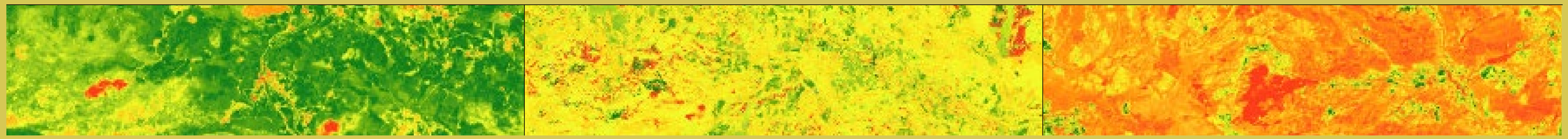
Copernicus Tools for Monitoring Global Change Effects in Rivers and Riparian Zones **(Cop.RIVER)** – The toolkit



The images featured on the cover correspond to products from the Copernicus Land Monitoring Service:

Normalized Difference Vegetation Index (left)
Plant Phenology Index Trajectories: End of Season Date (middle)
Plant Phenology Index (right)
Source: Copernicus Global Land Service, European Commission
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1.

INTRODUCTION

Index

1.

INTRODUCTION

Cop.RIVER aims to promote the use of Earth Observation (EO) in applications and services related to the ecological status of fluvial landscapes (i.e., rivers and their associated alluvial plains, floodplains, and riparian forests). The action will strengthen Copernicus user uptake by supporting regional and national authorities in the implementation of EU environmental policies, including the Biodiversity Strategy 2030, the Habitats and Birds Directives, and the Water Framework Directive.

This action has developed an innovative toolkit to define a selected set of standardized ecological indicators from both terrestrial and aquatic domains and evaluated the applicability of Copernicus Land Monitoring Service (CLMS) products to calculate them. CLMS products provide geographical information on land cover and its changes, land use, vegetation state, and water cycle, among others. The wide geographical and temporal coverage of CLMS products, combined with their spatio-temporal resolution and open access nature, make them ideal candidates to assess the ecological status of fluvial landscapes and monitor the effects of global change on riparian and river ecosystems.

The toolkit provides a methodological framework for monitoring elements, processes and services associated to fluvial landscapes (e.g., riparian forest composition, riparian habitat connectivity, water quality) using CLMS products and complementary approaches to support decision-making in biodiversity and water resource management, restoration, and conservation actions. First, the main guidelines, strategies, directives and monitoring approaches were reviewed to identify the reporting needs of national and regional authorities in the EU and Spain. Second, key ecological indicators to address monitoring variables were selected and the applicability of CLMS products was evaluated, combined with the identification of alternative remote-sensing products and approaches. Finally, the main features of key CLMS products are summarised, their strengths and weaknesses are evaluated and potential improvements are suggested.

2.

GUIDELINES, STRATEGIES, DIRECTIVES AND MONITORING APPROACHES

2.1 Overview of guidelines, strategies, directives and monitoring approaches

Cop.RIVER aims to develop a methodological framework to report the ecological status of fluvial landscapes, from regional to pan-European scale, using reproducible CLMS data and methods. To identify the reporting needs of national and regional authorities, several EU Directives and their transposition into Spanish legislation have been analysed. The focus has been placed on the Habitats Directive, the Water Framework Directive, and the EU Biodiversity Strategy for 2030, as they all aim to assess the ecological or optimal status of key fluvial landscapes components: the terrestrial domain (riparian forests) and the aquatic domain (streams). The Floods Directive was also considered, given its relevance to fluvial landscapes-related objectives such as identifying potential flood risk areas.

At the national level, Cop.RIVER has reviewed the **Spanish Law on Natural Heritage** and Biodiversity (Ley del Patrimonio Natural y la Biodiversidad). Although not specifically focused on fluvial landscapes, it provides variables applicable to their monitoring. This law was included due to the location of the pilot cases, which are situated in northern Spain (see Case studies Annex).

Additionally, Cop.RIVER has examined the variables required to monitor the effectiveness of **Nature-based Solutions** (NbS) and **Blue and Green Infrastructures** (BGIN) in supporting fluvial landscape services and processes. These are key pillars of EU environmental policy, with riparian ecosystems considered essential components.

2.2. Analysis of guidelines, strategies, directives and monitoring approaches

2.2.1. Habitats Directive

The **Habitats Directive** (Council Directive 92/43/EEC), adopted in 1992, provides a framework for safeguarding biodiversity in response to the degradation of habitats and species across Europe. Its main objective is to protect habitats and wild flora and fauna, promoting the maintenance or restoration of a favourable conservation status within the EU.

As the directive does not specify variables to assess the conservation status of riparian habitats, Cop.RIVER relied on the explanatory notes and guidelines for reporting under Article 17. These guidelines, developed by the European Topic Centre on Biological Diversity, aim to harmonize reporting across Member States. Notably, only the 2007–2012 reporting guidelines (Evans & Arvela, 2011) propose variables for assessing habitat conservation status.

Cop.RIVER also analysed national reporting practices for riparian habitats—primarily forested ecosystems—under the Habitats Directive. A list of responsible institutions was compiled for each Member State, along with the variables they use to assess riparian habitat conservation, where available. Only five countries—**Belgium**, **Germany**, **Italy**, **Spain**, and **The Netherlands**—were found to have documents specifying relevant indicators.

Additionally, the study considered the work of **Ruf & Kleeschulte *et al.* (2016)**, which highlights the contributions of the **Copernicus programme** to monitoring habitats, species, and the **Natura 2000** network.

Variables from the **Birds Directive** were excluded, as they focus on population status and trends, which are not measurable via remote sensing and do not directly reflect habitat ecological conditions.

2.2.2. Water Framework Directive

The **Water Framework Directive** (Directive 2000/60/EC), adopted in 2000, aims to harmonize water management across the EU, ensuring both the quantity and quality of water resources and achieving good ecological and chemical status of water bodies.

Cop.RIVER analysed the variables defined in the directive for assessing the ecological status of surface waters, focusing specifically on rivers. These include biological elements, hydromorphological elements supporting biological components, and chemical and physico-chemical elements.

To complement this, reporting guidelines from various Member States were reviewed. A list of responsible institutions was compiled, and ten countries were found to have published relevant indicators: **Croatia**, **Denmark**, **France**, **Germany**, **Italy**, **Ireland**, **Liechtenstein**, **Portugal**, **Spain**, and the **United Kingdom** (included for its contributions prior to Brexit).

Among these, the **River Habitat Survey** (Environment Agency, 2003) stands out for its comprehensive methodology for field sampling and assessment of river and stream conditions. Though originally developed for the UK and Ireland, it offers adaptable guidance for other regions.

Other relevant methodologies reviewed include:

- **Morphological Quality Index (MQI)** for river morphology (Rinaldi *et al.*, 2012),
- **QBR index** for riparian habitat quality (Munné *et al.*, 2003),
- **Riparian Quality Index (RQI)** for the ecological condition of riparian zones (González del Tánago & García de Jalón, 2011).

2.2.3. Biodiversity Strategy for 2030

The **EU Biodiversity Strategy for 2030 (BS2030)** is a long-term framework to halt and reverse biodiversity loss by 2030. It aligns with the **2030 Agenda for Sustainable Development** and supports the **Paris Agreement**.

Organized into four thematic pillars—**biodiversity**, **nature protection and restoration**, **transformative change**, and **global biodiversity leadership**—the strategy includes over 100 actions. These range from broad commitments, such as effective management of protected areas, to specific goals like planting three billion trees across the EU.

Although BS2030 does not provide a fixed list of reporting variables, several guidelines relevant to rivers and riparian zones were analysed:

- **Commission guidelines for defining, mapping, monitoring, and strictly protecting EU primary and old-growth forests** (DG Environment, 2023), linked to Target 3.
- **Barrier Removal for River Restoration** (DG Environment, 2022), supporting the goal of restoring 25,000 km of free-flowing rivers.
- **EU-wide methodology to map and assess ecosystem condition** (Vallecillo *et al.*, 2022), focused on improving conservation status and trends of habitats and species.

Only those BS2030 guidelines directly related to the ecological condition and characterization of rivers and riparian habitats were considered.

2.2.4. Floods Directive

The **Floods Directive** (Directive 2007/60/EC), adopted in 2007, aims to reduce the adverse impacts of flooding on human health, the environment, economic activities, and cultural heritage. It requires EU Member States to identify areas with significant flood risk, produce maps showing the extent of potential flooding and exposed elements (*e.g.*, residential zones and infrastructure), and develop flood risk management plans focused on minimizing risks, especially in vulnerable areas.

As the directive does not specify target variables, Cop.RIVER selected those useful for identifying potential flood risk areas. Reporting guidelines from individual Member States were reviewed, and the institutions responsible for Floods Directive reporting were identified. Only five countries—**Croatia**, **Greece**, **Latvia**, **Slovakia**, and **Spain**—were found to have published official documents proposing relevant indicators.

2.2.5.Spanish Law on Natural Heritage and Biodiversity

The **Spanish Law 42/2007 on Natural Heritage and Biodiversity** establishes the legal framework for the conservation, restoration, and sustainable use of biodiversity in Spain. It introduces planning and management instruments such as the **Spanish Inventory of Natural Heritage and Biodiversity**, and provides criteria for classifying species (*e.g.*, threatened, protected, or invasive). Variables proposed by this law—related to ecosystems, flora and fauna, genetic resources, natural resources, protected areas, and negative impacts—were included in the list of standardized ecological indicators alongside those from EU directives.

2.2.6. Nature-based solutions

Nature-based Solutions (NbS) are defined by the European Commission as “solutions inspired and supported by nature, which are cost-effective and provide environmental, social, and economic benefits while enhancing resilience.” Although EU-level policies such as *“Evaluating the impact of Nature-based Solutions”* (European Commission, 2021) and *“Nature-based solutions in Europe”* (EEA, 2021) exist, they do not propose specific indicators for assessing NbS effectiveness in riparian processes and services.

To address this gap, Cop.RIVER conducted a systematic literature review using **Web of Science**, with the search terms:

(“nature-based solutions” OR “nature-based solution”) AND (“river” OR “riparian” OR “catchment” OR "stream") AND ("key performance indicators" OR "assessment").

A total of 95 articles were retrieved. After screening titles and abstracts for relevance, 40 articles were selected for detailed analysis. Of these, only eight provided explicit lists of indicators for evaluating NbS effectiveness. These sources—**Beißler & Hack (2019)**, **Burdon *et al.* (2020)**, **Lilli *et al.* (2020)**, **Shah *et al.* (2020, 2023)**, **Pugliese *et al.* (2022)**, **Spray *et al.* (2022)**, and **Kettenhuber *et al.* (2023)**—were integrated into the overall indicator list.

2.2.7. Blue and Green Infrastructure

Regarding **Blue and Green Infrastructure (BGIN)**, the European Commission defines it as a "strategically planned network of natural and semi-natural areas designed to deliver ecosystem services such as water purification, air quality, recreation, and climate adaptation." This network of green (land) and blue (water) spaces contributes to improved environmental conditions and public well-being.

In addition to EU directives, Cop.RIVER reviewed national legislation on BGINs to identify variables for assessing their effectiveness in service provision and ecosystem processes. The key reference was the **"Scientific-technical basis for the State Strategy for Green Infrastructure and Ecological Connectivity and Restoration"**, which, although not prescribing a fixed set of indicators, offers examples of variables applicable to riparian monitoring.

View of the Deva River near Molleda, Cantabria (Spain).

3.

VARIABLES FOR ASSESSING THE ECOLOGICAL STATUS OF FLUVIAL LANDSCAPES

Index

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3.

VARIABLES FOR ASSESSING THE ECOLOGICAL STATUS OF FLUVIAL LANDSCAPES

Based on various European and national directives, laws, and frameworks related to the ecological status of fluvial landscapes—as well as associated actions and monitoring efforts aimed at improving habitat conditions and ensuring the provision of ecosystem services—a comprehensive list of relevant variables was compiled. For each variable, a set of ecological indicators was selected, and the applicability of CLMS products for calculating these indicators was assessed. The variables were grouped into thematic sections according to the specific ecological or management issues they address.

3.1. Terrestrial indicators

3.1.1. Connectivity

Connectivity plays a fundamental role in maintaining the ecological integrity of riparian ecosystems, directly influencing their capacity to deliver essential functions and ecosystem services. It reflects the exchange of matter, energy, and organisms across spatial units, and underpins the spatio-temporal dynamics of these habitats (Ward et al., 1999). This category encompasses variables related to habitat connectivity and fragmentation, including longitudinal connectivity (along the river corridor), transverse connectivity (floodplain adjacency), and patch-based spatial continuity.

3.1.1.1. Longitudinal connectivity

Longitudinal connectivity refers to the presence of discontinuities along the river network and assesses the extent of gaps relative to the optimal vegetation structure expected under natural conditions, whether dominated by tree or shrub strata (Lara et al., 2019).

Various methodological guidelines and strategies use different terminology to describe this concept, including longitudinal ecological connectivity (MITECO, 2019), corridor continuity (Munné et al., 2003), linear extent of functional vegetation (Rinaldi et al., 2012), and coverage and distribution patterns of riparian corridors (González del Tánago & García de Jalón, 2011).

Table 01 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 02 evaluates the applicability of key CLMS products in assessing this variable.

