,78–80].

The approach focuses on riparian zones since the potential to positively contribute to the socio-economic and environmental resilience of their area of influence has been proven [19,20,28,30,42] based on the following effects: improved water quality, positive trend of new natural riparian functionalities, enhanced environmental and morphological quality and increased awareness of stakeholders and citizens.

Specifically, the Riparian Zones dataset was used as the main input of the approach. Very few scientific experiences exist that refer to it [48,91]. In fact, the main product used, DRZP, is not validated by September 2019 due to lack of appropriate validation data comparable to it [48]. Thus, the developed approach contributes to increase the applicability of this dataset, not generally to riparian areas, but specifically to map and assess NWRM, which are important elements for the water sector, especially for regulating extreme events, such as floods or droughts. The method identifies NWRM in riparian regions, evaluates its capacity to deliver regulative ES and assesses its current preservation condition. The approach considered innovative elements to assess GI and allowed to find weaknesses that should be solved in existing datasets.

GI condition was assessed according to the following criteria (selected from the aforementioned indicator frameworks): (i) capacity to provide ES, (ii) membership or proximity to the Natura 2000 network and (iii) indicators of the ecosystem's functional attributes: greening response and water stress (Table 5). Obtaining the condition index by summing the indicators' values, equally scaled, allows its scalability in terms of integrating indicators from future frameworks. Considering the distance of GI to protected areas included in Natura 2000 is a significant and novel element of the approach. These areas play a distinct role in the natural ecosystem's functioning [27]. Therefore, the appropriate conservation of GI connected to these areas must be prioritised accordingly [39].

Firstly, the NWRM catalogue developed by DG-ENV [42] was used to identify GI as to ensure consistency with already existing and validated definitions. However, it shows weaknesses in the NWRM class definition (e.g., not including wetland riparian vegetation in the hydro-morphological sector). Also, it is challenging to translate some classes into specific LC/LU (e.g., green cover). Therefore, the process for identifying GI should remain more autonomous to increase the usability of the approach.

The analysis focused on vegetation riparian GI. Hydro-morphological types of GI (e.g., wetlands, saltmarshes or reeds) are also important for flood and drought regulation [42], but the interpretation of biophysical variables differ for "green" and "blue" GI, i.e., the reflectance values, annual developing trends and hence the meaning of the indices [50,51,78–80]. Therefore, appropriate indices to monitor this GI must be thoroughly selected and understood before this GI's assessment could be integrated in the approach. Annual trends also vary between different vegetation GI. Thus, the indices' values were rated per type of GI.

The approach used S2 data to calculate the biophysical variables with a high spatial resolution (10 m) [46] and thereby overcome the weakness of the CLMS [49]. Just Copernicus' global component provides bio-geophysical indices products, by September 2019. These products present 300 m/1 km spatial resolutions, not fulfilling the needs at local scales [52,54].

However, clouds and shadows remain a major inconvenience when processing and interpreting bio-geophysical indices, even after correcting the images from the atmospheric effect [51,92]. Therefore, the indices can sometimes show low or even negative values that do not correspond to the vegetation features.

This was solved by analysing the maximum values of the indices in the period of March–September 2018. Thus, the analysis considers the most vigorous, healthiest and highest leaf water content response of each GI development cycle in the analysed year [50,51]. However, the possibility of having evaluated values that represent a cloud or shadow instead of the natural surface condition must be considered.

Analysing the outcomes, the representativeness of each NWRM, as well as the capacity to provide regulative ES, can be quickly interpreted in the modelled area. In Po river basin, "forest riparian buffers", followed by "meadows and pastures", popped up as the greater GI areas (Table 6). Moreover, most of this surface presented a high or very high capacity to deliver regulative ES (Figure 8). Instead, "continuous cover forestry" was the less presented GI (Table 6).

Also, the delivered model shows GI condition. 12% of the riparian GI area in Po delta presented a high conservation priority (severe or critical condition) in the analysed year (Figure 9). Most of this GI was also closer to river streams (Figure 6). Thus, the condition index may result due to stressed or saturated vegetation conditions (i.e., very low values of the bio-geophysical indices) merged with a high capacity to supply regulative ES (Figure 5) and proximity to protected areas.

"Riverbanks" represent a frequently used nature-based measure for flood protection. This NWRM face severe and critical conditions in Po delta (Figure 10), while having a very high capacity for delivering regulative ES (Figure 8). However, it must be considered that riverbanks sometimes represent fully functional sparsely vegetated areas [42].

Alongside the regulation of water stress events, such as floods or droughts, riparian areas can provide other significant benefits to the environment and society [19,20,28,42]. Therefore, having open access to a tool that quickly highlights GI facing severe or critical conditions, hence not appropriately conserved, should raise awareness, help and motivate decision-makers to take action, supporting restoration and management strategies that improve the environmental quality of that area (e.g., revegetation measures) [23,31,43].

To this end, the interpretation of the model shall be supported by degradation assessments and analyses of the impact of GI presence or absence [93]. Also, inter-annual analyses would allow to interpret the GI condition index depending on previous trends (i.e., considering each GI likelihood to achieve different indices' maximum values). However, the required datasets do not perfectly fit inter-annual analyses, with the consequent impact on the results of using LC/LU datasets from other periods. In this regard, the upcoming Copernicus product CLC+ will ease a more analytic mapping of the Earth's surface and a more flexible combination with other datasets [94].

Finally, the decision of motivating either conservation initiatives on GI in a good condition or recovering strategies on damaged GI will depend on regional policy objectives and cost-effectiveness of the measures [93]. This decision could be further substantiated by applying an ES valuation exercise, supplementing the information derived from the condition indicators. However, this approach remains challenging due to the complexity of standardising ES values, which are strongly dependent on context specific circumstances that would require detailed local datasets [95].

5. Conclusions

There is a growing demand for GI and ES assessments due to their significant role in natural hazards mitigation and climate change adaptation. However, information on the condition of, and changes in, Europe's ecosystems dominated by vegetation is still limited. The presented approach represents a new method to overcome the current lack of data on riparian characteristics. The integration of highly detailed products from the CLMS (Riparian Zones) with other datasets (protected areas in Natura 2000) and high-resolution satellite data (S2) demonstrates, through the followed approach, their potential to: (i) identify GI in the riparian areas of a river network, specifically agriculture and forestry measures that serve for natural water retention; (ii) assess its disposition to deliver the related regulative ES; (iii) analyse its condition according to the existing indicator frameworks, such as the 2018 MAES report and (iv) rank its conservation priority. Policy-related factors, such as the latest initiatives of each region to either conserve GI in good condition or recover degraded GI, should be taken into account in the latter case.

GI sites are currently subjected to many pressures caused by both natural and anthropogenic actions, which decrease its capacity for delivering ES. Thus, Copernicus evolution depends on meeting the needs for ecosystems' monitoring and management coming from environmental and socio-economic policies and strategies at global, European and local scales. In this regard, the presented research highlights once more [52] the products' spatial resolution as a significant handicap, by September 2019. On one hand, having full access to bio-geophysical indices based on already processed data from S2 would ease the tasks of downloading and processing this data, as well as dealing with missing values. On the other hand, it would highly increase the spatial resolution of the products to 10 m, fulfilling users' needs for studies at local scales [54]. Then, these indices could be used to develop new products or improve the existing ones in the frame of mapping and assessing green areas. The upcoming CLMS High Resolution Vegetation Phenology and Productivity will help in this sense [96].

In conclusion, the approach allows to:

- Provide a scalable tool based on open-source data, mainly from the CLMS, to support environmental and sustainability policies and strategies in the field of mapping GI and monitoring its condition and pressures in riparian areas.
- Provide a design to account for the constitutive elements of nature-based solutions, such as GI, including its multifunctionality and a simultaneous delivery of environmental and social benefits, based on a multi-stakeholder engagement.

Finally, it can be concluded that it is possible to conjugate environmental protection and territorial development though the coordination of monitoring activities. Prioritising GI's need of restoration depending on its role in the river system, proximity to protected areas and current condition can help raising awareness and implementing actual needs in regional coordination actions. This determines the need of communication with the public and decision-makers to highlight the potential of Copernicus as an upstream service to collect, share, organize and elaborate data on natural resources management, both in real time and historical studies. In the future, a closer collaboration with policy and decision-makers could help in Copernicus uptake at local scale, creating services that suit their needs and requirements and making it a more real-world tool that facilitates the use of remotely-sensed information in policy.

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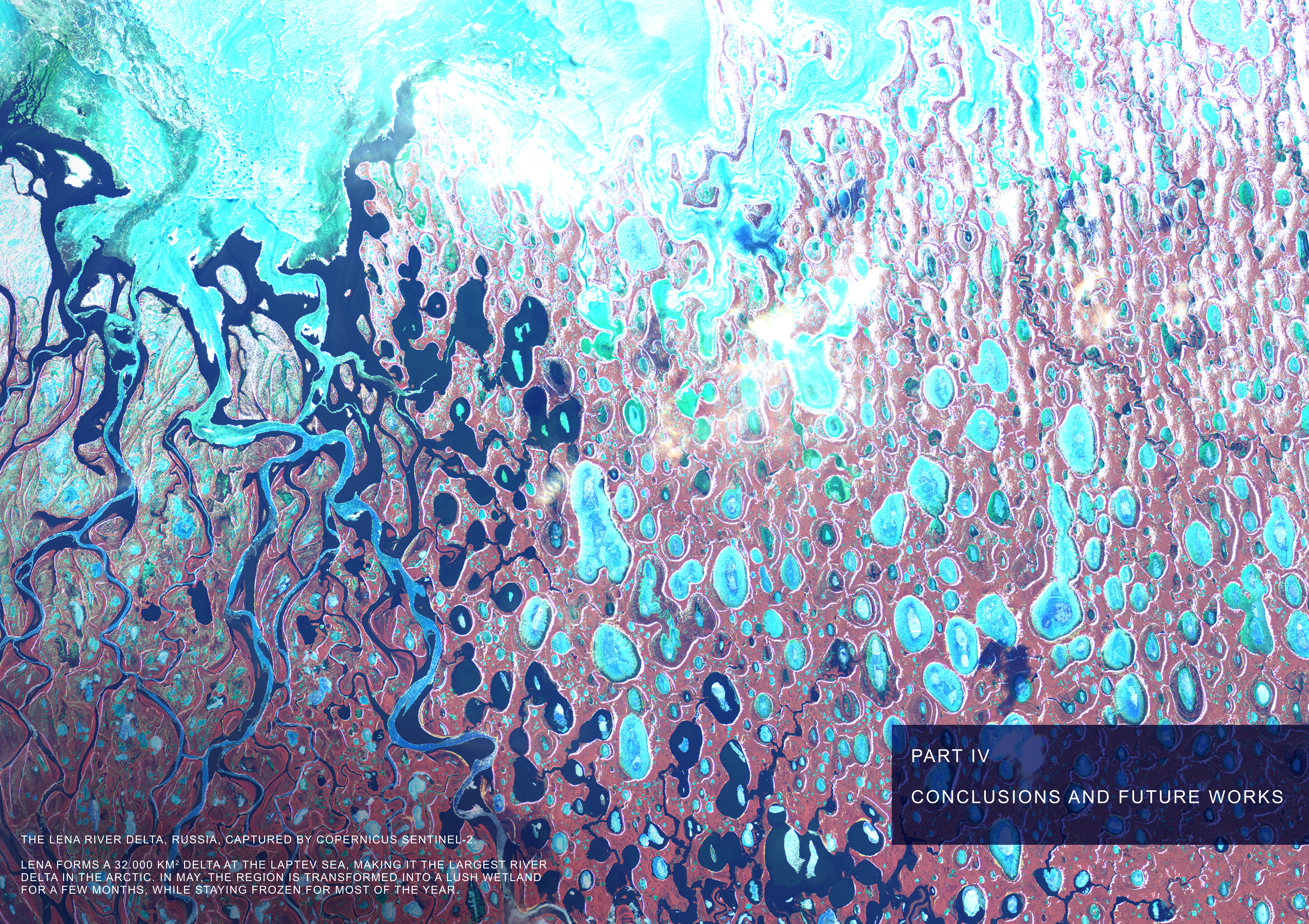