Table 03 lists all remote sensing-derived products identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 01. *Policy directives, strategies, and monitoring approaches that require or reference the longitudinal connectivity.* YES | NO

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
Tree Cover Density	Riparian Zones Land Use/ Land Cover
	Small woody features
	Corine Land Cover

Table 02. *Applicability of CLMS products for defining and quantifying longitudinal connectivity.*

Remote sensing-derived products	Source
Narrowband hyperspectral Indexes (MSI, NMDI, WBI, NDWI, NDII, CAI, LCAI, PSRI, PRI, MCARI, MRENDVI, MRESR, MTVI1, MTVI2, RENVI, TCARI, TVI, VREI1, VREI2, ARI1, ARI2, CRI1, CRI2, NDLI and NDNI)[1]	Airborne hyperspectral imagery
Topographic Indexes Derived from LiDAR Data (Elevation relative to low-flow water level, catchment area, catchment slope, topographic wetness index, multiresolution index of ridge top flatness, multiresolution index of valley bottom flatness, insolation and Topographic position index)[1]	LiDAR (Spain) LiDAR (Europe)
Structural metrics Derived from LiDAR Data (height parameters, different percentiles of heigh distribution, cumulative percentage of returns in the different layers and intensity parameters and different percentage of intensity returned by points classified as ground)[1]	Global canopy height Land Cover

Table 03. *Remote sensing-derived longitudinal connectivity indicators and references. Links to data sources. [1]Godfroy et al. 2023 [2]Liu, 2021.*

3.1.1.2. Transversal connectivity

Transversal connectivity refers to the interaction between riparian and hillside vegetation formations. The greater the contact between these two formations, the better the state of connectivity (Lara *et al.*, 2019).

Various methodological guidelines and strategies use different terminology to describe this variable, such as transversal ecological connectivity (MITECO, 2019), riparian-hillside forest connectivity (Munné *et al.*, 2003) or the woody riparian-hillside vegetation contact extent (Lara *et al.*, 2019).

Table 04 summarises the relevant Directives, Strategies, and monitoring approaches that either require or reference the use of this variable.

Table 05 evaluates the applicability of key CLMS products in assessing this variable.

Table 06 lists all remote sensing–derived products identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 04. *Policy directives, strategies, and monitoring approaches that require or reference the transversal connectivity.* **YES** | **NO**

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
Tree Cover Density	Riparian Zones Land Use/ Land Cover
	Small woody features
	Corine Land Cover

Table 05. *Applicability of CLMS products for defining and quantifying transversal connectivity.*

Remote sensing-derived products	Source
Narrowband hyperspectral Indexes (MSI, NMDI, WBI, NDWI, NDII, CAI, LCAI, PSRI, PRI, MCARI, MRENDVI, MRESR, MTVI1, MTVI2, RENVI, TCARI, TVI, VREI1, VREI2, ARI1, ARI2, CRI1, CRI2, NDLI and NDNI)[1]	Airborne hyperspectral imagery
Topographic Indexes Derived from LiDAR Data (Elevation relative to low-flow water level, catchment area, catchment slope, topographic wetness index, multiresolution index of ridge top flatness, multiresolution index of valley bottom flatness, insolation and Topographic position index)[1]	LiDAR (Spain)
Structural metrics Derived from LiDAR Data (height parameters, different percentiles of heigh distribution, cumulative percentage of returns in the different layers and intensity parameters and different percentage of intensity returned by points classified as ground)[1]	LiDAR (Europe)
	Global canopy height
	Land Cover

Table 06. *Remote sensing-derived transversal connectivity indicators and references. Links to data sources.[1] Godfroy et al. 2023;[2]Liu, 2021.*

3.1.1.3. Others

Methodological guidelines and strategic frameworks employ distinct terminology to describe connectivity variables that go beyond traditional longitudinal and transverse metrics. These include ecotone abundance (Pignalosa *et al.*, 2023), structural and functional connectivity pattern shifts (Raymond *et al.*, 2017), effective mesh density (Pignalosa *et al.*, 2023), Hanski's index (Pignalosa *et al.*, 2023), and fluvial connectivity (Shah *et al.*, 2020; Shah *et al.*, 2023).

Table 07 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 08 evaluates the applicability of key CLMS products in assessing this variable.

Table 09 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 07. *Policy directives, strategies, and monitoring approaches that require or reference the connectivity.* YES | NO

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
Tree Cover Density	Riparian Zones Land Use/ Land Cover
	Small woody features
	Corine Land Cover

Table 08. *Applicability of CLMS products for defining and quantifying connectivity.*

Remote sensing-derived products	Source
Narrowband hyperspectral Indexes (MSI, NMDI, WBI, NDWI, NDII, CAI, LCAI, PSRI, PRI, MCARI, MRENDVI, MRESR, MTVI1, MTVI2, RENVI, TCARI, TVI, VREI1, VREI2, ARI1, ARI2, CRI1, CRI2, NDLI and NDNI)[1]	Airborne hyperspectral imagery
Topographic Indexes Derived from LiDAR Data (Elevation relative to low-flow water level, catchment area, catchment slope, topographic wetness index, multiresolution index of ridge top flatness, multiresolution index of valley bottom flatness, insolation and Topographic position index) [1]	LiDAR (Spain) LiDAR (Europe) Global canopy height
Structural metrics Derived from LiDAR Data (height parameters, different percentiles of heigh distribution, cumulative percentage of returns in the different layers and intensity parameters and different percentage of intensity returned by points classified as ground)[1]	Land Cover

Table 09. *Remote sensing-derived connectivity indicators and references. Links to data sources.* [1]*Godfroy et al. 2023;* [2]*Liu, 2021.*

3.1.1.4. Fragmentation

Habitat fragmentation refers to the process by which large, continuous patches of habitat are divided into smaller, isolated fragments due to various human activities that create barriers to species dispersal.

The characterization of habitat fragmentation is commonly referenced across different monitoring strategies, directives and frameworks using habitat attributes such as patch size (Evans & Arvela, 2011), distance between patches (Evans & Arvela, 2011), or patch size variability (Angelini *et al.*, 2016).

Table 10 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 11 evaluates the applicability of key CLMS products in assessing this variable.

Table 12 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures
YES	YES	YES	NO	NO	YES	YES

Table 10. *Policy directives, strategies, and monitoring approaches that require or reference the fragmentation.* YES | NO

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
Tree Cover Density	Riparian Zones Land Use/ Land Cover
European Settlement Map	Small woody features
Imperviousness	Corine Land Cover

Table 11. *Applicability of CLMS products for defining and quantifying fragmentation.*

Remote sensing-derived products	Source
Fragstats landscape metrics[3][4][5]	Fragstats
Land Use[5][6]	Land Use
Mean Nearest Neighbor (average distance in meters from one forest patch to the nearest forest patch)[6]	Road density (Spain)
Road density[6]	Road density (Europe)
Area of forest (total core area index, class area and percentage of landscape)[6]	

Table 12. *Remote sensing-derived fragmentation indicators and references. Links to data sources. [3]Martín-Gallego et al., 2020; [4]Fynn & Campbell, 2019; [5]Kayiranga et al., 2016; [6]Heilman et al., 2002.*

3.1.2. Disturbances

Disturbances are a primary driver of ecosystem dynamics, with most originating from anthropogenic sources. They exert direct structural impacts on ecosystems, altering successional pathways and biodiversity patterns. Among disturbance types, the most ecologically relevant for riparian systems—and the most widely documented in the research literature—include: artificial elements, wildfires, surface imperviousness, floods, eutrophication, and droughts.

3.1.2.1 Artificial elements

Artificial elements encompass anthropogenic structures that impair connectivity and ecological quality in riverine and riparian ecosystems, including canalizations and dams.

A review of relevant directives, strategies, methodological guidelines, and monitoring frameworks reveals varied terminology used to describe this variable, including cities, buildings, and infrastructures (ΥΠΟΥΡΓΕΙΟ ΠΕΡΙΒΑΛΛΟΝΤΟΣ, ΕΝΕΡΓΕΙΑΣ ΚΑΙ ΚΛΙΜΑΤΙΚΗΣ ΑΛΛΑΓΗΣ, 2014), artificialisation of the physical structure of the watercourse (Vidal *et al.*, 2021), and canalisations, transverse structures, and other alterations (Munné *et al.*, 2003).

Table 13 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 14 evaluates the applicability of key CLMS products in assessing this variable.

Table 15 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 13. *Policy directives, strategies, and monitoring approaches that require or reference artificial elements.* YES | NO

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
Corine Land Cover European Settlement Map Imperviousness	

Table 14. *Applicability of CLMS products for defining and quantifying artificial elements.*

Remote sensing-derived products	Source
Anthropic Exposure Indicator for River Basins (AEIRB) [7]	Land Cover

Table 15. *Remote sensing-derived artificial elements indicators and references. Links to data sources.* [7]*do Nascimento Lopes et al., 2021.*

3.1.2.2 Wildfires

Wildfires represent a significant ecological disturbance that modifies vegetation successional dynamics and adversely impacts the air or water quality. These large-scale perturbations affect terrestrial ecosystems globally through substantial biomass combustion and alterations to soil properties, ultimately transforming ecosystem structure and disrupting fundamental ecological processes (Roces-Díaz *et al.*, 2022).

This perturbation variable was referred to in several methodological guidelines and strategies, using different terms to characterize wildfires such as wildfire frequency (Evans & Arvela, 2011), wildfire signs (Evans & Arvela, 2011), fire severity index (Ley 42/2007 del Patrimonio Natural y de la Biodiversidad), affected woodland area (Ley 42/2007 del Patrimonio Natural y de la Biodiversidad) or flammability index (Pignalosa *et al.*, 2023).

Table 16 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 17 evaluates the applicability of key CLMS products in assessing this variable.

Table 18 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures
NO	YES	YES	NO	YES	NO	NO

Table 16. *Policy directives, strategies, and monitoring approaches that require or reference wildfires.* YES | NO

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
NDVI Seasonal Trajectories	

Table 17. *Applicability of CLMS products for defining and quantifying wildfires.*

Remote sensing-derived products	Source
Burned Area (BA) product MCD64A1 Collection 6[8]	Sentinel-2 Data
NDVI[9]	Burned Area Product
NDWI[9]	
NBR[10][11]	

Table 18. *Remote sensing-derived wildfires indicators and references. Links to data sources. [8]Xie et al., 2020; [9]Nurdiana & Risdiyanto, 2015; [10] Saidi et al., 2021; [11]Lasaponara et al., 2018.*

3.1.2.3 Imperviousness

The creation of impervious surfaces through urban infrastructure development (*e.g.*, road construction, pavement installation, or building erection) establishes impermeable barriers that fundamentally alter soil hydrological properties, particularly infiltration capacity. This anthropogenic modification of surface permeability primarily contributes to habitat fragmentation through landscape dissection and increases flood risk due to a substantial reduction in soil water absorption capacity.

Various terms have been used to describe different aspects of this disturbance in the revised methodological guidelines and strategies, including limitation of permeability and alteration of functional riverbank materials by human activities (MITECO, 2019), substrate (González del Tánago & García de Jalón, 2011), and soil drainage—encompassing soil compaction and cementation (Burdon *et al.*, 2020).

Table 19 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 20 evaluates the applicability of key CLMS products in assessing this variable.

Table 21 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures
YES	YES	NO	YES	NO	YES	NO

Table 19. *Policy directives, strategies, and monitoring approaches that require or reference imperviousness.* YES | NO

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
Riparian zones Land Use/ Land Cover	Imperviousness
CORINE Land Cover	
Tree Cover Density	
NDVI	
FAPAR	
LAI	

Table 20. *Applicability of CLMS products for defining and quantifying imperviousness.*

Remote sensing-derived products	Source
Satellite images based classification[12][13][14][15]	Sentinel-2 Data

Table 21. *Remote sensing-derived imperviousness indicators and references. Links to data sources. [12]Luti et al., 2020; [13]Giacco et al., 2022; [14] Leinenkugel et al., 2011; [15]Ramezani et al. 2022.*

3.1.2.4 Floods

River flooding is a natural disturbance event characterized by the overflow of riverbanks, resulting in the inundation of adjacent areas that are typically not submerged (Douben, 2006). This phenomenon arises primarily from water accumulation due to intense precipitation events. The magnitude and frequency of river flooding are significantly influenced by land-use changes. For example, urbanization and the expansion of impervious surfaces reduce water infiltration, thereby exacerbating flood risk. Conversely, afforestation enhances infiltration capacity, helping to mitigate flood hazards.

Various methodological guidelines and strategies use different terminology to describe this variable or disturbance, including flood regime (Oosterlynck *et al.*, 2020), occasional flooding (Janssen *et al.*, 2014), flood risk (Valladares *et al.*, 2017), flood peaks (Kumar *et al.*, 2021), time delay to flood peak (Kumar *et al.*, 2021), and flood frequency (Spray *et al.*, 2022).

Table 22 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product allows for the quantification of this variable. In this context, it is worth mentioning the Global Flood Monitoring (GFM) products developed by the Copernicus Emergency Management Service (CEMS) using Sentinel-1 data. GFM products include 11 flood-related products, such as the observed flood extent, the observed water extent and the reference water mask.

Table 23 lists all remote sensing–derived flood that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures
YES	YES	NO	YES	NO	YES	YES

Table 22. Policy directives, strategies, and monitoring approaches that require or reference floods. YES | NO

Remote sensing-derived products	Source
Hydrologic model[16]	Precipitation data
Daily Precipitation Analysis[16]	

Table 23. Remote sensing-derived floods indicators and their data sources, as established in scientific literature. [16]Gao et al., 2017.

3.1.2.5 Droughts

Drought is characterized as a prolonged period of significantly reduced precipitation relative to the long-term climatic average for a given region. Standardized indices—such as thresholds based on three consecutive months with precipitation below 10% of historical records (Bond *et al.*, 2008)—are commonly used to quantify drought severity. The increasing frequency of drought events across many regions has profound hydrological consequences, including reduced groundwater recharge and diminished surface water availability in lakes, rivers, and associated riparian systems, ultimately leading to widespread water scarcity.

A review of relevant directives, strategies, methodological guidelines, and monitoring frameworks reveals varied terminology used to describe this variable or disturbance, including the Standardized Precipitation Index (SPI) and the Effective Drought Index (EDI) (Pignalosa *et al.*, 2023).

Table 24 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 25 evaluates the applicability of key CLMS products in assessing this variable.

Table 26 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures
NO	YES	NO	NO	NO	YES	NO

Table 24. Policy directives, strategies, and monitoring approaches that require or reference droughts. YES | NO

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
NDVI	

Table 25. *Applicability of CLMS products for defining and quantifying droughts.*

Remote sensing-derived products	Source
Forest:	Sentinel-2 Data
Canopy fluorescence yield[17]	Land Use
Forest Drought Response Index[18]	ERA5-Land monthly average dataGlobal fluorescence dataset GOSIF
Forest Vulnerability Index[19]	SPEIbase
River:	Precipitation data
Optimized Meteorological Drought Index (OMDI)[20]	Temperature data
Standardised Precipitation index (SPI-3, 12 and 24)[21]	Evapotranspiration
Humidity Index in soil (iHI and iH-3) [21]	Soil moisture
Standardised Normalised Difference Vegetation Index (iNDVI and iNDVI-6)[21]	Climate Hazards Center InfraRed Precipitation with Station data
Modified Palmer Drought Severity Index (PDSI)[21][22]	Advanced Microwave Scanning
Water Deficit Drought Index (WDDI) [23]	Radiometer
Standardized River Stage Index (SRSI) [24]	Satellite altimetry data

Table 26. *Remote sensing-derived drought indicators and references. Links to data sources. [17]Ma et al., 2022 [18]Tadesse et al., 2020 [19]Mildrexler et al., 2016 [20]Wei et al., 2021 [21]Ortega-Gómez et al., 2018 [22]Paredes-Trejo et al., 2022 [23]Han et al., 2022 [24]Zhong et al., 2022.*

3.1.3.Species composition

Species composition is a comprehensive ecological indicator that reflects both the identity and abundance of species within a community. This parameter encompasses species that signal poor ecological status (such as invasive species) as well as those indicative of good conservation status. The relative proportions and presence of these different groups provide critical insights into overall ecosystem condition.

3.1.3.1 Biodiversity

Biodiversity represents a comprehensive ecological concept encompassing multiple dimensions of biological variation. At its fundamental level, it describes the variety of living organisms within an ecosystem and their ecological complexes.

Given its multidimensional nature, methodological frameworks across various policy directives employ distinct terminology to describe specific aspects of biodiversity. For instance, different guidelines reference terms as sum of abundances (Bathe, 2010), vascular plant richness (Lara *et al.*, 2019), fern abundance (Lara *et al.*, 2019), humid forest species association (Janssen *et al.*, 2014), Shannon index (Pignalosa *et al.*, 2023) or functional group diversity (Pignalosa *et al.*, 2023).

Table 27 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 28 evaluates the applicability of key CLMS products in assessing this variable.

Table 29 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 27. Policy directives, strategies, and monitoring approaches that require or reference biodiversity. **YES** | **NO**

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
Tree Cover Density NDVI	

Table 28. *Applicability of CLMS products for defining and quantifying biodiversity.*

Remote sensing-derived products	Source
Height (Standard deviation of height)[25]	LiDAR (Spain)
Canopy cover[25]	LiDAR (Europe)
Canopy height density in different height ranges[25]	Sentinel-2 Data
Near infrared (NIR)[26][27]	
NDVI[27]	
Physiological reflectance adjusted index (PRI) [27]	
Anthocyanin reflectance adjusted index (ARI) [27]	
EVI[28]	

Table 29. *Remote sensing-derived biodiversity indicators and references. Links to data sources. [25]Guo et al., 2017; [26]Medeiros et al., 2019; [27]Wallis et al., 2016; [28]Waring et al., 2006.*

3.1.3.2 Naturalness of species composition

Naturalness is a key component of species composition and refers to the degree to which a habitat remains uninfluenced or unaltered by human activities (Machado, 2004). Although the concept can be challenging to define precisely, it is often operationalized through the distinction between allochthonous and autochthonous species within a given habitat. In this context, a higher degree of naturalness implies a lower level of anthropogenic disturbance, as evidenced by a species composition that reflects minimal human influence.

This concept has been integrated into various directives, strategies, and methodological frameworks using different terminology. Examples include the number of native species (Munné *et al.*, 2003), the naturalness of tree species composition (Evans & Arvela, 2011), the origin of forest stands (*i.e.*, natural regeneration vs. plantation forests) (Directorate-General for Environment, 2023), and the broader notion of landscape naturalness (Vallecillo *et al.*, 2022).

Table 30 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 31 evaluates the applicability of key CLMS products in assessing this variable.

Table 32 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 30. Policy directives, strategies, and monitoring approaches that require or reference the naturalness of the specific composition.

YES | NO

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
Tree Cover Density	

Table 31. *Applicability of CLMS products for defining and quantifying the naturalness of the specific composition.*

Remote sensing-derived products	Source
LiDAR derived height parameters (Hmean, Hsd, Hkurt, Hskew)[29] Coefficient of variation of echoes > 2m (Hcv) [29] Canopy density (density of echoes > 50% of the 95th percentile height to the total number of echoes) [29]	LiDAR (Spain) LiDAR (Europe)

Table 32. *Remote sensing-derived naturalness of the specific composition indicators and references. Links to data sources. [29]Ørka et al. 2022*

3.1.2.3 Indicator species of degraded or regressive ecological stages

This concept, closely linked to naturalness, pertains to the presence of exotic, ubiquitous, or disturbance-associated species, which often signal habitat degradation. A higher abundance of such allochthonous species suggests reduced naturalness and greater anthropogenic disturbance.

Various methodological guidelines, strategies, and directives have operationalized this concept through distinct metrics, such as proportion of ubiquitous or undemanding species (Bathe, 2010), cover of nitrophilous taxa (indicative of disturbance) (Lara *et al.*, 2019), presence of alien species (Evans & Arvela, 2011), percentage cover of alien species (BfN & BLAK, 2017), and invasive tree species in arboreal formations (Ley 42/2007 del Patrimonio Natural y de la Biodiversidad).

Table 33 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 34 evaluates the applicability of key CLMS products in assessing this variable.

Table 35 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 33. Policy directives, strategies, and monitoring approaches that require or reference the indicator species of regressive stages.

YES | NO

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
NDVI	

***Table 34.** Applicability of CLMS products for defining and quantifying the indicator species of regressive stages.*

Remote sensing-derived products	Source
Light intensity reaching the forest understory[30] Elevation[31] Precipitation[31] Slope (steepness and exposure) [31] Annual potential insolation (API) [31] Compound topographic index (CTI) [31] Overstory plant species map[31] Spectral bands (Red edge 1 (RE1), 2 (RE2) and 3 (RE3), Short-wave infrared 1 (SWIR-1) and 2 (SWIR-2), Near infrared 1(NIR1) and 2 (NIR2)) [32]Spectral indices (Chlorophyll Red-Edge (Chlred-edge), Visible Atmospherically Resistant Indices Red Edge (VARI-rededge), Normalized Difference 819/1649 (NDII2), Canopy Chlorophyll Content Index (CCCI), Carotenoid reflectance index 700 (CRI700), Normalized Difference 819/1600 (NDII), Modified Chlorophyll Absorption in Reflectance Index divided by the Optimized Soil Adjusted Vegetation Index (MCARI/OSAVI) and Normalized Difference NIR/Rededge Normalized Difference Red-Edge (NDRE))[32] Most suitable specific spectral band[33][34] NDVI[33][35] Canopy reflectance[36] Leaf and canopy water content[36] Pigment-related absorption features (reflectance derivatives)[36] Orthophotos[37] Δ pre-NDVI (NDVI pre flowering − NDVI blooming)[38] Δ pre-BR ((blue - red)/(blue + red) pre flowering) - ((blue - red)/(blue + red) blooming)) [38] Δ pre-RG (((red - green)/(red + green) pre flowering) - ((red - green)/(red + green) blooming)) [38] Δ BR-post ((blue - red)/(blue + red) blooming) - ((blue - red)/(blue + red) post flowering)) [38] Δ RG-post (((red - green)/(red + green) blooming) - ((red - green)/(red + green) post flowering)) [38] Soil Adjusted Vegetation Index (SAVI) [39] Perpendicular Vegetation Index-3 in the optimum bio window[39]	LiDAR (Spain) LiDAR (Europe) Precipitation data Digital Elevation Model (Spain) Digital Elevation Model (Europe) Sentinel-2 Data Orthophotos (Spain)

***Table 35.** Remote sensing-derived indicators for indicator species of regressive stages and references. Links to data sources. [30]Joshi et al., 2006; [31]Pouteau et al., 2011; [32]Masemola et al., 2020; [33]NG et al., 2016; [34]Taylor et al., 2013; [35]Liu et al., 2020; [36]Asner et al., 2008a; [37]Somodi et al., 2012; [38]Domingo et al., 2023; [39]Kandwal et al., 2009.*

3.1.3.4 Good status indicator species

In contrast to indicator species of regressive stages, this metric encompasses taxa associated with well-preserved habitat conditions. Such species may serve as bioindicators due to their association with mature successional stages, their rarity or conservation value, or their sensitivity to disturbance, where their presence reflects minimal anthropogenic impact. These organisms collectively function as positive indicators of habitat integrity, signalling high ecological quality and stability.

This concept has been integrated into various directives, strategies, and methodological frameworks using different terminology. Examples include occurrence of rare and threatened taxa (Bathe, 2010), Grass cover (BfN & BLAK, 2017), key species in the shrub and tree strata (Janssen *et al.*, 2014), or populations of protected species (Shah *et al.*, 2020).

Table 36 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product allows for the quantification of this variable.

Table 37 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 36. *Policy directives, strategies, and monitoring approaches that require or reference the good status indicator species.* **YES** | **NO**

Remote sensing-derived products	Source
Single tree detection with WorldView-2 images[40]	Worldview-2 data

Table 37. *Remote sensing-derived indicators for good status indicator species and references. Links to data sources. [40]Riedler et al., 2015.*

3.1.4 Age of canopy

Forest structure is a fundamental attribute of ecosystem condition, with structural complexity serving as a key metric for assessment. One critical aspect of this complexity is canopy age, a parameter that not only reflects the current state of the canopy and its associated biodiversity but also provides insights into future developmental trajectories (Vilén *et al.*, 2012). Additionally, deviations in age distribution can reveal past disturbances within the habitat.

Canopy age is closely linked to structural complexity and can be inferred from dasometric parameters such as tree height and diameter at breast height (DBH). Analysing these variables allows for the characterization of age-class distributions within the stand. A balanced representation of both older and younger age classes indicates successful recruitment alongside habitat maturity, the latter evidenced by the presence of well-developed individuals. Such a distribution suggests ecological continuity and structural integrity, which are hallmarks of a healthy forest ecosystem.

3.1.4.1 Stand age

The presence of a heterogeneous age structure, comprising stands at various developmental stages, serves as a fundamental indicator of undisturbed primary forest conditions. Since direct age determination requires intensive sampling, forest ecologists typically estimate stand age through correlated dasometric parameters such as DBH and canopy height. Importantly, this age mosaic must include both young and mature stands to maintain ecological functions, as their coexistence supports higher biodiversity and reflects proper successional dynamics in healthy forest ecosystems (Kuuluvainen & Gauthier, 2018).

Various methodological guidelines and strategies employ differing terminology to describe this variable, such as age diversity (González del Tánago & García de Jalón, 2011), stages of forest development (BfN & BLAK, 2017), part of the old-growth forest (Janssen *et al.*, 2014), number of smaller and larger stands of major forest species (Ley 42/2007 del Patrimonio Natural y de la Biodiversidad) or percentage of uneven-aged forest (Vallecillo *et al.*, 2022).

Table 38 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 39 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 38. Policy directives, strategies, and monitoring approaches that require or reference stand age.

YES | NO

Remote sensing-derived products	Source
LiDAR derived height parameters[41][42][43][44][45]	LiDAR (Spain)
Crown closure between certain ranges of height[45]	LiDAR (Europe)
Tasseled Cap transformation brightness (TCB), greenness (TCG), wetness (TCW), angle (TCA) and distance (TCD)[46]	Sentinel-2 Data
Number of years since greatest change[46]	Digital Elevation Model (Spain)
Attributed change type[46]	Digital Elevation Model (Europe)
Topographic wetness index (TWI)[45][46]	Sentinel-1
Topographic solar radiation index (TSRI)[46]	
Elevation[46]	
Slope[46]	
Texture (Mean intensity, Signal-to-noise value, First order variance, Kurtosis, First order entropy and Second order contrast)[47]	

Table 39. Remote sensing-derived stand age indicators and references. Links to data sources. [41]Lin et al., 2023; [42]Racine e al., 2014; [43]Yang et al., 2020; [44]Schumacher et al., 2020; [45]Wylie et al., 2019; [46]Matasci et al., 2018; [47]Champion et al., 2008.

3.1.4.2 Regeneration

Natural regeneration refers to the autogenic reestablishment of native forest species in disturbed or abandoned areas through ecological succession processes, such as post-fire recovery. While fundamentally a spontaneous ecological phenomenon, natural regeneration can be facilitated through anthropogenic interventions including grazing management and fire suppression measures to enhance recovery trajectories (Crouzeilles *et al.*, 2017).

Various methodological guidelines and strategies employ differing terminology to describe this variable, such as natural regeneration of woody species (González del Tánago & García de Jalón, 2011), seedling density (Angelini *et al.*, 2016) or afforestation rate (Shah *et al.*, 2020).

Table 40 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 41 evaluates the applicability of key CLMS products in assessing this variable.

Table 42 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 40. Policy directives, strategies, and monitoring approaches that require or reference regeneration. YES | NO

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
NDVI	

Table 41. *Applicability of CLMS products for defining and quantifying regeneration.*

Remote sensing-derived products	Source
Difference between the NDVI and NBR indices[48]	Landsat data
Forest Recovery Index (FRI)[49][50]	Sentinel-2 data
Fraction of Vegetation Cover (FVC)[49][50]	LiDAR (Spain)
Indices derived from NDVI: Half recovery time (HRT), Recovery trend index (RTI) and Cumulative Relative Recovery Index (CRRI)[51]	LiDAR (Europe)
Elevation metrics derived from the Digital Terrain Model (DTM)[52]	
Vegetation cover derived from LiDAR[52]	
NDVI[[52]	
Landsat Structural index[53]	
Landsat Bands[54]	

Table 42. *Remote sensing-derived regeneration indicators and references. Links to data sources. [48]Nioti et al., 2015; [49]Chu et al., 2017; [50] Chu et al., 2016; [51]Torres et al., 2018; [52]Míguez & Fernández, 2023; [53]Fiorella & Ripple, 1995; [54]Aguilar, 2005.*

3.1.4.3 Successional stages

Successional stages represent distinct phases of forest development characterized by temporal changes in community structure and composition, typically initiated by disturbance events. Canopy structural characteristics serve as fundamental diagnostic criteria for identifying these successional phases and evaluating ecological status (Chazdon *et al.*, 2009).