THE LENA RIVER DELTA, RUSSIA, CAPTURED BY COPERNICUS SENTINEL-2.

LENA FORMS A 32.000 KM² DELTA AT THE LAPTEV SEA, MAKING IT THE LARGEST RIVER DELTA IN THE ARCTIC. IN MAY, THE REGION IS TRANSFORMED INTO A LUSH WETLAND FOR A FEW MONTHS, WHILE STAYING FROZEN FOR MOST OF THE YEAR.

PART IV

CONCLUSIONS AND FUTURE WORKS

Part IV – Conclusions and future works

This chapter holds a summary of the contributions of this Doctoral Thesis. It includes the most relevant results and direction of future works.

1. Conclusions

The development of this research work has led to achieve a high level of understanding of the basis for remote sensing of the environment, especially through the analysis of biophysical parameters calculated with multispectral satellite data. This knowledge and its application are evidenced along the results of the presented scientific articles. The following subsections discuss the general and specific conclusions.

1.1. General conclusions

Ensuring ecosystems' conservation is a major goal in global sustainable development. Developing methods and workflows based on new data sources, such as space-borne platforms, improve and complement traditional techniques to control and monitor large agricultural and forest ecosystems in near-real-time and long-term studies.

Specifically, agriculture (including natural grassland) accounts for almost half of the EU area and forests cover around 38%. Indeed, agriculture represents the major EU land use and water demand (around 80%) and is a major component of the EU economy. The diversity of challenges faced by agricultural activities, the sustainable use of natural resources and ecosystems' conservation are addressed by a set of EU policies. These policies consider a wide range of concerns, such as food security, CCA and DRR.

This policy context, introduced in Part I of the Doctoral Thesis, is set at a time defined by digital transformation. Easy access to new and open-source technologies and services, such as the EU EO Copernicus programme, offers huge possibilities for valuable applications in the environmental domain. However, most developments are not yet fully exploited by stakeholders, e.g., policy or decision makers, or by the end-users, e.g., the farmers. New tools and policies in this domain frequently lack applicability and scalability, remaining academic or only usable for very specific purposes, thereby not scalable to other users, needs or territories.

In this regard, the EC encourages R&I actions to use, uptake, and feedback on, Copernicus, thereby increasing the applicability of already existing, or developing new, products and services. Moreover, the R&I actions should follow a demand-driven approach and ensure the scalability of the developed methods. Both recommendations have been pursued along this research work.

This Doctoral Thesis deals specifically with the interpretation of satellite-based biophysical parameters to monitor the environment, its status and benefits to society. The diagrams, methods and tools developed prove the potential of remote sensing to contribute to policy targets and decision-making. The methodological procedures and results have been published in impact journals as scientific articles.

Specifically, the developments presented in this Doctoral Thesis have successfully helped in detecting unregulated agricultural water use, planning efficiently on-the-spot checks, classifying crop types and detecting, monitoring and assessing the status of GI and ES. These objectives were set according to EU policies (CAP, WFD and 2020 BS) and specific stakeholders' requests at local scale. Moreover, all the developed processing algorithms and data analysis methodologies are based on open-source data and technologies to the Scientific Community. This ensures the full applicability of the developed approaches over time, to other users' needs and to other territories.

1.2. Biophysical parameters at global scale: Copernicus programme

"Paper I: Monitoring Green Infrastructure for Natural Water Retention Using Copernicus Global Land Products" answers to the first research question: *"Which biophysical parameters are available as full, open and free?"*. It conveys a better comprehension of the available bio-geophysical indices in Copernicus programme:

- CGLS is the only EO service that offers freely a wide range of already processed and qualified products of bio-geophysical indices. Directly using these products avoids time-consuming tasks of satellite images' selection, atmospheric correction and indices calculation.
- Sankey diagrams are used to represent the large amount of data resulting from a scientific review and thereby to interpret it. The diagrams show that the vegetation and energy indices offered in CGLS are able to detect agriculture, forest and hydro-morphology types of GI for water retention (NWRM). Moreover, the indices have been used in scientific studies to monitor NWRM's benefits, namely biophysical impacts, ES provided, and policy targets achieved through NWRM's implementation.
- Designing easy-to-read flow diagrams help informing users about the most substantial outputs from a research. Through the designed step-by-step diagrams, users can quickly identify, depending on the specific NWRM type or benefit to monitor, the most suitable index, temporal coverage and spatial resolution of that product in CGLS, and the consecutive most suitable index.
- NDVI, LAI and TOC reflectance pop up as the most suitable indices but also represent the earliest-developed spectral indices. More recent indices, such as FAPAR or FCOVER, also show high potential. Therefore, the complementary use of old and new indices would enlarge the range of information to monitor biophysical features of the environment.

- CGLS products provide very long-term data series (from 1999 onwards), but several lack good accuracy or quality assessments. Overall, the products present good spatial and temporal consistencies, except for winter periods or Northern latitudes. However, this would be easily solvable by filling data gaps with data from different sensors and homogeneous areas. The main handicap is the spatial resolution, a usual weakness of open satellite data. Bio-geophysical indices provided with coarse spatial resolutions of 300 m and 1 km do not fulfil the level of detail required by many environmental studies at local scale.
- Copernicus programme has not been conceived as a catalogue of final products. Instead, it provides a baseline to researchers and institutions to develop new, or adapt already existing, products according to evolving societal demands. Therefore, it represents a benchmark to bridge remote sensing and stakeholders' needs into products that help in policy and decision-making.

These conclusions led to formulate the second research question: *"How can biophysical parameters interpretation and local stakeholder needs be bridged?"*.

1.3. Biophysical parameters at local scale

At local scale, the bio-geophysical indices used (NDVI, EVI and NDWI) are calculated through open-source high-resolution multispectral satellite data in the visible, NIR and SWIR regions of the electromagnetic spectrum. The main disadvantages are the satellite imagery selection and pre-processing tasks, such as atmospheric correction or integration of multi-source data. The main advantage is the improvement of the spatial resolution and hence of the level of detail of the analysed data.

The following conclusions are drawn from the use of different sensors, individually and jointly, and the analysis of different biophysical parameters, inside automatic or semi-automatic procedures, for helping different groups of stakeholders in their tasks to accomplish EU environmental policies (CAP, WFD and 2020 BS). The methodologies and tools developed, as well as the results obtained, have been presented in papers II, III and IV. These developments answer to the second research question: *"How can biophysical parameters interpretation and local stakeholder needs be bridged?"*. The conclusions derived are divided in two subsections according to the two specific objectives pursued: (i) enhancing the monitoring of agricultural water use and crop types (papers II and III), and (ii) mapping and assessment of ecosystems and their services (paper IV).

1.3.1. Enhancing the monitoring of agricultural water use and crop types

Pursuing this objective led to develop complementary web-GIS and desktop-GIS tools (paper II) and a model that allow monitoring crop types in large areas (paper III). The specific conclusions derived are discussed hereunder.

- Complementary web-GIS and desktop-GIS tools
  - Inside a river basin Hydrographic Confederation, personnel have different tasks regarding the management, control and surveillance of irrigated areas and illegal irrigation. Indeed, in Duero Hydrographic Confederation, the HPO has to control water resources whereas the RSA performs on-the-spot checks randomly to monitor irrigated areas, crop types, crop phenological stages and irrigation systems used. Therefore, two different, but complementary, modules, a web-GIS and a desktop-GIS, based on the NDVI response, are created.
  - The desktop-GIS module allows the HPO to detect automatically and in near-real-time unregulated irrigation in areas of special interest. Instead, the web-GIS allows the RSA to monitor irrigated crops' NDVI patterns, estimate crop types and check its correlation with the farmers' declarations to the CAP (EC, 2010c).
  - In the summer period of 2017, the desktop-GIS tool detected 4097 irrigated crops, 7120 ha, without irrigation rights. Most of them were located in areas suffering of water scarcity, where irrigation is forbidden (Directive 2000/60/EC). In 2019, the number of irrigated crops without irrigation rights has decreased to 780 (81%), which proves the high impact of the developed tool on farmers' responsibilities.
  - 320 field inspections were performed in 2017 to validate the results. The visits are geographically distributed to the most severe infringements according to the irrigated surface, distance to the nearest regulated well and concession lower than 7000 m^3/ha/year with surface larger than 9 ha (Directive 2000/60/EC). This way, on-the-spot checks are not performed randomly but efficiently.
  - The tools allow a better communication between the HPO and the RSA in an open-source GIS environment, detecting unregulated irrigation in near-real-time and optimizing field inspections. The tasks are performed more efficiently, organized, complementarily and in a semi-automatic way.