Table 43 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 44 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures
NO	YES	NO	NO	NO	YES	NO

Table 43. Policy directives, strategies, and monitoring approaches that require or reference successional stages. YES | NO

Remote sensing-derived products	Source
Lorey's height (based on Skewness of Heights, Kurtosis of Heights, 90th height percentile and 6th height decile)[55][56]	LiDAR (Spain)
Gray Level occurrence measures (GLCM) (Contrast, Variance, Mean and Dissimilarity)[55]	LiDAR (Europe)
Shadow fraction[55]	Land Use Land Cover
Normalized Difference Moisture Index (NDMI)[57]	Sentinel-2 data
Moisture stress index (MSI)[57]	
Inverse Minimum Noise Fraction (MNF) transformed bands[57]	
Tasselled cap transformation brightness (TCB) and wetness (TCW)[58]	

Table 44. *Remote sensing-derived successional stages indicators and references. Links to data sources. [55]Zhang et al., 2017b; [56]Bispo et al., 2019; [57]Qi et al., 2013; [58]Boonprong et al., 2018.*

3.1.5 Land Uses

Land use and land cover (LULC) mapping has emerged as a critical tool in environmental monitoring, particularly for assessing fluvial ecosystem health. Anthropogenic land use changes represent one of the most significant drivers of ecosystem alteration (Martínez & Mollicone, 2012), directly influencing hydrological regimes, sediment transport, and riparian habitat quality. The systematic analysis of LULC patterns provides essential baseline data for identifying critical transition zones affecting fluvial processes and establishing spatially explicit indicators of ecosystem condition.

3.1.5.1 Protected areas of community interest

Protected areas have long been established to safeguard natural habitats, species, and ecological processes, delivering critical ecosystem services such as biodiversity conservation, watershed protection, and carbon sequestration. In the European Union, the Natura 2000 network serves as the cornerstone of nature and biodiversity policy, encompassing 27,312 terrestrial and marine sites across the 28 EU Member States. As of the latest assessment, these sites cover 1,147,956 km^2 (18.12% of EU land area) (Zisenis, 2017). Member States are required to submit periodic reports every six years on the status of protected species and habitats within their respective biogeographical regions.

Due to the range of protection tools that exist and the wide variety of terms that can be used to refer to this concept, this was designated in the different legislative and methodological frameworks in distinct ways. Some of them were the presence of habitats of Directive 92/43/EEC (MITECO, 2019), protected areas (%) (Shah et al., 2020), forest area (%) in Protected Natural Areas and/or Natura 2000 Network or Protected Natural Areas by IUCN category (Ley 42/2007 del Patrimonio Natural y de la Biodiversidad).

Table 45 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 46 evaluates the applicability of key CLMS products in assessing this variable.

We found no remote sensing–derived products (different from CLMS products) useful for characterizing this variable in the literature.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures
YES	YES	NO	YES	YES	YES	NO

Table 45. *Policy directives, strategies, and monitoring approaches that require or reference protected areas of community interest.* **YES** | **NO**

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
Natura 2000	

Table 46. *Applicability of CLMS products for defining and quantifying protected areas of community interest.*

3.1.5.2 Land Use/ Land Cover

Land cover refers to the observable physical coverage of the Earth's surface, whereas land use denotes the anthropogenic utilization of land resources (Jansen & Di Gregorio, 2003). Although these concepts are inter-related, they are not identical.

Both land use and land cover, whether considered jointly or separately, have been incorporated into various methodologies for reporting under environmental directives and frameworks. These classifications have been described using differing terminologies, including land use within a 5-meter riparian buffer (Environment Agency, 2003), soil categories (*e.g.*, natural, cultivated, or ploughed) (Evans & Arvela, 2011), and forest land designation by use (Ley 42/2007 del Patrimonio Natural y de la Biodiversidad).

Table 47 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 48 We found no remote sensing–derived products (different from CLMS products) useful for characterizing this variable in the literature.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures
YES	YES	NO	YES	YES	YES	NO

Table 47. *Policy directives, strategies, and monitoring approaches that require or reference land use / land cover*

YES | NO

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
Tree Cover Density	Riparian Zones Land Use/ Land Cover
Imperviousness	Small woody Features
	Corine Land Cover

Table 48. *Applicability of CLMS products for defining and quantifying land use / land cover.*

3.1.5.3 Vegetation cover on the riverbank

Vegetation cover refers to the percentage of ground surface covered by green plant foliage when viewed vertically (Gao *et al.*, 2020). This parameter provides essential information for characterizing spatial vegetation patterns and detecting temporal changes in plant distribution, making it a widely used indicator for monitoring ecosystem dynamics and assessing habitat quality. Due to its responsiveness to environmental changes, vegetation cover serves as a fundamental metric in ecosystem status evaluations.

This variable was referred to in several sources, using different terms to refer to it, such as percentage of vegetation cover (Munné *et al.*, 2023), dimensions of land with riparian vegetation (González del Tánago & García de Jalón, 2011), space occupied by the vegetation type in a standard band along the riverbanks (Lara *et al.*, 2019) o cover of woody species (Pignalosa *et al.*, 2023).

Table 49 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 50 evaluates the applicability of key CLMS products in assessing this variable.

Table 51 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 49. Policy directives, strategies, and monitoring approaches that require or reference vegetation cover on the riverbank. **YES** | **NO**

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
Tree Cover Density	Riparian Zones Land Use/ Land Cover
Imperviousness	Small woody Features
NDVI	Corine Land Cover

Table 50. *Applicability of CLMS products for defining and quantifying vegetation cover on the riverbank.*

Remote sensing-derived products	Source
MODIS product Vegetation Continuous Fields[59]	MODIS

Table 51. *Remote sensing-derived vegetation cover on the riverbank indicators and references. Links to data sources. [59]Huete et al., 2012.*

3.1.6 Forest mensuration

Forest mensuration parameters, particularly those related to tree canopy structure, play a fundamental role in assessing the ecological status of forest habitats. National Forest Inventories have systematically collected stand-level data for decades, monitoring both individual tree attributes (*e.g.*, physical dimensions) and aggregate stand characteristics (Magnuson *et al.*, 2024). These measurements form the basis for quantifying forest structure and serve as primary indicators for evaluating ecosystem condition at broader scales.

3.1.6.1 Height

Canopy height serves as a critical indicator of aboveground biomass and carbon storage, while also reflecting structural heterogeneity within forest ecosystems (Lang *et al.*, 2023). Despite its widespread use, the global drivers of canopy height distribution remain incompletely understood; while water availability is a well-established influence, the role of other environmental factors requires further investigation (Tao *et al.*, 2016).

Although conceptually straightforward, canopy height encompasses multiple measurement approaches, leading to varied terminology across guidelines, including formation height (mode) (Lara *et al.*, 2019), mean canopy height (Angelini *et al.*, 2016) or large tree metrics (Directorate-General for Environment, 2023).

Table 52 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 53 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures
NO	YES	YES	NO	NO	YES	NO

Table 52. *Policy directives, strategies, and monitoring approaches that require or reference vegetation height.* YES | NO

Remote sensing-derived products	Source
Canopy height characteristics derived from LiDAR[60][61][62][63][64][65]	LiDAR (Spain)
Canopy cover fraction[60][66]	LiDAR (Europe)
Difference in years between sampling and LiDAR data collection date[60]	Digital Surface Model (Spain)
Digital Surface Model (DSM)[67][68]	Digital Elevation Model (Spain)
Digital Elevation Model (DEM)[67]	Digital Elevation Model (Europe)
Spectral bands (SWIR1, Red, Green)[69]	Sentinel-2 data
Spectral bands combination (NIR/Green, SWIR1/Red, SWIR2/NIR, SWIR1/Green, Red/Green, SWIR1/Green, SWIR2/SWIR1 and SWIR2/Red) [69]	
GSAVI (Green Soil Adjusted Vegetation Index) [69]	
NDII (Normalized Difference Infrared Index) [69]	
Distance of the beginning signal and ground peaks[70]	

Table 53. *Remote sensing-derived vegetation height indicators and references. Links to data sources. [60]Vayreda et al., 2019; [61]Bohlin et al., 2021; [62]Kotivuori et al., 2016; [63]Næsset, 2002 [64]Watt et al., 2013; [65]Ma et al., 2012; [66]Liu et al., 2019; [67]Lee et al., 2020; [68]Windisch et al., 2014; [69] Staben et al., 2018; [70]Yang et al., 2020.*

3.1.6.2 Vertical complexity

Canopy vertical complexity, defined by height variation and stratification (Wang *et al.*, 2023), serves as a critical indicator of forest ecological condition. This structural attribute directly influences canopy architecture, tree growth patterns, and understory community composition (Latha *et al.*, 1998). Vertical stratification dynamics reflect ecological processes including competitive exclusion, gap formation through mortality, regeneration establishment, and disturbance regimes such as fire events.

Various methodological guidelines and strategies employ differing terminology to describe this variable, such as connection between strata (MITECO, 2019), complexity of the vertical structure of the community (Lara *et al.*, 2019) or gradient with previous vegetation (usually shrublands) (Janssen *et al.*, 2014).

Table 54 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 55 evaluates the applicability of key CLMS products in assessing this variable.

Table 56 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures
YES	YES	YES	NO	NO	NO	NO

Table 54. *Policy directives, strategies, and monitoring approaches that require or reference vertical complexity.* YES | NO

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
NDVI	

Table 55. *Applicability of CLMS products for defining and quantifying vertical complexity.*

Remote sensing-derived products	Source
Digital Surface Model (DSM)[71][72]	Digital Surface Model (Spain)
RGB image[72]	Sentinel-1
Digital Terrain Model (DTM)[72]	Sentinel-2 data
Foliage Height Diversity (FHD)[73]	Digital Terrain Model (Spain)
Effective number of layers (NoLs)[73]	LiDAR (Spain)
Sentinel-1 VV and VH backscatter coefficients[74]	LiDAR (Europe)
Surface reflectance of Sentinel-2 bands[74]	
LiDAR derived height parameters[75][76]	
Sentinel-2 indices: NDVI, NDWI1, NDWI2, NDre1, NDre2[77]	
CA texture maps[77]	

Table 56. *Remote sensing-derived regeneration indicators and references. Links to data sources. [48]Nioti et al., 2015; [49]Chu et al., 2017; [50] Chu et al., 2016; [51]Torres et al., 2018; [52]Míguez & Fernández, 2023; [53]Fiorella & Ripple, 1995; [54]Aguilar, 2005.*

3.1.6.3 Deadwood

Historically, dead wood was viewed negatively as a sign of neglected forest management and a potential source of pests (Merganičová *et al.*, 2012). However, it is now recognized as a fundamental component of forest ecosystems, providing critical habitat for numerous species, such as fungi, saproxylic beetles, and birds, and thus strongly influencing biodiversity (Seidling *et al.*, 2014). As a key structural element alongside living trees, dead wood is particularly linked to mature, unmanaged forests, making its presence a valuable indicator of favourable ecosystem condition.

This variable was referred to in several sources after checking the methodological guidelines and strategies taken into account on this work, using different terms to refer to this variable, such as amount of dead wood, age of dead wood (Evans & Arvela, 2011), presence of scattered dead trees (Janssen *et al.*, 2014) or ratio of the volume of dead wood to total wood in tree formations (Ley 42/2007 del Patrimonio Natural y de la Biodiversidad).

Table 57 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 58 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures
YES	YES	YES	NO	YES	NO	NO

Table 57. *Policy directives, strategies, and monitoring approaches that require or reference deadwood.* YES | NO

Remote sensing-derived products	Source
Dead wood Potential (DWP)[78]	Sentinel-2 data
Blue[79]	LiDAR (Spain)
Hue[79]	LiDAR (Europe)
Saturation[79]	
Height[79]	
Spectral bands combinations (Red to all band ratio and Blue Infrared Ratio)[79]	
Blue Infrared Ratio (B/I)[79]	
NDVI[79][80]	
Red-green index[80]	
LiDAR derived percentiles of height[81]	
Height metrics derived from LiDAR[81][82]	
NPV (Non-photosynthetic vegetation)[83]	

Table 58. *Remote sensing-derived deadwood indicators and references. Links to data sources. [78]Forsius et al., 2021; [79]Zielewska-Büttner et al., 2020; [80]Hart & Veblen, 2015; [81]Bater et al., 2009; [82]Pesonen et al., 2008; [83]Asner et al., 2008b.*

3.1.4.4 Stand density

Density, in its general definition, refers to the number of individuals per unit area. In forestry, stand density specifically describes tree density, though it may also incorporate other metrics such as basal area or volume (Curtis, 1970). This parameter reflects local forest conditions, quantifying tree competition for growth within constrained space (Chivhenge *et al.*, 2024). While stand density is positively linked to certain ecological processes (*e.g.*, carbon flux and productivity), it can adversely affect others, such as understory vegetation heterogeneity (Hausle *et al.*, 2023). Despite these contrasting effects on habitat assessment, it remains a key indicator for characterizing forest stands.

Various methodological guidelines and strategies employ differing terminology to describe this variable, such as presence/abundance of trees with large trunks (Lara *et al.*, 2019), number of stands per hectare (BfN & BLAK, 2017), density (Kettenhuber *et al.*, 2023) or number of smaller and larger stands of the main forest species (Ley 42/2007 del Patrimonio Natural y de la Biodiversidad).

Table 59 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 60 evaluates the applicability of key CLMS products in assessing this variable.