- Monitoring crop types in large areas: integration of multi-source satellite data and definition of agro-climatic spatial regions
  - Monitoring crop types in large areas needs to consider the different agro-climatic conditions, phenological patterns and landscapes. Crop classification accuracy has been increased through a model that performs in separated spatial regions.
  - The combination of multi-source satellite data, S2 and L8, increases the spatial and temporal resolution for crop type mapping and monitoring in large areas. Spatial regions are defined in accordance to sensors' characteristics to allow the perfect coherence between multi-source data.
  - Considering agronomic and edaphic criteria to filter the NDVI input data increase the efficiency of a classification process. Computation timing decreases due to avoiding redundant data. In Duero river basin, which represents almost 80,000 km^2, just 16 hours were needed to compute the most accurate crop classifier, the Ensemble Bagged Trees (EBT).

  - Crop type mapping proves to be both efficient and accurate in large areas using EBT classifier. In Duero river basin, 2017 crop classification is obtained with an OA of 87% and 92% for individual and grouped crop classes, respectively.
  - Zoning the area in spatial regions also allows for analysing the spatial distribution of crop classification's OA along the basin.

1.3.2. Mapping and assessment of ecosystems and their services

Pursuing this objective led to develop an approach that uptakes a product from CLLS and measures ecosystems' condition indicators by using remotely-sensed bio-geophysical indices (paper IV). The specific conclusions derived are discussed hereunder.

- Copernicus uptake: combination of datasets to attend societal needs
  - Copernicus evolution depends on meeting the needs for ecosystems' monitoring and management coming from environmental and socio-economic policies and strategies at global, European and local scales.
  - The combination of Copernicus products with local databases and other satellite-based data increase the applicability of the existing services. The developed approach combines detailed products from CLLS with high-resolution satellite data from S2 to overcome the lack of data on riparian characteristics.
  - Action 5 of the 2020 BS (EC, 2011a, p. 12) calls the Member States to map and assess the condition and pressures on ecosystems and their services. The models obtained following the approach allow for detecting NWRM in Po river network, their capacity to provide regulative ES and their condition in 2018. Such models prioritise NWRM's need of restoration. This information can help policy and decision makers in establishing environmental management strategies accordingly.

- Ecosystems' condition indicators: combination of bio-geophysical indices
  - The EEA, through the MAES initiative, has developed a set of ES condition indicators (Maes et al., 2018). Remote sensing helps in understanding and measuring these theoretical parameters.
  - A combination of biophysical parameters improves the information retrieved on ecosystems' functional attributes. The complementary use of two vegetation indices (NDVI and EVI) and a water index (NDWI) allows for interpreting ecosystems' greenness and water stress condition.

2. Future works

After the development of this Doctoral Thesis, several research lines and implementations are open to improvements, which are discussed hereunder. Some of them are in line with upcoming or on-going European projects.

2.1. Biophysical parameters at global scale: Copernicus programme

- There is a need of developing bio-geophysical indices' products that satisfy the requirements of environmental studies at local scale, i.e., a higher spatial resolution. Using S2 data could be a potential solution to develop products with 10 m spatial resolution.
- The upcoming High Resolution Vegetation Phenology and Productivity product in CLMS will allow for a much more detailed assessment of vegetation characteristics and changes. This new product shall be object of extensive further analysis of its effectiveness to monitor green areas and NBS.
- CGLS could be developed further by including new products of bio-geophysical indices that are frequently used and qualified globally, such as the EVI. This index is referred to as the second most effective vegetation index, after NDVI, to characterize the global range of vegetation states and processes by the MODIS Land Discipline Group.

2.2. Biophysical parameters at local scale

2.2.1. Enhancing the monitoring of agricultural water use and crop types

- The developed tools will be periodically upgraded, attending new requests from the HPO and feedback on the results' validation from the RSA's field visits. This way, the GIS tools will be continuously calibrated, ensuring the satellite-based outputs' reliability.
- The tools will be regularly updated following the release of new versions of the GIS software, database system and programming language that they are based on.
- An integration of optical and radar satellite data could increase the range of information on water foot print, land use dynamics and phenology patterns. Sentinel-1 data could be used to get characteristics on the below ground of environment, minimizing false positives of irrigated agricultural plots and increasing the accuracy of crop classification. Moreover, analyses on crop water productivity could be performed.

2.2.2. Mapping and assessment of ecosystems and their services

- The developed approach allows for assessing ecosystems' current condition. Inter-annual analyses would support the evaluation of ecosystems' condition and trends. However, S2 recent launch does not allow for long-term studies further back to 2015 and Copernicus LC/LU datasets are updated in six-year-long periods. Therefore, future works will focus on:

  - Integrating high-resolution multispectral data from different sensors for long-term analyses: combination with the Landsat family of satellites.
  - Performing more detailed spectral data analysis, such as Principal Component Analysis (PCA), Linear Spectral Mixture Analysis (LSMA) and Empirical Orthogonal Function (EOF). This kind of data analyses will allow for detailed erosion and degradation assessments on detected vegetation fractions. The benefits and effectiveness of NWRM's implementation could be detected. This information is important for spatial planning initiatives.
  - The next generation Corine Land Cover (CLC) product in Copernicus, named CLC+, will cope LC/LU information for the coming 10 to 15 years. Using this product will facilitate the mapping of LC/LU through a more flexible combination with other datasets.

- From a Copernicus evolution perspective, there is a need of cooperation with public and private users, bridging scientific needs, societal demands and technological capabilities into ad hoc missions and services. In this line, the research presented in this Doctoral Thesis will be developed further as part of the ESA's on-going project *"ESA RFP/3-15502/18/NL/IA: Chime Mission Requirements Consolidation"*. The goal is to assess if the development of a hyperspectral satellite mission provides added value to the current S2 mission in the *"Agriculture/Food Security"* application domain. Multispectral and hyperspectral vegetation indices will be calculated, compared and analysed together with field data.

2.3. Linking remote sensing and socio-environmental science

This Doctoral Thesis proves the usefulness of remotely-sensed data and GIS systems to contribute to environmental policy and decision-making. Despite this usefulness, evidenced by the presented case studies, satellite images have not always been a popular data source for socio-environmental science research for several reasons. Firstly, variables of interest are often not directly measured from raw satellite data. Abstract variables that explain and measure the appearance and transformation of land use, effectiveness of environmental policies and strategies, or environmental biophysical and chemical processes, are not directly reflected in the bands of the electromagnetic spectrum. As remarked in Part I of this Doctoral Thesis, spectral indices have been developed as a combination of two or more of the original spectral bands in order to interpret biophysical parameters of interest. Also, socio-environmental scientists lack knowledge on pixels' characteristics, how clouds may affect data quality, or the processes, methods and statistical models used to interpret satellite data. It is a fact that incorporating remotely-sensed data into socio-environmental science is not straightforward. Satellite images have to be atmospherically corrected and processed, both georeferencing and contextualizing the spectral data (e.g., LC/LU or biophysical parameters), with respect to the original image, to provide value-added information.

As outlined along this research work, there is growing interest in making EO data useful to the widest array of users. At EU level, there is increased availability of funding for R&I actions that focus on supporting the 2030 UN's SDG using, and further developing, the EU EO Copernicus programme. The goal is maximising the benefits provided by Copernicus data, services and downstream services. This confluence of interests sets the stage for representatives involved in EO research and environmental and socio-economic policies to collaborate (e.g. scientists, end-users, public service bodies, industries and policy and decision makers). Sharing needs, perspectives and technological capabilities shall stimulate the application of remote sensing to address evolving societal demands.

Such an approach shall allow not only for the development and implementation of a collaborative and integrated EU EO Strategy, but also the development of interdisciplinary approaches that integrate and support further specific studies. Among the affected knowledge areas, the tools and approaches developed within this Doctoral Thesis could support near-real-time, and evidence-based, hydrological modelling, assessment of water resources, estimation of crop water demand, analyses on water footprint, carbon footprint and aquifer balance, analysis of environmental biophysical and chemical processes, effectiveness of NBS' implementation and environmental management strategies, socio-economical models, and assessment of different climate change scenarios provided by the Intergovernmental Panel on Climate Change (IPCC).

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Appendix A. Indexation and impact factor of the journals

Paper I: Monitoring Green Infrastructure for Natural Water Retention Using Copernicus Global Land Products

Paper IV: Assessment of Green Infrastructure in Riparian Zones Using Copernicus Programme

Journal	**Remote Sensing**
Editorial	MDPI
ISSN	2072-4292
Impact factor (2018)	4.118
Ranking	7/30
Quartile	Q1

2018 Journal Performance Data for: Remote Sensing

ISSN: 2072-4292
eISSN: 2072-4292
MDPI
ST ALBAN-ANLAGE 66, CH-4052 BASEL, SWITZERLAND
SWITZERLAND

TITLES
ISO: Remote Sens.
JCR Abbrev: REMOTE SENS-BASEL

LANGUAGES
English

CATEGORIES
REMOTE SENSING - SCIE

PUBLICATION FREQUENCY
12 issues/year

Open Access from 2009

Key Indicators 2018

IMPACT METRICS		
Total Cites	23,567	✓Trend
Journal Impact Factor	4.118	Trend
5 Year Impact Factor	4.740	Trend
Immediacy Index	0.879	Trend
Impact Factor Without Journal Self Cites	2.991	Trend

INFLUENCE METRICS		
Eigenfactor Score	0.04866	Trend
Article Influence Score	0.926	Trend
Normalized Eigenfactor	5.78925	Trend

SOURCE METRICS		
Citable Items	2,030	Trend
% Articles in Citable Items	98.18	Trend
Average JIF Percentile	78.333	Trend
Cited Half-Life	3.1	Trend
Citing Half-Life	7.1	Trend

Journal Impact Factor Calculation

2018 Journal Impact Factor = $\frac{9,594}{2,330}$ = 4.118

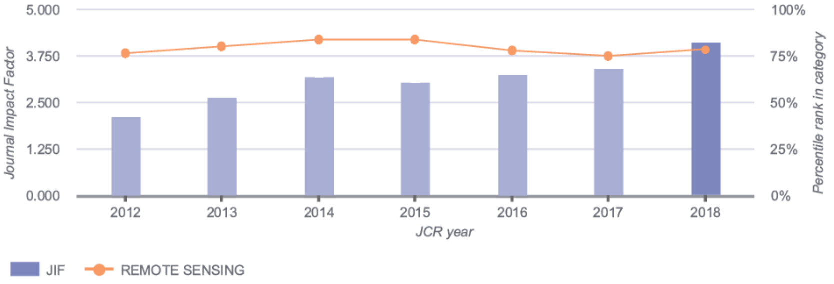
How is Journal Impact Factor Calculated?