Table 61 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures
YES	YES	YES	NO	YES	YES	NO

Table 59. Policy directives, strategies, and monitoring approaches that require or reference stand density. YES | NO

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
Tree Cover Density	

Table 60. *Applicability of Copernicus products for defining and quantifying stand density.*

Remote sensing-derived products	Source
Fractional vegetation coverage[84]	Sentinel-2 data
Summing the segments that contained the centroid within the sample plot[85]	LiDAR (Spain)
Number of trees using the Digital Surface Model for the individual tree count[86]	LiDAR (Europe)
SWIR-1[87]	Digital Surface Model (Spain)

Table 61. *Remote sensing-derived stand density indicators and references. Links to data sources. [84]Zhang et al., 2022; [85]Lisiewicz et al., 2022; [86]Albuquerque et al., 2021; [87]Chrysafis et al., 2017.*

3.1.4.5 Diameter

In forest inventories and stand characterization, diameter is one of the most fundamental parameters, alongside tree height. These two measures are closely related and are often used jointly in allometric operations, such as biomass estimation (Gehring *et al.*, 2008). Diameter is typically measured at breast height (~1.30 m), a standard known as diameter at breast height (DBH). This metric serves as a key input for calculating tree volume (Gering & May, 1995), but its importance extends beyond individual trees. The distribution of diameter classes across a stand provides critical insights into canopy structure, underscoring diameter's role as a key indicator.

Various methodological guidelines, strategies, and directives have operationalized this concept through distinct metrics, such as mean tree trunk diameter (Lara *et al.*, 2019), amount of thick wood (diameter greater than 40 cm) (Oosterlynck *et al.*, 2020) or number of diametric classes (Pignalosa *et al.*, 2023).

Table 62 summarizes the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 63 evaluates the applicability of key CLMS products in assessing this variable.

Table 64 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 62. Policy directives, strategies, and monitoring approaches that require or reference tree diameter. YES | NO

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
NDVI	

Table 63. *Applicability of Copernicus products for defining and quantifying tree diameter.*

Remote sensing-derived products	Source
Canopy cover fraction[88]	LiDAR (Spain)
Difference in years between sampling and LiDAR data collection date[88]	LiDAR (Europe)
Height metrics derived from LiDAR[88][89][90][91][92]	
Crown Projection Area (CPA)[90]	

Table 64. *Remote sensing-derived tree diameter indicators and references. Links to data sources. [88]Vayreda et al., 2019; [89]Dalponte et al., 2011; [90]Fu et al., 2017; [91]Rosette et al., 2011; [92]Parker & Mitchel, 2005.*

3.1.4.6 Biomass

Biomass, typically referring to plant biomass, represents the total weight or number of organisms per unit area or volume. As a key ecological indicator, it reflects ecosystem status, carbon dynamics (release or sequestration), and the impacts of natural disturbances or forest succession (Tian *et al.*, 2023). Many countries monitor biomass stocks through National Forest Inventories, particularly to inform climate change policies and carbon emission/removal assessments (Avitabile & Camia, 2018).

Various methodological guidelines and strategies employ differing terminology to describe this variable, such as carbon stocks (Valladares *et al.*, 2017), carbon storage and sequestration in vegetation (Raymond *et al.*, 2017) or aboveground tree biomass (Pignalosa *et al.*, 2023).

Table 65 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 66 evaluates the applicability of key CLMS products in assessing this variable.

Table 67 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 65. *Policy directives, strategies, and monitoring approaches that require or reference biomass.* YES | NO

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
Tree Cover Density NDVI LAI	

Table 66. *Applicability of Copernicus products for defining and quantifying biomass.*

Remote sensing-derived products	Source
Difference in years between sampling and LiDAR data collection date[93] Height metrics derived from LiDAR[93][94][95][96][97] Canopy cover fraction[93][98] Maximal Stand density index (SDIsmax)[95] Aboveground volume-weighted mean wood density (WDsAGV)[95] Leaf Area Index (LAI)[97][98] Fraction of Absorbed Photosynthetically Active Radiation (FPAR)[98] Chlorophyll content in the leaf (Cab)[98] Texture characteristics of Sentinel-1[98] Temperature data (annual mean temperature and greater than 0- accumulated temperature data)[99] Mean rainfall data (PA)[99] Digital Elevation Model (DEM)[99] Slope data (ASP)[99][99] Perpendicular Vegetation Index (PVI)[99][99] Ratio vegetation index (RVI)[99][99]Soil Adjusted Ratio Vegetation Index (SARVI)[99][99] Transformative Soil adjusted ratio vegetation index (TSAVI)[99][99] Fractional cover[99][99]NDVI[99][100][101][102] Simple Ratio (SR)[101] Soil Adjusted Vegetation Index (SAVI)[101] ICR[102] Green[102] SWIR-2[103][104] Textural measure image developed from spectral SWIR-2 (B7_W5_ME)[103] VH (backscatter coefficients for polarizations VH of Sentinel-1B)[100] VV (backscatter coefficients for polarizations VV of Sentinel-1B)[100] Canopy Chlorophyll Content (LAIcb) and Canopy Water Content (LAIcw)[104] Chlorophyll index calculated using red-edge bands (Clre)[104] SWIR Band[104] Entropy measure derived from the summer NDVI[104] Pigment Specific Simple Ratio (PSSR)[105] Near Infrared Band[105] NDI45[106] Enhanced Vegetation Index (EVI)[106] Red[107] Sentinel band textures (contrast, correlation, variance, entropy and second moment)[107] Normalized Difference Water Index (NDWI)[108]	LiDAR (Spain) LiDAR (Europe)

Table 67. *Remote sensing-derived* biomass *indicators and references. Links to data sources. [93]Vayreda et al., 2019; [94]Tian et al., 2012; [95]Knapp et al., 2020; [96]Clark et al., 2011; [97]Xi et al., 2016; [98]Chen et al., 2018; [99]Diao et al., 2016; [100]Norovsuren et al., 2019; [101]Macedo et al., 2018; [102] López-Serrano et al., 2021; [103]Yu et al., 2019; [104]Molisse et al., 2022; [105]Bulut et al., 2022; [106]Nuthammachot et al., 2018; [107]Li et al., 2020; [108] Imran et al., 2021.*

3.1.7 Habitat condition

Habitat condition reflects the degree of degradation caused by anthropogenic disturbances compared to the natural condition (Harwood *et al.*, 2016). This parameter integrates indicators of riparian habitat quality, size and width, serving as a broad measure of ecological status. In essence, it functions as a composite of variables that collectively define a habitat's overall status.

3.1.7.1 Habitat quality

Habitat quality reflects the structural and functional conditions necessary for a habitat's long-term sustainability and the survival of its species (Riedler *et al.*, 2015). This parameter inherently encompasses other key factors used to assess the ecological status of riparian habitats.

Various methodological guidelines and strategies employ differing terminology to describe this variable, such as habitat quality (Valladares *et al.*, 2017), ecological quality of vegetation (Pugliese *et al.*, 2022) or conservation status of habitats of Community interest (Ley 42/2007 del Patrimonio Natural y de la Biodiversidad).

Table 68 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 69 evaluates the applicability of key CLMS products in assessing this variable.

Table 70 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 68. *Policy directives, strategies, and monitoring approaches that require or reference habitat quality.* YES | NO

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
Tree Cover Density	

Table 69. *Policy directives, strategies, and monitoring approaches that require or reference habitat quality.*

Remote sensing-derived products	Source
Riparian Forest Composite indicator[109] Tree cover[110]	Digital Surface Model (Spain) WorldView-2 data Sentinel-2 data LiDAR (Spain) LiDAR (Europe)

Table 70. *Remote sensing-derived habitat quality indicators and references. Links to data sources. [109]Riedler et al., 2015; [110]Li et al., 2021.*

3.1.7.2 Habitat width

Riparian vegetation width is a critical indicator of ecological status, as it directly influences habitat functionality (Sweeney & Newbold, 2014). An adequate width protects river ecosystems by reducing sediment input and enhancing water quality (Wenger, 1999). It also supports biodiversity by providing breeding grounds for birds and serving as essential migratory corridors (Fischer & Theriot, 2000). For these reasons, riparian width is a fundamental measure of habitat condition, ensuring the health of both the forest and the adjacent river.

Various methodological guidelines and strategies employ differing terminology to describe this variable, such as functional vegetation width (Rinaldi *et al.*, 2012) or vegetation buffer width (Burdon *et al.*, 2020).

Table 71 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 72 evaluates the applicability of key CLMS products in assessing this variable.

Table 73 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures
YES	NO	NO	NO	NO	YES	NO

Table 71. Policy directives, strategies, and monitoring approaches that require or reference habitat width. **YES** | **NO**

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
Riparian Zones Land Use/ Land Cover Small woody Features Corine Land Cover Tree Cover Density	

Table 72. *Policy directives, strategies, and monitoring approaches that require or reference habitat width.*

Remote sensing-derived products	Source
Using the riparian forest patch detection process[111]	LiDAR (Spain) LiDAR (Europe)

Table 73. *Remote sensing-derived habitat* width *indicators and references. Links to data sources.* [111]*Michez et al., 2013.*

3.1.7.3 Habitat size

Habitat size is a critical variable for assessing ecological status, as it directly influences riparian forest functionality. While width is important, a minimum habitat area is also necessary to effectively filter pollutants, sustain biodiversity (Marczak *et al.*, 2010), and maintain connectivity for species migration (Rojas *et al.*, 2024). The required size varies depending on the species and ecological functions involved. Like habitat width, size is therefore a key indicator of overall habitat condition.

Various methodological guidelines, strategies, and directives have operationalized this concept through distinct metrics, such as minimum structure of 10 ha (Oosterlynck *et al.*, 2020) or forest area per formation (Ley 42/2007 del Patrimonio Natural y de la Biodiversidad).

Table 74 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 75 evaluates the applicability of key CLMS products in assessing this variable.

Table 76 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 74. *Policy directives, strategies, and monitoring approaches that require or reference habitat size.* YES | NO

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
Riparian Zones Land Use/ Land Cover Small woody Features Corine Land Cover Tree Cover Density	

Table 75. *Policy directives, strategies, and monitoring approaches that require or reference habitat width.*

Remote sensing-derived products	Source
Processing satellite images to get landscape metrics[112][113]	Sentinel-2 data
Fragstats landscape metrics[114]	Fragstats
Land cover[115]	Land Use Land Cover

Table 76. *Remote sensing-derived habitat size indicators and references. Links to data sources. [112]Gudmann et al., 2020; [113]Appiah & Agyemang-Duah, 2021; [114]Walker et al., 2019; [115]Amarnath et al., 2003.*

3.1.8 River morphology

River morphology refers to the shape and structure of river channels and it is a fundamental indicator of ecological status, integrating complex bio-physical interactions. As a dynamic system, a river's specific morphological pattern, whether straight, meandering, or braided (Xin *et al.*, 2018), is not only shaped by the underlying geology but is also actively modified by the stabilizing influence of its riparian vegetation (Corenblit *et al.*, 2024). This interplay between the physical template and biological agents creates a distinct morphology (Tadaki *et al.*, 2014) that ultimately determines the habitat condition, making it a power tool to measure the ecosystem's overall state.

3.1.8.1 River flow

Hydrological regimes are fundamental to the structural and functional integrity of riverine ecosystems. As a primary driver of physical habitat conditions, flow influences essential processes such as sediment transport, nutrient cycling, and dissolved oxygen concentrations (Warren *et al.*, 2015). Consequently, flow regimes are a principal determinant of aquatic species distribution and community structure (Poff *et al.*, 1997). Alterations to natural flow patterns disrupt these processes, leading to significant shifts in both abiotic conditions and the associated native biota, thereby determining the overall ecological status of the fluvial landscape.

This variable was referred to in several sources, using different terms to refer to this variable, such as flow type (Environment Agency, 2003), water flow connectivity (Regierung des Fürstentums Liechtenstein, 2019), natural/disturbed hydrology (Evans & Arvela, 2011), maximum flow (Pignalosa *et al.*, 2023 or river water level above and below a certain threshold (Shah *et al.*, 2020).

Table 77 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 78 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures
YES	YES	NO	YES	NO	YES	NO

Table 77. Policy directives, strategies, and monitoring approaches that require or reference river flow. **YES** | **NO**

Remote sensing-derived products	Source
Width related parameters[116][117]	Digital Elevation Model (Spain)
Convert the drainage areas to discharges (from a DEM)[118]	Digital Elevation Model (Europe)
At-many-stations hydraulic geometry (AMHG)[119]	Sentinel-2 data
Correlation between observed discharge and the ratio of a land pixel for calibration (C) and a water pixel for measurement (M) (C/M Method)[120]	Sentinel-1
SWOT (Surface Water and Ocean Topography) VM (Virtual Mission) measurements[121]	Surface Water and Ocean Topography (SWOT)
Remote Sensing Hydrological Station[122]	

Table 78. *Remote sensing-derived river flow indicators and references. Links to data sources. [116]Gaurav et al., 2021; [117]Sun et al., 2010; [118]Biron et al., 2013; [119]Gleason et al., 2014; [120]Shi et al., 2022; [121]Durand et al. 2010 [122]Lou et al., 2022.*

3.1.8.2 Vegetation

The presence and composition of in-channel vegetation is critical to riverbed morphological stability. Vegetation alters flow resistance and turbulence, thereby acting as a key control on sediment dynamics (Crouzy *et al.*, 2013). Conversely, the establishment of this vegetation is itself regulated by hydrological forces (*e.g.*, scour during flooding) and the prevailing substrate conditions (Afzalimehr *et al.*, 2019). Given its central role in this feedback loop with geomorphic processes, vegetation is a key indicator of overall fluvial landscape ecological status.

Various methodological guidelines and strategies employ differing terminology to describe this variable, such as vegetation choking the river, causing impediment to flow (Environment Agency, 2003) or vegetation and organic debris in the riverbed (Vode, 2023).

Table 79 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 80 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 79. *Policy directives, strategies, and monitoring approaches that require or reference vegetation in the river.* YES | NO

Remote sensing-derived products	Source
NGAI (near-infrared (NIR)-Green Angle Index)[123]	IKONOS data

Table 80. *Remote sensing-derived indicators of in-channel vegetation and references. Links to data sources.* [123] *Tian et al., 2010.*

3.1.8.3 Channel features

The morphological characteristics of a river channel are vital indicators of its overall condition, as attributes such as width and sinuosity directly regulate critical processes like erosion (Turowsky, 2018). As a result, any alteration to these attributes disrupts these processes, thereby impairing fundamental river function. Furthermore, such modifications, including the construction of dykes or channelization, can elevate flooding risks (Lóczy *et al.*, 2009). Therefore, the preservation of natural channel characteristics is crucial not only for maintaining functional river systems but also for achieving good ecological status.

This variable was referred to in several sources, using different terms to refer to it, such as channel bed structure (Rinaldi *et al.*, 2012), cross-sectional variability (Rinaldi *et al.*, 2012), channel shape and sinuosity (Vidal *et al.*, 2021) or channel width (Vidal *et al.*, 2021).

Table 81 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 82 lists all remote sensing-derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 81. Table 74. *Policy directives, strategies, and monitoring approaches that require or reference channel features.* YES | NO

Remote sensing-derived products	Source
Channel width:	Sentinel-1
Bank-to-bank width at the cross section[124]	Digital Elevation Model (Spain)
Separate water and dry pixels from Sentinel-1 images[125]	Digital Elevation Model (Europe)
Digital Elevation Model (DEM)[126][127]	Sentinel-2 data
By algorithm that progressively increased the centerline from the raw DEM until thresholds of elevation differences and slopes were reached[128]	Landsat data
Distance between bank edges perpendicular to the centerline[129][130]	LiDAR (Spain)
Modified Normalized Difference Water Index (MNDWI)[129]	LiDAR (Europe)
Measured at bankfull (bank to bank) using Cartesian coordinate method in ArcGIS[131]	Surface Water and Ocean Topography (SWOT)
Sinuosity:	
Sinuosity Index (SI)[129][132][133]	
Accurate delineation of a channel centerline[130]	
Channel Sinuosity (S)[134][135]	
Ratio of the linear distance (D) to the actual river length (I)[127]	
Channel slope:	
Centreline extracted from the raw LiDAR DEM[136]	
SWOT (Surface Water and Ocean Topography) VM (Virtual Mission) measurements[137]	
River depth:	
SWOT (Surface Water and Ocean Topography) VM (Virtual Mission) measurements[137]	

Table 82. *Remote sensing-derived channel features indicators and references. Links to data sources. [124]Bhuiyan & Kumamoto, 2015; [125]Gaurav et al., 2020; [126]Eidmann & Gallen, 2023; [127]Shi et al., 2022; [128]Biron et al., 2013; [129]Clavijo-Rivera et al., 2023; [130] Fisher et al., 2013; [131]Ibitoye, 2021; [132]Saikia et al., 2023; [133]Gugliotta et al. 2019 [134]Manjare et al., 2021; [135]Bhatt et al., 2007; [136]Biron et al., 2013; [137]Durand et al., 2009.*

3.1.8.4 Typical structures

Through sediment transport, flow, and the resulting erosion and deposition, rivers form distinct geomorphic structures within their channels or in the floodplains. These features, such as riffle-pool sequences, bars, and rills, constitute unique and key habitats for aquatic biota (Belletti *et al.*, 2017). The presence of these structures, particularly rhythmic riffle-pool sequences which create heterogeneity in flow velocity and substrate size, is frequently indicative of a dynamic equilibrium within the river system and is thus associated with a good ecological status (Emery *et al.*, 2004).

Various methodological guidelines and strategies employ differing terminology to describe this variable, such as presence of typical fluvial forms in the floodplain (Rinaldi *et al.*, 2012), number of riffles, pools and point bars (Environment Agency, 2003), number of gravel bars (Pugliese *et al.*, 2022) or rills and channels (Burdon *et al.*, 2020)

Table 83 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 84 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 83. *Policy directives, strategies, and monitoring approaches that require or reference typical river structures.* **YES** | **NO**

Remote sensing-derived products	Source
Rill:	Orthophotos (Spain)
Photointerpretation of stereoscopic satellite images[138]	LiDAR (Spain)
Aerial photographs[139]	LiDAR (Europe)
Rills depth estimated using two moving mean filters[139]	Sentinel-1
Visual interpretation of differences in coloration, tonality, texture, and shape[140]	Sentinel-2 data
Riffles:	WorldView-2 data
Width related parameters[141]	
Influenced channel slope and wood abundance[141]	
Bars:	
Mask product of water and land[142]	
Surface reflectance[142]	
Sentinel-1 contour lines[143]	
Modified Normalized Difference Water Index (MNDWI)[144]	
Near-Infrared band (NIR)[145]	

Table 84. *Remote sensing-derived features indicators of typical river structures and references. Links to data sources. [138]Fiorucci et al., 2015; [139]Regmi et al., 2019; [140]Ríos et al., 2020; [141]Pfeiffer & Finnegan, 2017; [142]Wang & Xu, 2015 [143]Kryniecka et al., 2022; [144]Wang et al., 2018; [145]Wang & Xu, 2018.*

3.1.9 Phenology

The International Biological Program working group defined phenology as “the study of the timing of recurrent biological events, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species” (Lieth, 2013) While this term is often used in the context of discrete annual events, its scope also encompasses continuous biological changes over time (Badeck *et al.*, 2004). This concept generally refers to the phenology of vegetation, a factor that serves as an indicator of ecological status.

3.1.9.1 Phenology

Plant phenology serves as a key indicator for assessing the impact of climatic conditions, particularly under varying precipitation and temperature scenarios (Wang *et al.*, 2021). Furthermore, its sensitivity to extreme events makes it a valuable tool for detecting ecosystem alteration, thereby providing critical insight into ecological status.

Table 85 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 86 evaluates the applicability of key CLMS products in assessing this variable.

Table 87 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 85. Table 50. *Policy directives, strategies, and monitoring approaches that require or reference phenology.* YES | NO

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
Plant Phenology Index FAPAR LAI	NDVI Seasonal Trajectories

Table 86. Table 51. *Policy directives, strategies, and monitoring approaches that require or reference phenology.*

Remote sensing-derived products	Source
Enhanced vegetation index (EVI) time series (to measure SOS and EOS)[146][147][148][149] Normalized Difference Vegetation Index (NDVI) time series (to measure SOS and EOS)[148][150] Phenology Index (PI) (a combination between NDVI and NDII) (to measure SOS and EOS)[148] MERIS Terrestrial Chlorophyll Index (MTCI) time series (to measure SOS and EOS)[148] EVI2 (two bands EVI (without the blue band)) time series (to measure SOS and EOS)[148] Normalized Difference Water Index (NDWI) time series (to measure SOS and EOS)[148] Length of season (LOS) (Based on EVI time series)[149] Amplitude (AMPL) (Based on EVI time series)[149] Leaf Area Index (LAI) time series (to measure SOS and EOS)[148][151] Growing Season Index (GSI)[151] Maximum temperature (close relation to senescence)[152] Start of foliage season (SFS) (based on NDVI time series)[152] Maximum of foliage season (MFS) (based on NDVI time series)[152] Optimal foliage/leaf senescence (OFS) (based on NDVI time series)[152] End of foliage season (EFS) (based on NDVI time series)[152] Length of foliage season (LFS) (based on NDVI time series)[152]	Sentinel-2 data Vegetation seasonal trajectories Temperature data Daily radiation

Table 87. *Remote sensing-derived phenology indicators and references. Links to data sources. [146]Xin et al., 2020; [147]Peng et al., 2018; [148]Caparros-Santiago et al., 2021; [149]Medeiros et al., 2022; [150]Li et al., 2022; [151]Stöckli et al., 2008; [152]Prabakar et al., 2023.*

3.1.10. Functions

Ecosystem functions refer to the intrinsic properties of ecosystems that facilitate the provision of goods and services for human benefit (Hölting et al., 2019). These benefits can be thematic, ranging from provisioning and regulating to cultural services. Consequently, these functions are fundamental to nature-based solutions, which utilize the study of these ecosystem goods to advance conservation and restoration efforts.

3.1.10.1 Shading of the active watercourse

Summer water temperature is a critical habitat determinant for many aquatic species, such as salmon, particularly as elevated temperatures reduce dissolved oxygen levels (Beschta, 1997). Riparian forest buffers perform a key regulatory function by shading the active watercourse and reducing solar radiation incidence on the riverbed (Ghermandi *et al.*, 2009). This mitigation of thermal stress directly improves habitat quality for temperature-sensitive species, safeguarding them both from thermal extremes and associated oxygen deprivation.

Table 88 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

Table 89 evaluates the applicability of key CLMS products in assessing this variable.

Table 90 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 88. *Policy directives, strategies, and monitoring approaches that require or reference the function of shading of the active watercourse.*

YES | NO

Products that may offer useful information for this variable, but require additional data for accurate assessment	Products that offer useful information for this variable
LAI	

Table 89. *Policy directives, strategies, and monitoring approaches that require or reference the function of shading of the active watercourse.*

Remote sensing-derived products	Source
Leaf Area Index (LAI)[153]	LiDAR (Spain)
Mean Manning roughness coefficient[153]	LiDAR (Europe)
Land cover[154]	Land Cover
Digital Surface Model (DSM) of first returns (including vegetation)[154]	Sentinel-2 data
Canopy height model (via LiDAR)[155]	Digital Surface Model (Spain)

Table 90. *Remote sensing-derived indicators for shading of the active watercourse and references. Links to data sources. [153]Kałuza et al., 2020; [154]Bolick et al., 2021; [155]Bachiller-Jareno et al., 2019.*

3.1.10.2 Erosion reduction

Deforestation and anthropogenic activities accelerate riverbank erosion, leading to excessive sediment deposition in riverbeds (Broadmeadow & Nisbet, 2004). Riparian forest buffers mitigate this process by stabilizing banks with their root systems, which reduces and regulates sediment transport into the watercourse (Hughes, 2016). Therefore, riparian restoration is a critical management strategy for erosion control. This practice enhances overall ecological status by concurrently protecting terrestrial ecosystems from soil loss and aquatic ecosystems from sedimentation.

Table 91 summarises the relevant Directives, Strategies, and monitoring approaches that either dictate or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

We found no remote sensing–derived products useful for characterizing this variable in the literature.

Waterº framework Directive	Directive Habitats Directive	Biodiversity Strategy for 2030	Floods Directive	Spanish Law on Natural Heritage and Biodiversity	Nature-based solutions	Blue and Green Infrastructures

Table 91. *Policy directives, strategies, and monitoring approaches that require or reference the function of erosion reduction.* YES | NO

3.2 Water indicators

3.2.1 Solids

Solids, encompassing all organic and inorganic matter, whether dissolved or suspended, is a key water quality parameter linked to pollution and turbidity. Urbanization strongly influences these parameters, as increased runoff delivers higher loads of impurities to river sections (Ciupa & Suligowski, 2020). Consequently, the concentration of solids serves as a direct indicator of anthropogenic pressure and a reflection of the overall pollution burden affecting the ecological status of aquatic habitats.

3.2.1.1 Total suspended solids

While suspended solids occur naturally in watercourses, elevated concentrations, often resulting from anthropogenic disturbances like domestic or industrial wastewater, degrade habitat quality (Bilotta & Brazier, 2008; Zhang *et al.*, 2017a). This increase has wide-ranging effects, altering physical conditions (*e.g.*, light penetration) and chemical parameters (*e.g.*, by transporting heavy metals) (Bilotta & Brazier, 2008). These physicochemical alterations directly impact aquatic biota, with taxon-specific effects that collectively diminish water quality and the ecosystem health.

Table 92 summarises the relevant Directives, Strategies, and monitoring approaches that either dictate or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 93 lists all remote sensing–derived products identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive

Table 92. *Policy directives, strategies, and monitoring approaches that require or reference the total suspended solids.* **YES** | **NO**

Remote sensing-derived products	Source
Spectral bands (Blue, Coastal blue, Green, Red, NIR)[156][157][158][159][160][161][162]	Sentinel-2 data

Table 93. *Remote sensing-derived indicators of total suspended solids indicators and references. [156]Unpublished, Freshwater ecosystem department - IH Cantabria; [157]Das et al., 2022a; [158]Abbas et al., 2019; [159]Japitana & Burce, 2019; [160]Zahra & Hussain, 2020; [161]Lobo et al., 2015; [162]Adjovu et al., 2023.*

3.2.1.2 Total dissolved solids

Total Dissolved Solids (TDS) occur naturally in watercourses, with concentrations influenced by geology, atmospheric deposition, and the evaporation-precipitation balance (Scanell & Jacobs, 2001). However, anomalously high levels are a clear indicator of anthropogenic influence (O'Connor, 1976). Common constituents include sulphate, nitrates, and cations such as calcium, sodium, magnesium, and potassium (World Health Organisation, 2003). While not directly toxic, elevated TDS increases turbidity, reduces light penetration, and subsequently impairs photosynthetic activity, thereby degrading the overall ecological status of aquatic ecosystems (Rohaningsih & Aisyah, 2023).

Waterº framework Directive	Directive Habitats Directive

__Table 94.__ Policy directives, strategies, and monitoring approaches that require or reference the total dissolved solids. YES | NO

Table 94 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 95 Table 98 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Remote sensing-derived products	Source
Remote sensing-derived indicators of total dissolved solids and references. [163]Abbas et al., 2019; [164]Al-Jassani et al., 2022; [165]Japitana & Burce, 2019.	Sentinel-2 data

__Table 95.__ Remote sensing-derived indicators of total suspended solids indicators and references. [156]Unpublished, Freshwater ecosystem department - IH Cantabria; [157]Das et al., 2022a; [158]Abbas et al., 2019; [159]Japitana & Burce, 2019; [160]Zahra & Hussain, 2020; [161]Lobo et al., 2015; [162]Adjovu et al., 2023.