$$JIF = \frac{\text{Citations in 2018 to items published in } \mathbf{2016\ (4,917) + 2017\ (4,677)}}{\text{Number of citable items in } \mathbf{2016\ (1,016) + 2017\ (1,314)}} = \frac{9,594}{2,330}$$

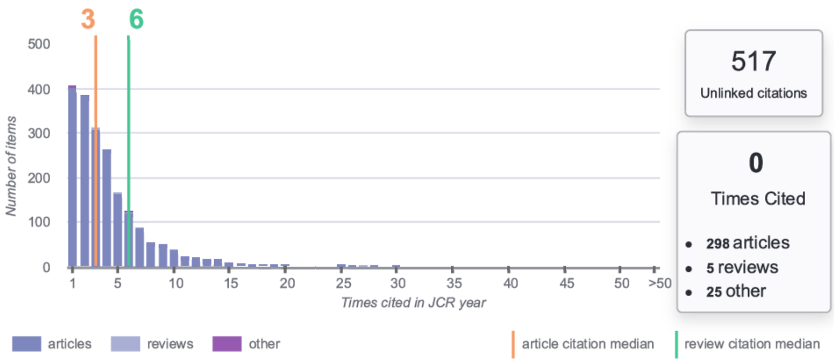
The data in the two graphs below and in the Journal Impact Factor calculation panels represent citation activity in 2018 to items published in the journal in the prior two years. They detail the components of the Journal Impact Factor. Use the "All Years" tab to access key metrics and additional data for the current year and all prior years for this journal.

2018 Journal Impact Factor & percentile rank in category for: Remote Sensing

4.118
2018 Journal Impact Factor



2018 JIF Citation Distribution for: Remote Sensing



Citations in 2018 (9,594)

TITLE	CITATIONS COUNTED TOWARDS JIF
REMOTE SENSING	2623
REMOTE SENSING OF ENVIRONMENT	437
IGARSS 2018 - 2018 IEEE INTERNATIONAL GEOSCIENCE AND REMOTE SENSING SYMPOSIUM	357
SENSORS	343
INTERNATIONAL JOURNAL OF REMOTE SENSING	241
INTERNATIONAL JOURNAL OF APPLIED EARTH OBSERVATION AND GEOINFORMATION	210
ISPRS JOURNAL OF PHOTOGRAMMETRY AND REMOTE SENSING	203
IEEE JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATIONS AND REMOTE SENSING	200
ISPRS INTERNATIONAL JOURNAL OF GEO-INFORMATION	186
IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING	156

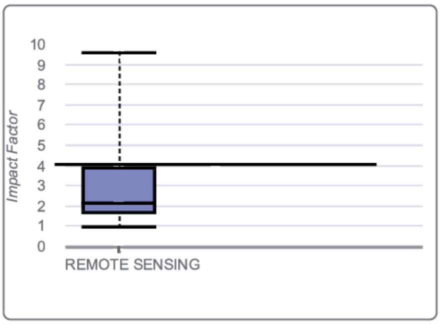
Box plot

Category Box Plot 2018

Category Box Plot

The category box plot depicts the distribution of Impact Factors for all journals in the category. The horizontal line that forms the top of the box is the 75th percentile (Q1). The horizontal line that forms the bottom is the 25th percentile (Q3). The horizontal line that intersects the box is the median Impact Factor for the category.
Horizontal lines above and below the box, called whiskers, represent maximum and minimum values.
The top whisker is the smaller of the following two values:
the maximum Impact Factor (IF)
Q1 IF + 3.5(Q1 IF - Q3 IF)
The bottom whisker is the larger of the following two values:
the minimum Impact Factor (IF)
Q1 IF - 3.5(Q1 IF - Q3 IF)
Box Plots are provided for the current JCR year for each of the categories in which the journal is indexed.

REMOTE SENS-BASEL, IF: 4.118



Rank

Rank

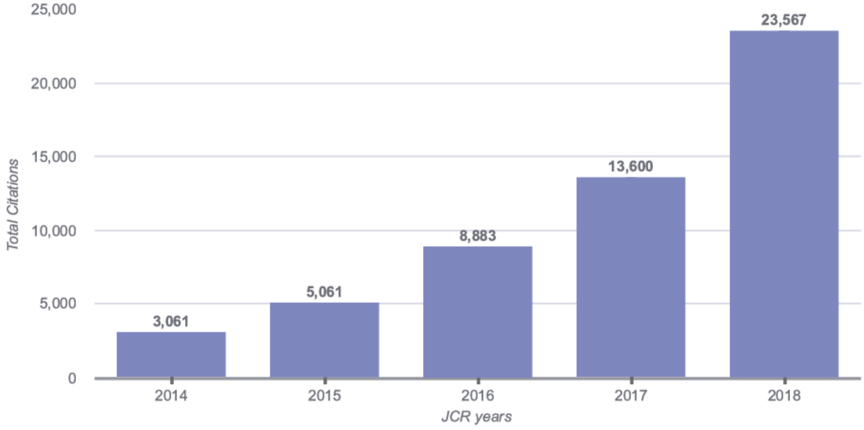
JCR Impact Factor

JCR Year	REMOTE SENSING		
	Rank	Quartile	JIF Percentile
2018	7/30	Q1	78.333
2017	8/30	Q2	75.000
2016	7/29	Q1	77.586
2015	5/28	Q1	83.929
2014	5/28	Q1	83.929
2013	6/27	Q1	79.630
2012	7/27	Q2	75.926

ESI Total Citations

Rank

JCR Year	GEOSCIENCES
2018	21/421-Q1
2017	41/419-Q1
2016	60/417-Q1
2015	89/408-Q1
2014	116/393-Q2
2013	154/388-Q2

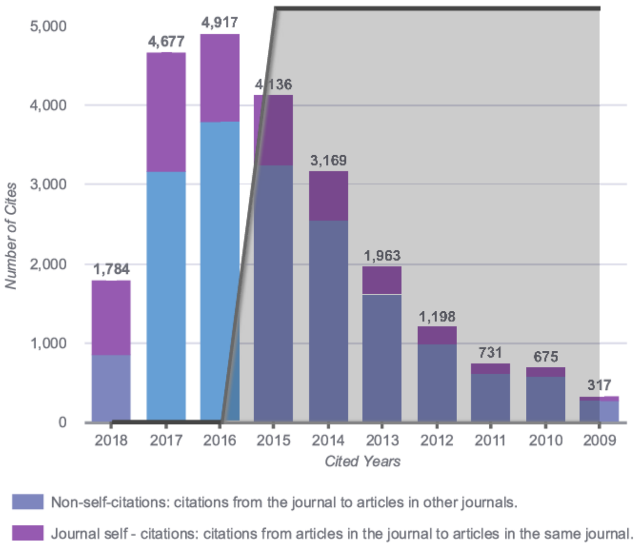


Cited Journal Data

Cited Half-Life Data

Cited Year	2018	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008-All
#Cites from 2018	1,784	4,677	4,917	4,136	3,169	1,963	1,198	731	675	317	0
Cumulative %	7.57%	27.42%	48.28%	65.83%	79.28%	87.61%	92.69%	95.79%	98.65%	100.00%	100.00%

Cited Journal Graph 2018



CITED JOURNAL GRAPH

The Cited Journal Graph shows the distribution (by cited year) of citations published in journals during the JCR year to items published in the Journal during the last 10 years.

The white/grey division indicates the cited half-life (if < 10.0). Half of the citations are to items that were published more recently than the cited half-life.

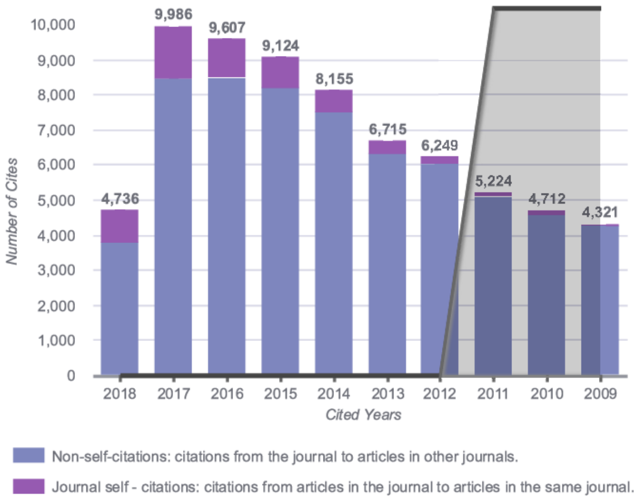
The two light-blue columns indicate citations used to calculate the Impact Factor (always the 2nd and 3rd columns).

Citing Journal Data

Citing Half-Life Data

Citing Year	2018	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008-All
#Cites from 2018	4,736	9,986	9,607	9,124	8,155	6,715	6,249	5,224	4,712	4,321	41,344
Cumulative %	4.30%	13.36%	22.08%	30.36%	37.77%	43.86%	49.53%	54.27%	58.55%	62.47%	100.00%

Citing Journal Graph 2018



CITING JOURNAL GRAPH

The Citing Journal Graph shows the distribution (by cited year) of citations published in the Journal during the JCR year to items published in journals during the last 10 years.

The white/grey division indicates the citing half-life (if < 10.0). Half of the citations are to items that were published more recently than the citing half-life.