3.2.1.3 Turbidity

As a measure of light attenuation, turbidity serves as a fundamental parameter for assessing aquatic habitat status by directly regulating photosynthesis and phytoplankton community structure (Davies-Colley & Smith, 2001). Elevated turbidity results from higher loads of suspended sediments, which are frequently mobilized by heavy rainfall. Intense precipitation events, especially in tropical zones susceptible to typhoons, can cause sharp, impactful degradations in water clarity (Lee *et al.*, 2016). This relationship is further exacerbated during flood conditions, which dramatically increase sediment influx (Göransson *et al.*, 2013).

Table 96 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 97 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive

Table 96. *Policy directives, strategies, and monitoring approaches that require or reference turbidity.* YES | NO

Remote sensing-derived products	Source
Spectral bands (Green, Red, Blue, NIR, TIRS)[166][167][168] Spectral bands ratio(Coastal aerosol/Red, Blue/Red, NIR/Blue)[168][169] Normalised Difference Turbidity Index (NDTI)[170]	Sentinel-2 data

Table 97. *Remote sensing-derived turbidity indicators and references. [166]Hossain et al., 2021; [167]Japitana & Burce, 2019; [168]Najafzadeh & Basirian, 2023 [169]Sharma et al., 2019; [170]Das et al., 2022a.*

3.2.2 Nutrients

Closely linked to solid variables, elevated nutrient concentrations represent another major impact on riparian habitats, typically resulting from anthropogenic pollution. Nutrient enrichment is among the most significant causes of degraded river quality, triggering cascading effects such as oxygen depletion and uncontrolled algal blooms (Poikane *et al.*, 2021).

3.2.2.1 Nitrate

Nitrate pollution, largely originating from agricultural fertilisers, is one of the most pressing water quality issues in Europe. Although regulatory measures like the Nitrates Directive have achieved some progress in reducing concentrations, further action is urgently needed (Bouraoui & Grizzetti, 2011). High nitrate concentrations impair ecosystem health at multiple scales; they degrade riverine habitats and, upon reaching the sea, act as a primary driver of eutrophication and harmful algal blooms (Zhang *et al.*, 2021).

Table 98 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 99 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive

Table 98. *Policy directives, strategies, and monitoring approaches that require or reference nitrate concentration.* **YES** | **NO**

Remote sensing-derived products	Source
Spectral bands(Blue, Green, Red, SWIR1)[171][172] Spectral bands ratio(SWIR1/NIR)[171] Satellite bands combination((SWIR2 – NIR)/(SWIR2 + NIR))[173]	Sentinel-2 data

Table 99. *Remote sensing-derived nitrate concentration indicators and references. [171]Najafzadeh & Basirian, 2023; [172]Abbas et al., 2021; [173] Huang et al., 2016.*

3.2.2.2 Sulphate

High concentrations of sulphate can promote eutrophication through complex redox reactions, mirroring the impact of nitrate (Ekholm *et al.*, 2020). A primary anthropogenic source for both ions is agricultural fertiliser application (Kopáček *et al.*, 2014). Beyond its role in nutrient enrichment, high sulphate levels are directly harmful to aquatic biota, serve as an indicator of water acidification (Stoddard *et al.*, 1999), and ultimately contribute to the degradation of waterbody condition.

Table 100 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 101 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive

Table 100. *Policy directives, strategies, and monitoring approaches that require or reference sulphate concentration.* YES | NO

Remote sensing-derived products	Source
Spectral bands ratio (TIRS/Green, TIRS/Red, Red/Green)[174][175] Spectral bands (Blue, SWIR1)[175]	Sentinel-2 data

Table 101. *Remote sensing-derived sulphate concentration indicators and references. [174]Al-Jassani et al., 2022; [175]Najafzadeh & Basirian, 2023.*

3.2.2.3 Dissolved organic matter

Naturally present and functionally critical, dissolved organic matter (DOM) derived from terrestrial and biological debris supports fundamental chemical and biological processes in rivers (Spencer *et al.*, 2012; Yu *et al.*, 2015). Anthropogenic activities, however, can lead to supra-natural concentrations, particularly in urban watersheds receiving effluent from wastewater treatment plants and sewer overflows (Tang *et al.*, 2019). Such enrichment degrades aquatic habitat quality by altering the carbon cycle (Feng *et al.*, 2022) and enhancing the mobility and transport of heavy metal contaminants (Liang *et al.*, 2023).

Waterº framework Directive	Directive Habitats Directive

Table 102. *Policy directives, strategies, and monitoring approaches that require or reference dissolved organic matter.* YES | NO

Table 102 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 103 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Remote sensing-derived products	Source
Spectral bands ratio(NIR/Green, Blue/Green[176] Spectral bands (Red, NIR)[176][177]	Sentinel-2 data

Table 103. *Remote sensing-derived dissolved organic matter indicators and references. [176]Abbas et al., 2021; [177]Slonecker et al., 2016.*

3.2.3 Temperature

Water temperature of streams is highly sensitive to climate and other factors of change (Hannah & Garner, 2015). Due to climate change, typical patterns of this variable are changing, which has an impact on aquatic ecosystems, their biodiversity and their overall ecological status (Van Vliet *et al.*, 2013).

3.2.3.1 Temperature

Water temperature is a highly sensitive and integrative measure of aquatic health, directly governing the distribution, metabolism, and survival of aquatic species (Hannah & Garner, 2015). It also exerts an indirect yet critical influence by regulating dissolved oxygen concentrations. Consequently, thermal regimes are a key determinant of habitat viability. This is exemplified by salmonid species, for whom targeted temperature management is a primary focus of conservation and recovery efforts (Bartholow, 2005).

Table 104 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 105 lists all remote sensing–derived products that have been identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive

Table 104. *Policy directives, strategies, and monitoring approaches that require or reference water temperature.* **YES** | **NO**

Remote sensing-derived products	Source
Brightness temperatures[178]	Sentinel-2 data
Atmospherically corrected brightness[179]	
Spectral bands ratio(Coastal aerosol/Red, Blue/Red)[180]	
Level-2 Provisional Surface Temperature (pST) estimates derived from satellite data[181]	
Temperature metrics estimated using satellite data	
Top of Atmosphere (TOA) spectral radiance	

Table 105. *Remote sensing-derived water temperature indicators and references.[178]Abbas et al., 2019; [179]Das et al., 2022a; [180]Sharma et al., 2019; [181]Baughman & Conaway, 2021; [182]Tavares et al., 2020; [183]Das et al., 2022b.*

3.2.4 Oxygen

The concentration of dissolved oxygen serves as a vital indicator of ecological status due to its absolute necessity for the survival of aquatic organisms (Kannel *et al.*, 2007). Consequently, the maintenance of oxygen within ranges that support biological viability is synonymous with good ecosystem conservation.

3.2.4.1 General oxygenation conditions

Oxygenation conditions serve as a fundamental indicator of river health due to their prevalent influence on chemical processes, nutrient dynamics, and the spatial distribution of aquatic organisms (Riđanović *et al.*, 2010). A primary regulator of dissolved oxygen is water temperature, which controls its solubility; elevated temperatures can depress oxygen levels to a point of deficiency (Mariolakis *et al.*, 2006), jeopardizing survival of oxygen-sensitive biota. Progression to anoxic conditions represents a severe state of degradation, resulting in fish mortality and a pronounced decline in water quality, including the development of noxious odours (Cox, 2003).

Waterº framework Directive	Directive Habitats Directive

Table 106. *Policy directives, strategies, and monitoring approaches that require or reference general oxygenation conditions.* **YES** | **NO**

Table 106 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 107 Table 110 lists all remote sensing-derived products identified as useful for characterizing this variable in at least one published source.

Remote sensing-derived products	Source
Spectral bands(Green, Red, Vegetation Red Edge)[184]	Sentinel-2 data

Table 107. *Remote sensing-derived indicators of general oxygenation condition and references. [184]Unpublished, Freshwater ecosystem department - IH Cantabria.*

3.2.4.2 Chemical oxygen demand

As a standard measure of water quality, chemical oxygen demand (COD) quantifies the amount of oxygen necessary to chemically oxidize organic and oxidizable inorganic matter in a water sample (Kamarudin *et al.*, 2020). It provides a critical estimate of organic pollutant load by representing the oxygen needed to oxidize discharged materials (Prambudy *et al.*, 2019), where higher COD values indicate greater organic pollution and poorer water quality. An elevated COD signifies an imbalance between oxygen-consuming processes and oxygen-producing photosynthesis, which can deplete dissolved oxygen to levels inadequate for sustaining ecosystem balance (Haider & Haydar, 2013).

Table 108 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 109 lists all remote sensing–derived products identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive

Table 108. *Policy directives, strategies, and monitoring approaches that require or reference chemical oxygen demand.* YES | NO

Remote sensing-derived products	Source
Spectral bands (Green, Red, Blue)[185][186]	Sentinel-2 data
Spectral bands ratio (Blue/Coastal Aerosol)[185]	
Band 2 of wavelet fusion of 432 Landsat-8 image and Sentinel-2 band 2[186]	

Table 109. *Remote sensing-derived chemical oxygen demand indicators and references.[185]Sharma et al., 2019; [186]Rangzan et al., 2020.*

3.2.4.3 Biological oxygen demand

Biological oxygen demand (BOD), also known as biochemical oxygen demand (Dogan *et al.*, 2009), measures the oxygen required for microbial oxidation of organic matter, in contrast to chemical oxygen demand (COD), which encompasses both organic and inorganic compounds. Alongside COD, BOD is a key indicator of water quality, as it reflects the organic load in aquatic systems derived from wastewater or effluents (Prambudy *et al.*, 2019). Elevated BOD values suggest excessive organic inputs, which may lead to oxygen depletion and ultimately anoxic conditions (Ahmed, 2017), negatively affecting aquatic fauna.

Table 110 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 111 Table 114 lists all remote sensing–derived products identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive

Table 110. *Policy directives, strategies, and monitoring approaches that require or reference biological oxygen demand.* **YES** | **NO**

Remote sensing-derived products	Source
Spectral bands (Red, Coastal Aerosol)[187][188]	Sentinel-2 data
Spectral bands ratio (Coastal Aerosol/Blue)[187]	Landsat data
Band 2 of Gram-Schmidt transform (GST) of 432 Landsat-8 image and Sentinel-2 band 2[189]	

Table 111. *Remote sensing-derived biological oxygen demand indicators and references. [187]Sharma et al., 2019; [188]Japitana & Burce, 2019; [189] Rangzan et al., 2020.*

3.2.4.4 Dissolved oxygen

Dissolved oxygen (DO) is a fundamental water quality parameter widely used to assess the impact of industrial effluents on river ecosystems (Kannel *et al.*, 2007). As DO is essential for aquatic organism survival, it exerts a primary control over species distribution, metabolism, and overall community structure (Cox, 2003). Consequently, low DO concentrations directly reduce biodiversity and degrade ecological quality. Ultimately, DO dynamics reflect the equilibrium between oxygen-consuming processes, such as respiration and chemical oxidation, and oxygenating photosynthesis where a disruption of this balance results in fundamental changes to ecosystem integrity (Ahmed, 2017).

Table 112 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 113 lists all remote sensing–derived products identified as useful for characterizing this variable in at least one published source

Waterº framework Directive	Directive Habitats Directive

Table 112. *Policy directives, strategies, and monitoring approaches that require or reference dissolved oxygen.* **YES** | **NO**

Remote sensing-derived products	Source
Spectral bands (Coastal aerosol, Blue, Green, NIR, Red, Red edge1, Red edge 3)[190][191][192]	Sentinel-2 data
Spectral bands ratio(Coastal aerosol/Red, Blue/Red)[193]	Landsat data
Band 1 of Intensity–hue–saturation transform (IHS) of 432 Landsat-8 image and Sentinel-2 band 2[194]	
Band 3 of cross-fusion of Intensity-hue-saturation (IHS) output and Gram–Schmidt transform (GST) band 2 based on IHS transform[194]	

Table 113. *Remote sensing-derived dissolved oxygen indicators and references.[190]Das et al., 2022a; [191]Japitana & Burce, 2019;[192]Abbas et al., 2019; [193]Sharma et al., 2019; [194]Rangzan et al., 2020.*

3.2.5 Other water properties

Aquatic fauna exhibits high sensitivity to a suite of physicochemical parameters beyond those previously discussed, solidifying their role as robust indicators of ecosystem health (Hassan *et al.*, 2009). Variables such as pH, alkalinity, salinity, and water hardness are particularly significant. They are fundamental to both ecological function, governing species distribution and water quality, and to public health, as they are essential criteria for assessing potable water quality (Jain *et al.*, 2022).

3.2.5.1 Alkalinity

Alkalinity, a measure of water's capacity to neutralize acids, is determined by the concentration of ions from dissolved mineral salts (Jain *et al.*, 2022). Its value as an ecological indicator lies in quantifying a river's sensitivity to acidic pollutants from wastewater and acid rain (Islam & Majumder, 2020). Although natural alkalinity depends on geology, human activities such as effluent discharge and agricultural runoff drastically alter it by introducing carbonate and bicarbonate ions (Tappin *et al.*, 2018). For this reason, alkalinity is an effective integrator of anthropogenic influence, and its measurement provides critical insight into water quality and ecosystem health (Gbarakoro *et al.*, 2020).

Table 114 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 115 lists all remote sensing–derived products identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive

Table 114. *Policy directives, strategies, and monitoring approaches that require or reference alkalinity.* **YES** | **NO**

Remote sensing-derived products	Source
Spectral bands ratio (Green/SWIR 2, Red/Coastal aerosol, Red/Blue, TIRS2/Red)[195][196][197] Satellite bands combination ((TIRS2-Blue)/(TIRS2+Blue), (TIRS2- Coastal aerosol)/(TIRS2 + Coastal aerosol))[197]	Sentinel-2 data

Table 115. *Remote sensing-derived alkalinity indicators and references.[195] Al-Jassani et al., 2022; [196]Sharma et al., 2019 ; [197]Najafzadeh & Basirian, 2023.*

3.2.5.2 Total hardness

Total hardness is a key water quality parameter defined by the presence of alkaline earth metals, primarily calcium and magnesium, whose combined concentration is used for its calculation (Majeed *et al.*, 2022; Oliveira-Filho *et al.*, 2014). It is correlated with total dissolved solids (Jain *et al.*, 2022) and serves as an ecological regulator by buffering the detergent and soaps effluents and modulating the toxicity of heavy metals to aquatic organisms (Pyle *et al.*, 2022; Kiyani *et al.*, 2013). Furthermore, deviations from optimal ranges, whether too low or too high, adversely affect the life cycle development of aquatic biota (Kim *et al.*, 2015; Majeed *et al.*, 2022).