Paper II: HidroMap: A New Tool for Irrigation Monitoring and Management Using Free Satellite Imagery

Journal	**ISPRS International Journal of Geo-Information**
Editorial	MDPI
ISSN	2220-9964
Impact factor (2018)	1.840
Ranking	19/30
Quartile	Q3

2018 Journal Performance Data for: ISPRS International Journal of Geo-Information

ISSN: 2220-9964
eISSN: 2220-9964
MDPI
ST ALBAN-ANLAGE 66, CH-4052 BASEL, SWITZERLAND
SWITZERLAND

TITLES
ISO: ISPRS Int. Geo-Inf.
JCR Abbrev: ISPRS INT J GEO-INF

LANGUAGES
English

CATEGORIES
GEOGRAPHY, PHYSICAL - SCIE

REMOTE SENSING - SCIE

PUBLICATION FREQUENCY
12 issues/year

Open Access from 2012

Key Indicators 2018

IMPACT METRICS

Total Cites	2,196	✓Trend
Journal Impact Factor	1.840	Trend
5 Year Impact Factor	2.022	Trend
Immediacy Index	0.532	Trend
Impact Factor Without Journal Self Cites	1.343	Trend

INFLUENCE METRICS

Eigenfactor Score	0.00355	Trend
Article Influence Score	0.295	Trend
Normalized Eigenfactor	0.42244	Trend

SOURCE METRICS

Citable Items	476	Trend
% Articles in Citable Items	98.74	Trend
Average JIF Percentile	38.667	Trend
Cited Half-Life	2.3	Trend
Citing Half-Life	7.0	Trend

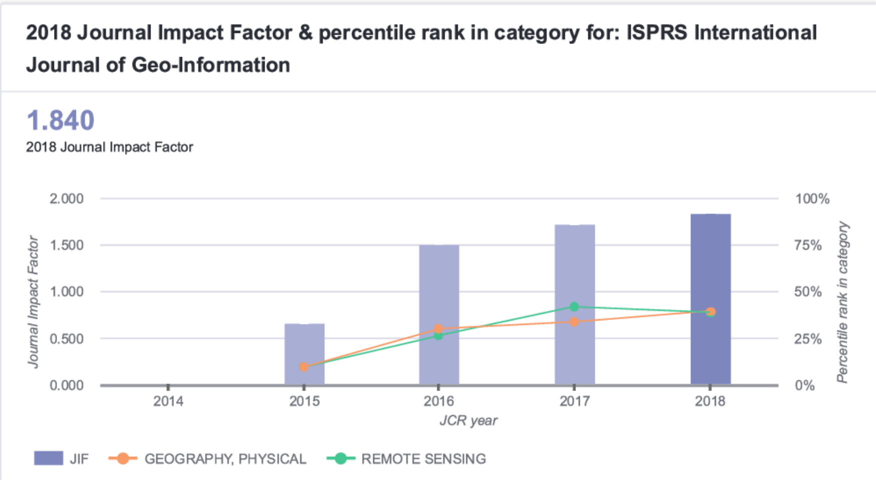
Journal Impact Factor Calculation

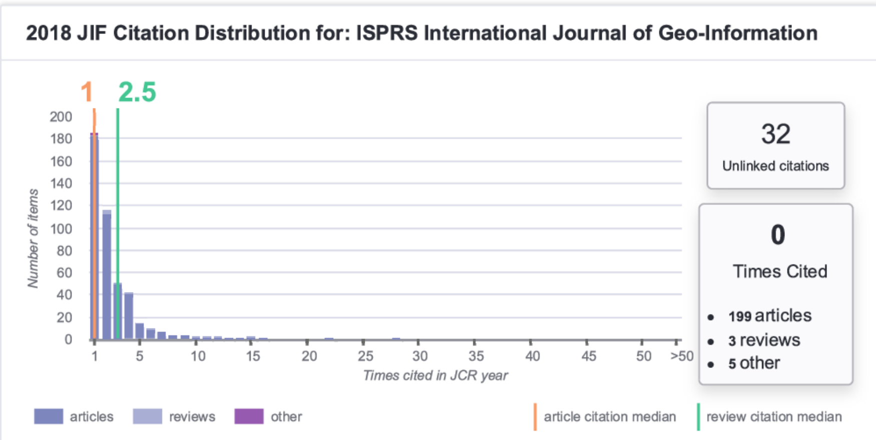
2018 Journal Impact Factor $= \frac{1,185}{644} =$ 1.840

How is Journal Impact Factor Calculated?

$$\text{JIF} = \frac{\text{Citations in 2018 to items published in } \mathbf{2016\ (523) + 2017\ (662)}}{\text{Number of citable items in } \mathbf{2016\ (243) + 2017\ (401)}} = \frac{1,185}{644}$$

The data in the two graphs below and in the Journal Impact Factor calculation panels represent citation activity in 2018 to items published in the journal in the prior two years. They detail the components of the Journal Impact Factor. Use the "All Years" tab to access key metrics and additional data for the current year and all prior years for this journal.





Citations in 2018 (1,185)

TITLE	CITATIONS COUNTED TOWARDS JIF
ISPRS INTERNATIONAL JOURNAL OF GEO-INFORMATION	320
REMOTE SENSING	57
SENSORS	53
SUSTAINABILITY	48
TRANSACTIONS IN GIS	22
INTERNATIONAL JOURNAL OF GEOGRAPHICAL INFORMATION SCIENCE	21
IEEE ACCESS	19
LAND	13
PLOS ONE	13
COMPUTERS ENVIRONMENT AND URBAN SYSTEMS	12

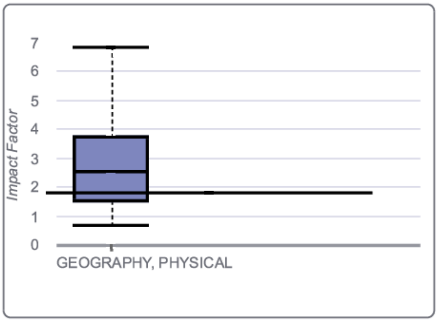
Box plot

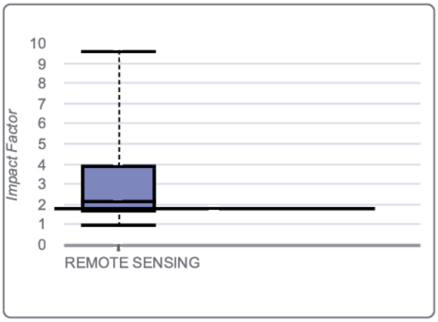
Category Box Plot 2018

Category Box Plot

The category box plot depicts the distribution of Impact Factors for all journals in the category. The horizontal line that forms the top of the box is the 75th percentile (Q1). The horizontal line that forms the bottom is the 25th percentile (Q3). The horizontal line that intersects the box is the median Impact Factor for the category.
Horizontal lines above and below the box, called whiskers, represent maximum and minimum values.
The top whisker is the smaller of the following two values:
the maximum Impact Factor (IF)
Q1 IF + 3.5(Q1 IF - Q3 IF)
The bottom whisker is the larger of the following two values:
the minimum Impact Factor (IF)
Q1 IF - 3.5(Q1 IF - Q3 IF)
Box Plots are provided for the current JCR year for each of the categories in which the journal is indexed.

ISPRS INT J GEO-INF, IF: 1.840





Rank

Rank

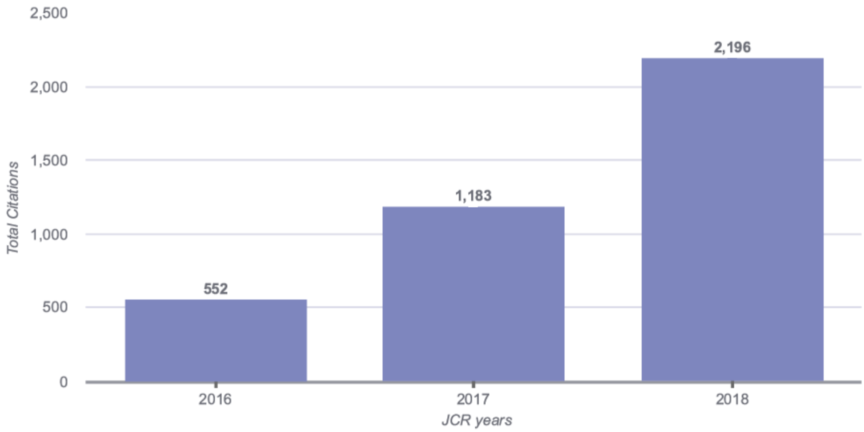
JCR Impact Factor

JCR Year	GEOGRAPHY, PHYSICAL			REMOTE SENSING		
	Rank	Quartile	JIF Percentile	Rank	Quartile	JIF Percentile
2018	31/50	Q3	39.000	19/30	Q3	38.333
2017	33/49	Q3	33.673	18/30	Q3	41.667
2016	35/49	Q3	29.592	22/29	Q4	25.862
2015	45/49	Q4	9.184	26/28	Q4	8.929

ESI Total Citations

Rank

JCR Year	GEOSCIENCES
2018	191/421-Q2
2017	228/419-Q3
2016	295/417-Q3

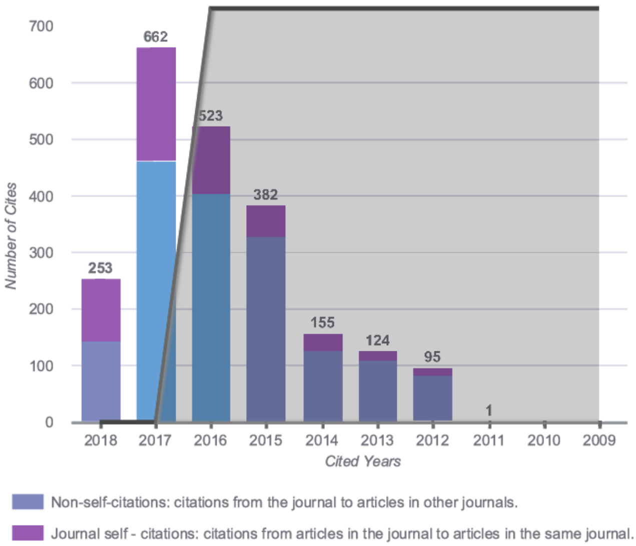


Cited Journal Data

Cited Half-Life Data

Cited Year	2018	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008-All
#Cites from 2018	253	662	523	382	155	124	95	1	0	0	1
Cumulative %	11.52%	41.67%	65.48%	82.88%	89.94%	95.58%	99.91%	99.95%	99.95%	99.95%	100.00%

Cited Journal Graph 2018



CITED JOURNAL GRAPH

The Cited Journal Graph shows the distribution (by cited year) of citations published in journals during the JCR year to items published in the Journal during the last 10 years.

The white/grey division indicates the cited half-life (if < 10.0). Half of the citations are to items that were published more recently than the cited half-life.

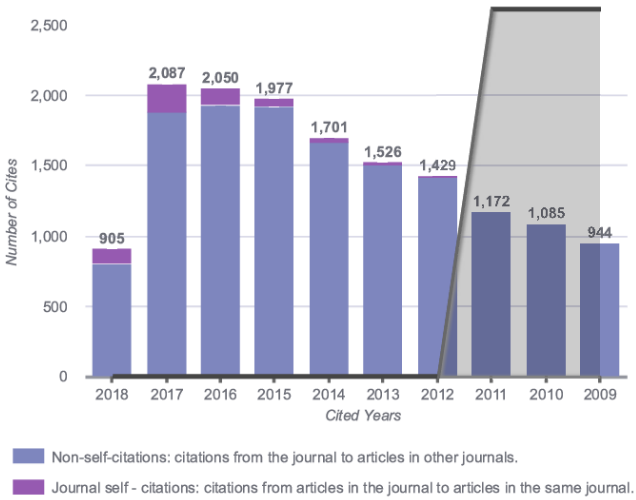
The two light-blue columns indicate citations used to calculate the Impact Factor (always the 2nd and 3rd columns).

Citing Journal Data

Citing Half-Life Data

Citing Year	2018	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008-All
#Cites from 2018	905	2,087	2,050	1,977	1,701	1,526	1,429	1,172	1,085	944	8,514
Cumulative %	3.87%	12.79%	21.56%	30.01%	37.28%	43.81%	49.91%	54.93%	59.56%	63.60%	100.00%

Citing Journal Graph 2018



CITING JOURNAL GRAPH

The Citing Journal Graph shows the distribution (by cited year) of citations published in the Journal during the JCR year to items published in journals during the last 10 years.

The white/grey division indicates the citing half-life (if < 10.0). Half of the citations are to items that were published more recently than the citing half-life.

Paper III: Scalable pixel-based crop classification combining Sentinel-2 and Landsat-8 data time series: Case study of the Duero river basin

Journal	**Agricultural Systems**
Editorial	Elsevier SCI LTD
ISSN	0308-521X
Impact factor (2018)	4.131
Ranking	1/57
Quartile	Q1

2018 Journal Performance Data for: AGRICULTURAL SYSTEMS

ISSN: 0308-521X
eISSN: 1873-2267
ELSEVIER SCI LTD
THE BOULEVARD, LANGFORD LANE, KIDLINGTON, OXFORD OX5 1GB, OXON, ENGLAND
NETHERLANDS

TITLES
ISO: Agric. Syst.
JCR Abbrev: AGR SYST

LANGUAGES
English

CATEGORIES
AGRICULTURE, MULTIDISCIPLINARY - SCIE

PUBLICATION FREQUENCY
9 issues/year

Key Indicators 2018

IMPACT METRICS

Total Cites	6,747	✓Trend
Journal Impact Factor	4.131	Trend
5 Year Impact Factor	4.155	Trend
Immediacy Index	1.179	Trend
Impact Factor Without Journal Self Cites	3.491	Trend

INFLUENCE METRICS

Eigenfactor Score	0.00722	Trend
Article Influence Score	0.892	Trend
Normalized Eigenfactor	0.85935	Trend

SOURCE METRICS

Citable Items	173	Trend
% Articles in Citable Items	94.22	Trend
Average JIF Percentile	99.123	Trend
Cited Half-Life	7.7	Trend
Citing Half-Life	7.2	Trend

Journal Impact Factor Calculation

2018 Journal Impact Factor $= \frac{1,169}{283} = 4.131$

How is Journal Impact Factor Calculated?

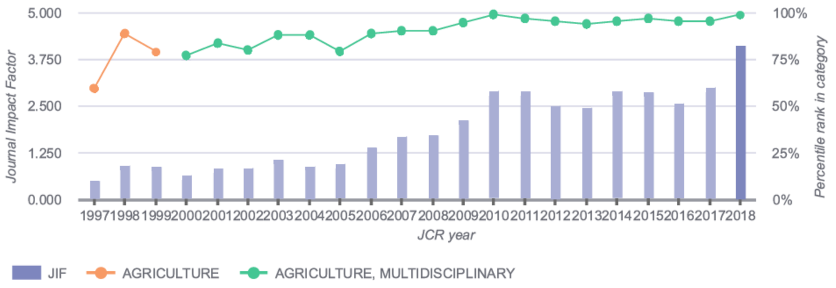
$$\text{JIF} = \frac{\text{Citations in 2018 to items published in } \mathbf{2016\ (503) + 2017\ (666)}}{\text{Number of citable items in } \mathbf{2016\ (121) + 2017\ (162)}} = \frac{1,169}{283}$$

The data in the two graphs below and in the Journal Impact Factor calculation panels represent citation activity in 2018 to items published in the journal in the prior two years. They detail the components of the Journal Impact Factor. Use the "All Years" tab to access key metrics and additional data for the current year and all prior years for this journal.

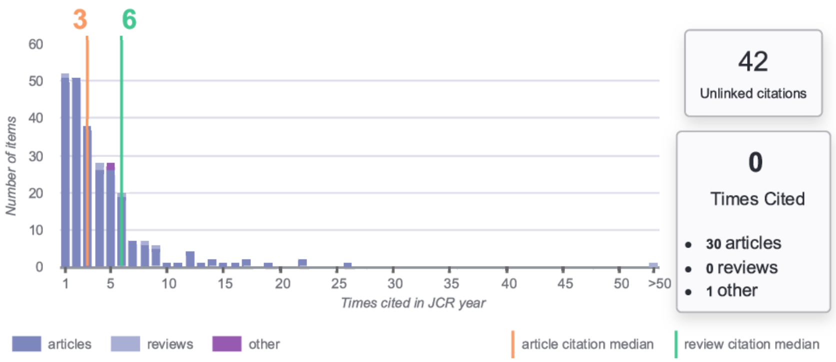
2018 Journal Impact Factor & percentile rank in category for: AGRICULTURAL SYSTEMS

4.131

2018 Journal Impact Factor



2018 JIF Citation Distribution for: AGRICULTURAL SYSTEMS



Citations in 2018 (1,169)

TITLE	CITATIONS COUNTED TOWARDS JIF
AGRICULTURAL SYSTEMS	181
SUSTAINABILITY	50
JOURNAL OF CLEANER PRODUCTION	46
SCIENCE OF THE TOTAL ENVIRONMENT	32
EUROPEAN JOURNAL OF AGRONOMY	27
AGRICULTURAL AND FOREST METEOROLOGY	23
LAND USE POLICY	22
AGRONOMY-BASEL	18
COMPUTERS AND ELECTRONICS IN AGRICULTURE	18
PLOS ONE	16

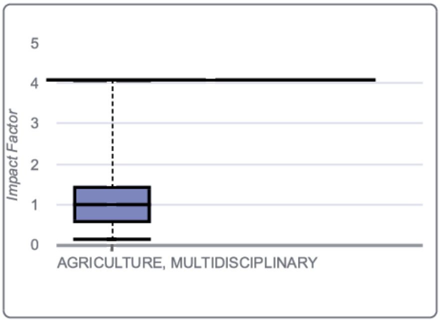
Box plot

Category Box Plot 2018

Category Box Plot

The category box plot depicts the distribution of Impact Factors for all journals in the category. The horizontal line that forms the top of the box is the 75th percentile (Q1). The horizontal line that forms the bottom is the 25th percentile (Q3). The horizontal line that intersects the box is the median Impact Factor for the category.
Horizontal lines above and below the box, called whiskers, represent maximum and minimum values.
The top whisker is the smaller of the following two values:
the maximum Impact Factor (IF)
Q1 IF + 3.5(Q1 IF - Q3 IF)
The bottom whisker is the larger of the following two values:
the minimum Impact Factor (IF)
Q1 IF - 3.5(Q1 IF - Q3 IF)
Box Plots are provided for the current JCR year for each of the categories in which the journal is indexed.

AGR SYST, IF: 4.131



Rank

Rank

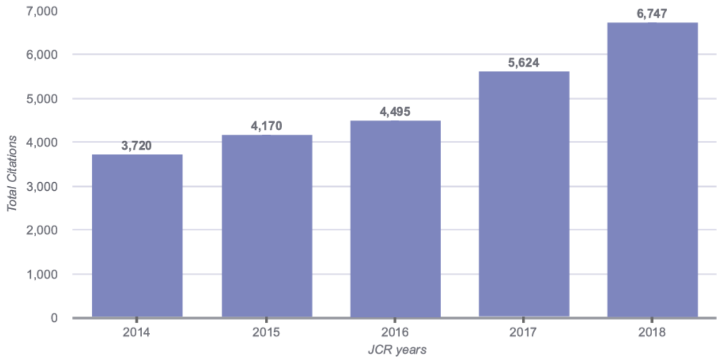
JCR Impact Factor

JCR Year	AGRICULTURE, MULTIDISCIPLINARY			AGRICULTURE		
	Rank	Quartile	JIF Percentile	Rank	Quartile	JIF Percentile
2018	1/57	Q1	99.123	N/A	N/A	N/A
2017	3/57	Q1	95.614	N/A	N/A	N/A
2016	3/56	Q1	95.536	N/A	N/A	N/A
2015	2/57	Q1	97.368	N/A	N/A	N/A
2014	3/56	Q1	95.536	N/A	N/A	N/A
2013	4/56	Q1	93.750	N/A	N/A	N/A
2012	3/57	Q1	95.614	N/A	N/A	N/A
2011	2/57	Q1	97.368	N/A	N/A	N/A
2010	1/55	Q1	99.091	N/A	N/A	N/A
2009	3/45	Q1	94.444	N/A	N/A	N/A
2008	4/35	Q1	90.000	N/A	N/A	N/A
2007	4/35	Q1	90.000	N/A	N/A	N/A
2006	4/31	Q1	88.710	N/A	N/A	N/A
2005	7/31	Q1	79.032	N/A	N/A	N/A
2004	4/29	Q1	87.931	N/A	N/A	N/A
2003	4/29	Q1	87.931	N/A	N/A	N/A
2002	6/28	Q1	80.357	N/A	N/A	N/A
2001	5/28	Q1	83.929	N/A	N/A	N/A
2000	7/28	Q1	76.786	N/A	N/A	N/A
1999	N/A	N/A	N/A	24/113	Q1	79.204
1998	N/A	N/A	N/A	13/111	Q1	88.739
1997	N/A	N/A	N/A	46/112	Q2	59.375

ESI Total Citations

Rank

JCR Year	AGRICULTURAL SCIENCES
2018	60/352-Q1
2017	62/344-Q1
2016	69/337-Q1
2015	67/336-Q1
2014	65/325-Q1
2013	69/323-Q1

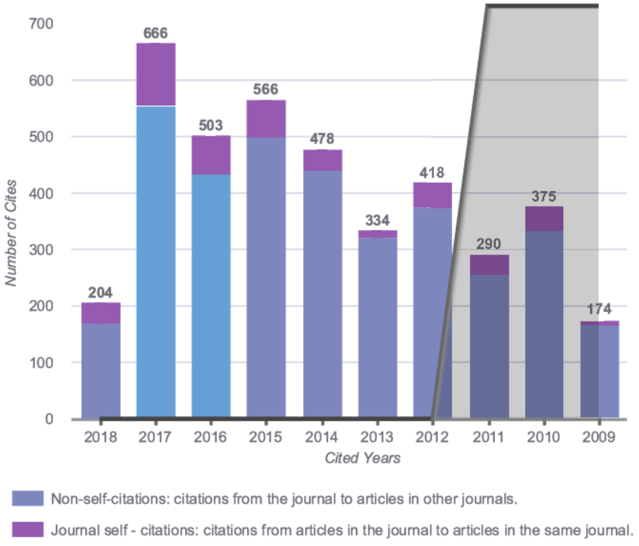


Cited Journal Data

Cited Half-Life Data

Cited Year	2018	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008-All
#Cites from 2018	204	666	503	566	478	334	418	290	375	174	2,739
Cumulative %	3.02%	12.89%	20.35%	28.74%	35.82%	40.77%	46.97%	51.27%	56.83%	59.40%	100.00%

Cited Journal Graph 2018



CITED JOURNAL GRAPH

The Cited Journal Graph shows the distribution (by cited year) of citations published in journals during the JCR year to items published in the Journal during the last 10 years.

The white/grey division indicates the cited half-life (if < 10.0). Half of the citations are to items that were published more recently than the cited half-life.

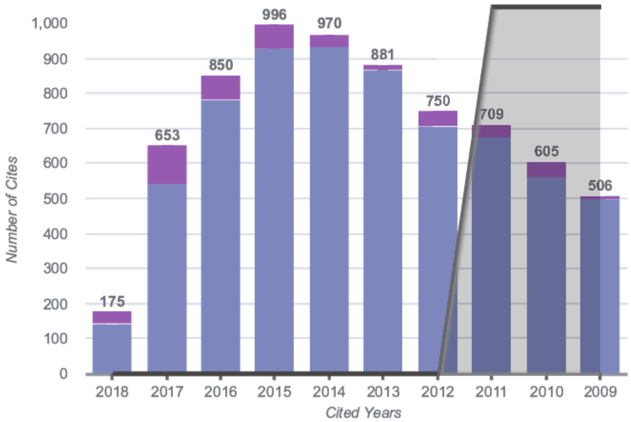
The two light-blue columns indicate citations used to calculate the Impact Factor (always the 2nd and 3rd columns).

Citing Journal Data

Citing Half-Life Data

Citing Year	2018	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008-All
#Cites from 2018	175	653	850	996	970	881	750	709	605	506	3,754
Cumulative %	1.61%	7.63%	15.47%	24.65%	33.59%	41.71%	48.62%	55.16%	60.73%	65.40%	100.00%

Citing Journal Graph 2018



Non-self-citations: citations from the journal to articles in other journals.

Journal self - citations: citations from articles in the journal to articles in the same journal.

CITING JOURNAL GRAPH

The Citing Journal Graph shows the distribution (by cited year) of citations published in the Journal during the JCR year to items published in journals during the last 10 years.

The white/grey division indicates the citing half-life (if < 10.0). Half of the citations are to items that were published more recently than the citing half-life.

Appendix B. HidroMap software

HidroMap

A tool for irrigation monitoring and management using free satellite imagery

Type: Registration of intellectual property

Reference Number: SA-00/2019/2424

Administrative Institution: University of Salamanca

UNESCO Codes:	1203.14	Environmental control systems
	1209.03	Data analysis
	2506.16	Remote sensing
	3102.05	Irrigation
	3103.03	Crop management

Authors: González Aguilera, D., Del Pozo Aguilera, S., Piedelobo Martín, L., Hernández López, D., Ballesteros González, R., Moreno Hidalgo, M.A., Charco Toboso, J.R., Ortega Terol, D., Guerrero Sevilla, D.

Abstract

HidroMap is an open-source tool organized in two modules, desktop-GIS and web-GIS, with complementary roles and functionalities, and based on a PostgreSQL/PostGIS database. It effectively combines algorithms and methodologies for downloading, storing and pre-processing satellite images from S2 and L8 that cover the Spanish territory of Duero river basin. The developed workflow allows intersecting satellite-based data, namely the NDVI, with spatial data from Mirame-IDEDuero (http://www.mirame.chduero.es/) and from the Spanish Geographic Information System of Agricultural Plots (SIGPAC) (i.e., parcel delimitations, irrigation rights, land use and unauthorised areas for irrigation). HidroMap allows managing unregulated irrigation, temporally monitoring irrigated agricultural plots and optimizing surveillance resources to efficiently plan on-the-spot checks. The tool is developed using Python programming language for QGIS (PyQGIS).

HidroMap is developed for the Duero Hydrographic Confederation within the regional project *"452-A.640.02.07/2015. RevelaDuero: Earth Observation image analysis system for the determination of irrigated plots and crop classification in the Duero river basin"* and is periodically upgraded, such as within the project *"452-A. 640.02.02/2019. RevelaDuero: Maintenance and improvement of the Earth Observation image analysis system for the determination of irrigated plots in the Duero river basin"*. The tool is available online at: https://github.com/TIDOP/hidromap.

Application

HidroMap is created for the Duero Hydrographic Confederation. Its open-source approach allows its easy adaptability to new needs and its scalability to other river basins. It allows performing two processes automatically: (i) detecting agricultural plots with unregulated irrigation activity (named cases), prioritizing larger surfaces, further distance to regulated wells and water scarce areas; and (ii) estimating the irrigated area and number of irrigated agricultural plots. All the inputs needed (i.e., NDVI image and area of interest) and prioritizing parameters (i.e., cases' area and NDVI thresholds) are defined by the user.

Partial Features

Automatic downloading and pre-processing of satellite images

Several scripts are developed in Python for automatically downloading, storing and pre-processing satellite images from S2 and L8 that cover the Spanish territory of Duero river basin. The scripts are based on Olivier Hagolle's codes *"LANDSAT-Download"* (https://github.com/olivierhagolle/LANDSAT-Download) and *"Sentinel-download"* (https://github.com/olivierhagolle/Sentinel-download), available on GitHub software development platform. The NDVI is automatically calculated as the normalized ratio between the NIR and R bands, adapted to the sensors' characteristics (Table B.1). Values are multiplied for 100 in order to work with integers, thereby increasing the efficiency of the main process.

Table B.1. The NDVI equation and bands used for Sentinel-2 (S2) and Landsat-8 (L8) satellite platforms.

NDVI=(NIR-R)/(NIR+R)	
S2	Band 4 (R: 645–683 nm) Band 8 (NIR: 762–907 nm)
L8	Band 4 (R: 630–680 nm) Band 5 (NIR: 845–885 nm)

Database

A PostgreSQL/PostGIS database is consumed and fed by HidroMap model. Its main structure consists of fields, relations of tables and triggers that allow cases' detection and prioritization.

Main process

This process is developed under the name of `quick_process.py` with PyQGIS and represents the main algorithm of the tool. It consists of more than 30 automatic processes. It takes advantage of the available geo-processing tools in QGIS (i.e., GDAL and SAGA) to perform spatial intersections between several layers and surface calculation. An area of interest, defined either by a shapefile or by selecting a municipality from the 2067 spatial tables inside the PostgreSQL/PostGIS database, is the input for starting the algorithm process within a NDVI image. Specific parameters can be defined by the user, such as the cases' area and NDVI thresholds. Firstly, the irrigated area and number of irrigated agricultural plots are estimated. After that, SAGA spatial difference algorithm allows processing intersections with spatial data from Mirame-IDEDuero (i.e., irrigation rights, unauthorised areas for irrigation or urban areas). Spatial data concerning irrigation rights is automatically updated every month in the PostgreSQL/PostGIS database. SAGA intersection algorithm has been improved so as to perform geospatial differences one by one, taking out all the invalid and incorrect geometries per intersection. The cases are obtained as a shapefile after geometric validation, intersections with the SIGPAC spatial data (i.e., parcel delimitations and land use) and the RSA's sectors, filtering forest or non-agricultural areas (if requested), and prioritizing the cases according to the parameters defined by the user. The outputs from every sub-process are added to QGIS map canvas with a settled style so as to allow users analysing any result.

Automatic detection of irrigated area in a period of time

This processing model is developed with QGIS model builder to quickly estimate the irrigated area and number of irrigated agricultural plots in an area of interest during a period of time. The user must select HidroMap results (i.e., cases' shapefiles) from different dates.

Inputs

The different inputs that must be defined in the desktop-GIS module interface are specified as follows:

- Definition of the workspace root.
- Selection of the processing type: cases automatic generation or total irrigated surface.
- Definition of the study area: shapefile or municipality.
- NDVI image.
- Request of filtering SIGPAC's forest or non-agricultural areas.
- Parameters setting: NDVI threshold, cases' area threshold, number of cases to prioritize and artifices area threshold; defined by default as 70, 0.5 ha., 5 and 0.1 ha.

Outputs

The output is a shapefile whose information depend on the selected processing type:

- Cases automatic generation: the output consists of a shapefile holding the generated cases and corresponding spatial information. The user must click on the Adobe PDF file icon to print the cases. These PDF reports show all the geo-spatial information needed to perform on-the-spot checks.
- Total irrigated surface: the output consists of a rapid text message informing about the irrigated area and number of irrigated agricultural plots in the area of interest.

HidroMap desktop-GIS

This module is currently used by the HPO to detect unregulated irrigation using the NDVI response. The RSA and the HPO plan on-the-spot checks to the most severe infringements.

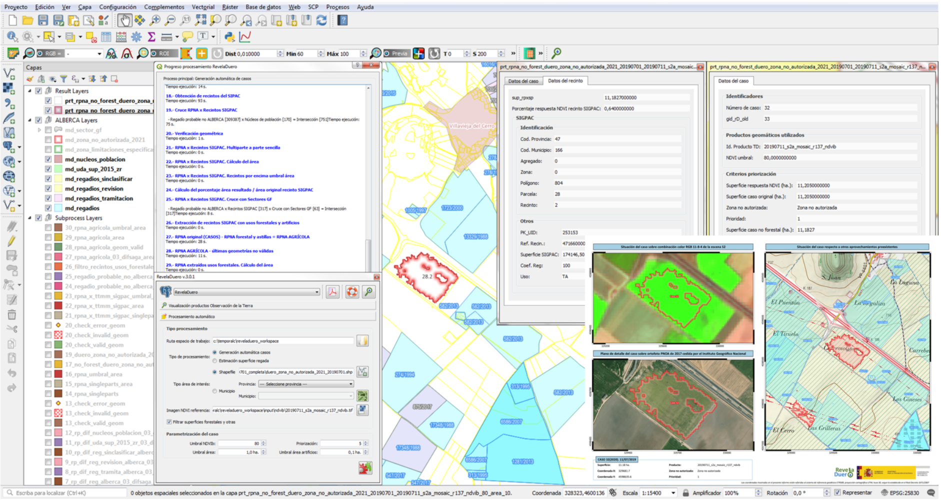


Figure B.1. Screenshot of the desktop-GIS interface showing the most significant results.

HidroMap web-GIS

This module offers agronomical experts of the Duero Hydrographic Confederation an user-friendly environment to quickly monitor irrigated crops and estimate crop types according to their NDVI signature. Crop classification, farmers' declarations to the CAP and data from the field visits can be displayed, among other layers.

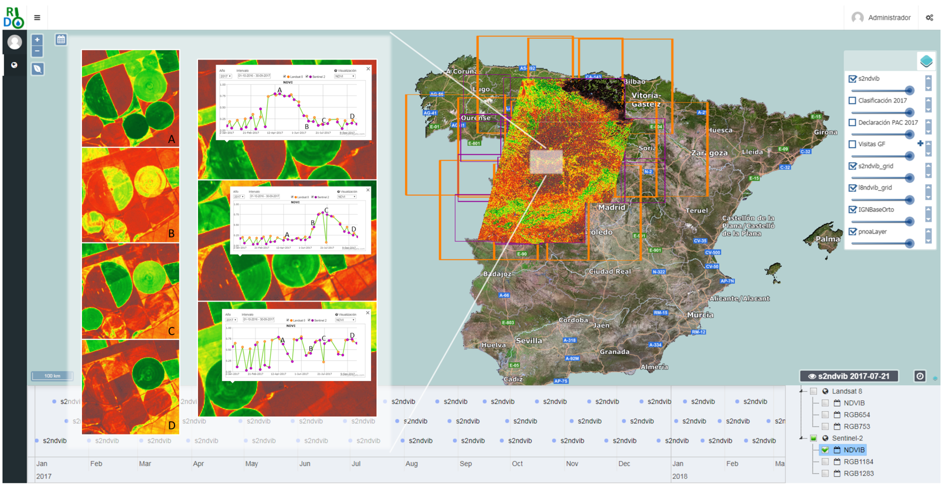


Figure B.2. Screenshot of the web-GIS interface showing the most significant results.

Innovation Award

The Innovation Award as the Best Research Project in Ávila province in 2018, granted by *Diario El Mundo* to TIDOP Research Group, is attached hereunder.

CERTIFICADO DE ORIGINALIDAD

D. J. Joaquín Rodríguez Martín, autor, conforme a la definición establecida en el artículo 5 del texto refundido de la Ley de Propiedad Intelectual, certifica mediante el presente documento, que el Premio Innovador es una pieza realizada en piedra de Villamayor (Salamanca) y que, inspirada en la sobriedad del románico palentino, intenta transmitir esos mismos valores de creatividad, originalidad, firmeza, vocación y trabajo.

En Valladolid a 12 abril del 2018

PREMIO INNOVADOR AL MEJOR PROYECTO DE ÁVILA.

GRUPO DE TECNOLOGÍAS DE LA INFORMACIÓN PARA LA DOCUMENTACIÓN DEL PATRIMONIO DE LA UNIVERSIDAD DE SALAMANCA

Por la herramienta creada para la CHD para vigilar el uso ilegal de los riegos.

Figure B.3. The Innovation Award granted by *Diario el Mundo* in 2018.

Curriculum Vitae

Laura Piedelobo Martín

05/08/1992 Born in Ávila, Spain

Education

2016-2020 PhD in Geotechnologies Applied to Construction, Energy and Industry. Department of Cartographic and Land Engineering, University of Salamanca (USAL) (Ávila, Spain).

2015-2017 Mining and Energy Engineering BSc. USAL (Ávila, Spain) and Faculty of Sciences of the University of Lisbon (FCUL) (Lisbon, Portugal) (Erasmus+ Programme).

2010-2015 Civil Engineering BSc. USAL (Ávila, Spain).

Research Experience

2020-2021 Institute of Advanced Studies of Pavia (IUSS) (Pavia, Italy), Institute for Environmental Protection and Research (ISPRA) (Rome, Italy). Supervisor: Dr. Andrea Taramelli. From April 2020 to April 2021.

2016-2020 TIDOP Research Group, USAL (Ávila, Spain). Supervisor: Prof. Dr. Diego González Aguilera. From October 2016 to October 2020.

2019 ISPRA (Rome, Italy). Supervisor: Dr. Andrea Taramelli. From April to December 2019.

2018 IUSS (Pavia, Italy), ISPRA (Rome, Italy), European Centre for Training and Research in Earthquake Engineering (EUCENTRE) (Pavia, Italy). Supervisor: Dr. Andrea Taramelli. From June to December 2018.

2017 Institute for Regional Development (IDR), University of Castilla-La Mancha (UCLM) (Albacete, Spain). Supervisor: Dr. David Hernández López. February 2017.

2015 Department of Geology, FCUL (Lisbon, Portugal). Supervisor: Dr. Catarina Silva. From February to July 2015.

Teaching Experience

2017-2020 Hydraulics. Civil Engineering BSc. USAL (Ávila, Spain). Supervisors: Dr. José Luis Molina González and José María Montejo Marcos.

Publications

2020 Sáez Blázquez, C., Piedelobo, L., Fernández-Hernández, J., Martín Nieto, I., Farfán Martín, A., Lagüela, S., González-Aguilera, D. (2020). Novel Experimental Device to Monitor the Ground Thermal Exchange in a Borehole Heat Exchanger. *Energies, 13*(5), 1270.

2019 Piedelobo, L., Taramelli, A., Schiavon, E., Valentini, E., Molina, J. -L., Nguyen Xuan, A., & González-Aguilera, D. (2019). Assessment of Green Infrastructure in Riparian Zones Using Copernicus Programme. *Remote Sensing, 11*(24), 2967.

2019 Taramelli, A., Lissoni, M., Piedelobo, L., Schiavon, E., Valentini, E., Nguyen Xuan, A., & González-Aguilera, D. (2019). Monitoring Green Infrastructure for Natural Water Retention Using Copernicus Global Land Products. *Remote Sensing, 11*(13), 1583.

2019 Piedelobo, L., Hernández-López, D., Ballesteros, R., Chakhar, A., Del Pozo, S., González-Aguilera, D., & Moreno, M. A. (2019). Scalable pixel-based crop classification combining Sentinel-2 and Landsat-8 data time series: Case study of the Duero river basin. *Agricultural Systems, 171*, 36-50.

2018 Piedelobo, L., Ortega-Terol, D., Del Pozo, S., Hernández-López, D., Ballesteros, R., Moreno, M. A., Molina, J. -L., & González-Aguilera, D. (2019). HidroMap: A New Tool for Irrigation Monitoring and Management Using Free Satellite Imagery. *ISPRS International Journal of Geo-Information, 7*(6), 220.

Research Projects and Grants

2020 ESA RFP/3-15502/18/NL/IA. Chime Mission Requirements Consolidation – European project. Main researcher: Dr. Andrea Taramelli (ISPRA). From January 2018 to December 2020. Role: researcher.

2019-2020 452-A. 640.02.02/2019. RevelaDuero: Maintenance and improvement of the Earth Observation image analysis system for the determination of irrigated plots in the Duero river basin – Regional project. Main researcher: Prof. Dr. Diego González Aguilera (USAL). From February 2019 to February 2020. Role: researcher.

2016-2020 Training Programme for Academic Staff (FPU PhD grant). Spanish Ministry of Education, Culture and Sport. From October 2016 to October 2020.

2019 FPU PhD grant. Predoctoral research stay. Spanish Ministry of Education, Culture and Sport. From April to December 2019.

2018 G.A. ECHO/SUB/2016/740172/PREV18. GREEN: Green infrastructure for disaster risk reduction protection: evidence, policy instruments and marketability – European project. Main researcher: Dr. Andrea Taramelli (EUCENTRE). From January 2016 to December 2018. Role: researcher.

2017-2018 452-A.640.02.07/2015. RevelaDuero: Earth Observation image analysis system for the determination of irrigated plots and crop classification in the Duero river basin – Regional project. Main researcher: Prof. Dr. Diego González Aguilera (USAL). From February 2017 to February 2018. Role: researcher.

Intellectual Properties

2018 González Aguilera, D., Del Pozo Aguilera, S., Piedelobo Martín, L., Hernández López, D., Ballesteros González, R., Moreno Hidalgo, M. A., Charco Toboso, J. R., Ortega Terol, D., & Guerrero Sevilla, D. (2018). *HidroMap – A tool for irrigation monitoring and management using free satellite imagery. Application No SA-00/2019/2424*. Madrid: Intellectual Property Registry, Ministry of Culture and Sport.

Congresses and Conferences

2020 Italian Pavilion – Venice Architecture Biennale 2020. Role: article and poster contribution.

2019 Space Week – International Conference dedicated to Space Access and Services Technologies. 4th Edition: Rome, Italy. 9-11 October 2019. Role: participant.

2019 CIPA – International Committee of Architectural Photogrammetry. 27th International Symposium: Ávila, Spain. 1-5 September 2019. Role: scientific committee.

Awards

2019 National Prize in Engineering/Architecture BSc. Granted by the Spanish Ministry of Education, Culture and Sport. For the academic results in Civil Engineering BSc.

2018 Innovation Award as the Best Research Project in Ávila province in 2018. Granted by *Diario El Mundo*. For the creation of a tool for the Duero Hydrographic Confederation to monitor unregulated irrigation.

2017 Extraordinary Prize. Granted by USAL. For the academic results in Mining and Energy Engineering BSc.

2016 Extraordinary Prize. Granted by USAL. For the academic results in Civil Engineering BSc.