Table 116 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 117 lists all remote sensing–derived products identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive

Table 116. *Policy directives, strategies, and monitoring approaches that require or reference total hardness.* YES | NO

Remote sensing-derived products	Source
Spectral bands ratio(Coastal aerosol/Red, Red/Coastal aerosol, Coastal aerosol/Panchromatic, Red/Green)[198][199][200]	Sentinel-2 data
Spectral bands (Coastal aerosol, Red)[198][199]	

Table 117. *Remote sensing-derived total hardness indicators references. [198]Al-Jassani et al., 2022; [199]Sharma et al., 2019 ; [200]Najafzadeh & Basirian, 2023.*

3.2.5.3 Salinity

Salinity, a measure of ionic concentration in water and a broader concept than total dissolved solids (Majeed *et al.*, 2022), is a critical determinant of ecological status. River salinization is a global issue that degrades water quality and reduces biodiversity in riparian ecosystems (Estévez *et al.*, 2019). While naturally influenced by geology, particularly in headwaters where ions are released from rocks and soils (Kaczmarek *et al.*, 2023), salinity is ultimately governed by multiple factors including river flow, rainfall, and sea-level rise (Vineis *et al.*, 2011). Generally measured in parts per thousand (ppt), it strongly regulates faunal distribution, where higher concentrations typically decrease species richness, with taxon-specific tolerance dictating community composition (Arle & Wagner, 2013; Majeed *et al.*, 2022).

Table 118 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 119 lists all remote sensing–derived products identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive

Table 118. *Policy directives, strategies, and monitoring approaches that require or reference salinity.* **YES** | **NO**

Remote sensing-derived products	Source
Spectral bands(Coastal Aerosol, Blue, Green)[201]	Sentinel-2 data

Table 119. *Remote sensing-derived salinity indicators and references. [201]Ansari & Akhoondzadeh, 2020.*

3.2.5.4 pH

The pH of water, measured as the negative log of hydrogen ion activity, indicates its acidic or basic character (Majeed *et al.*, 2022). Values near 7 are neutral, characteristic of pure water (Jain *et al.*, 2022). Although subject to natural variation, pH is significantly altered by human activities, particularly through effluent discharges that shift values beyond natural ranges (Majeed *et al.*, 2022). Industrial emissions like nitrogen oxides acidify rivers via atmospheric deposition and runoff (Mant *et al.*, 2013). Such shifts in pH serve as a key indicator of ecological impairment, frequently reducing reproductive success and recruitment in aquatic biota rather than causing immediate mortality, ultimately leading to declining fish populations and loss of biodiversity (Baldigo & Lawrence, 2001).

Table 120 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 121 lists all remote sensing-derived products identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive

Table 120. *Policy directives, strategies, and monitoring approaches that require or reference pH.* **YES** | **NO**

Remote sensing-derived products	Source
Spectral bands (Red, Red Edge 2, Red Edge 3, NIR, Blue, TIRS2)[202][203][204][205] Spectral bands ratio (Coastal Aerosol/NIR, Coastal Aerosol/Blue, Red/Coastal Aerosol)[206][207][208]	Sentinel-2 data

Table 121. *Remote sensing-derived pH indicators and references. [202]Das et al., 2022a; [203]Najafzadeh & Basirian, 2023; [204]Abbas et al., 2019; [205]Abbas et al., 2021; [206]Japitana & Burce, 2019; [207]Al-Jassani et al., 2022; [208]Sharma et al., 2019.*

3.2.6 Pollution

Anthropogenic drivers, namely industrialisation and urbanisation, intensify pollution pressures on rivers by increasing loads of domestic and industrial waste (Xu *et al.*, 2022). Pollution serves as an integrative indicator of ecological status, encapsulating the combined effects of numerous parameters—including turbidity, dissolved organic matter, and pH. Comprehensive monitoring of these combined metrics is therefore critical for evaluating and maintaining the ecological condition of river systems (Sharma *et al.*, 2022).

3.2.6.1 Pollution

As an integrative indicator, river pollution encompasses multiple contaminant types, including chemical, biological, and thermal, that collectively degrade water quality. While affecting water suitability for humans (Qu & Fan, 2010), its most immediate consequence is environmental harm, severely disrupting habitat conditions and jeopardizing aquatic biodiversity. The use of multi-metric indices to quantify pollution enables effective monitoring of ecological trends, supports targeted pollution mitigation, and facilitates management actions aimed at restoring ecosystem integrity (Son *et al.*, 2020).

Table 122 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 123 Table 126 lists all remote sensing-derived products identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive

Table 122. *Policy directives, strategies, and monitoring approaches that require or reference pollution.* YES | NO

Remote sensing-derived products	Source
Spectral bands (Water vapour, Blue, Green, Red)[209]	Sentinel-2 data

Table 123. *Remote sensing-derived pollution indicators and references. [209]Unpublished, Freshwater Ecosystems Group - IH Cantabria.*

3.2.6.2 Eutrophication

Eutrophication represents one of the most significant ecological disturbances affecting aquatic ecosystems. This process is driven by excessive nutrient enrichment, primarily nitrogen and phosphorus, originating predominantly from anthropogenic sources such as agricultural fertilizers and wastewater discharges (Nijboer & Verdonschot, 2004). The resultant nutrient loading severely alters aquatic biodiversity and ecosystem function, notably through oxygen depletion and degradation of water quality (Monteagudo *et al.*, 2012).

Various methodological guidelines and strategies employ differing terminology to describe this variable/ disturbance, such as eutrophication and eutrophication indicators (BfN & BLAK, 2017) or exceedance of critical eutrophication loads (Vallecillo *et al.*, 2022).

Table 124 summarises the relevant directives, strategies, and monitoring approaches that require or reference the use of this variable.

The assessment reveals that no current CLMS product enables the quantification of this variable.

Table 125 lists all remote sensing–derived products identified as useful for characterizing this variable in at least one published source.

Waterº framework Directive	Directive Habitats Directive

Table 124. *Policy directives, strategies, and monitoring approaches that require or reference pollution.* YES | NO

Remote sensing-derived products	Source
Total nitrogen concentration (with Huan Jing-1 satellite bands combination)[210]	
Chl-a concentration (with SABI and NDWI)[211][212]	
Total phycocyanin (with R705 and R665)[213]	

Table 125. *Remote sensing-derived pollution indicators and references. [210]Huang et al., 2016; [211]Fedonenko et al., 2022; [212]Wu et al., 2020; [213] Pérez-González et al., 2023.*

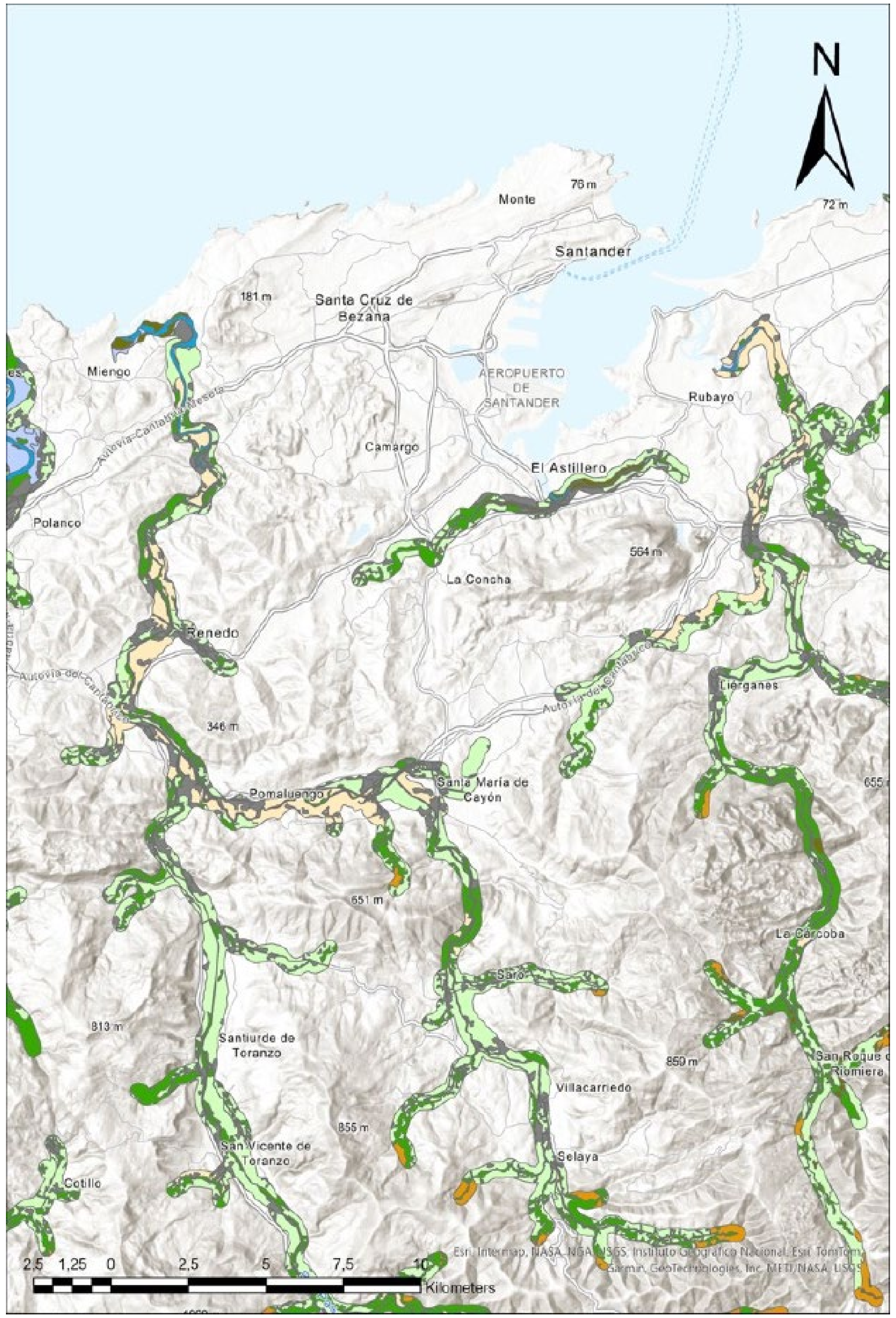
4.

OVERVIEW OF CLMS PRODUCTS

4.

COPERNICUS PRODUCTS

In this section, the most relevant CLMS products to assess the ecological status of fluvial landscapes are evaluated. The key aspects of each CLMS product are summarised, including their spatio-temporal resolution and extent. The strengths, weaknesses, and possible improvements are also indicated.



View of the lower Pas and Miera River basins, Cantabria, North of Spain.

Riparian Zones

Frequency: every 6 years

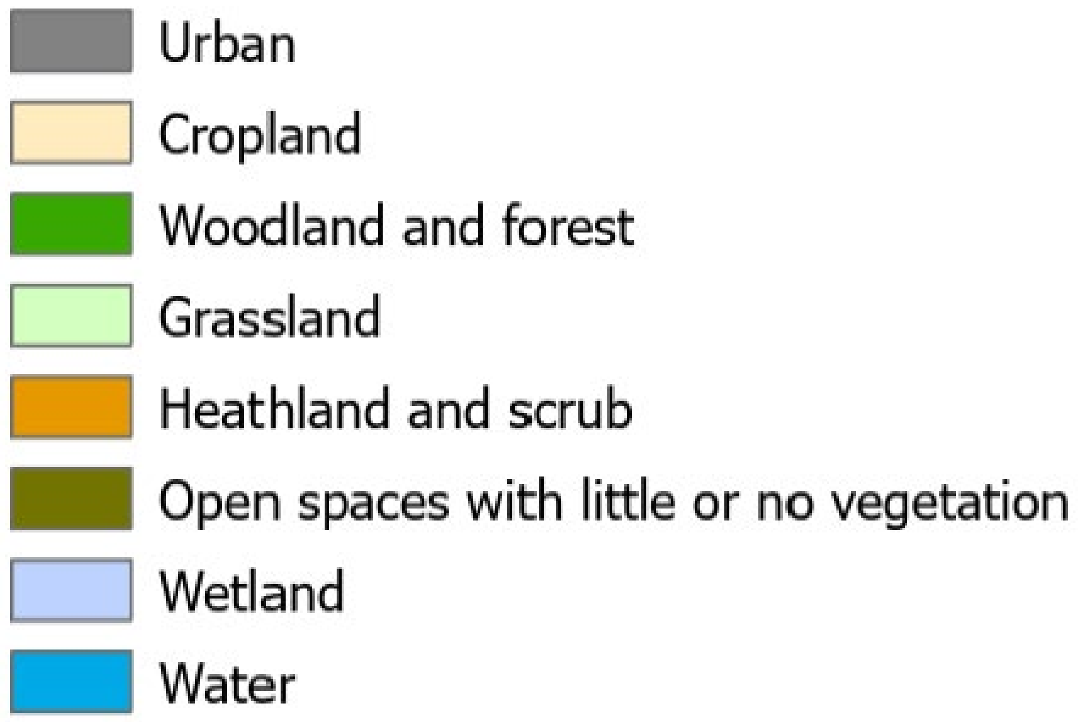
Temporal extent: 2012 - present

Geometric accuracy: 10m

Geographic extent: Europe

Link to the product: Riparian Zones

Riparian Zones Land Cover Level 1:



Strengths:

. Information on land cover and land use at different levels of detail (up to 55 thematic classes)

. Spatial coverage at the European level

. High spatial resolution

Weaknesses:

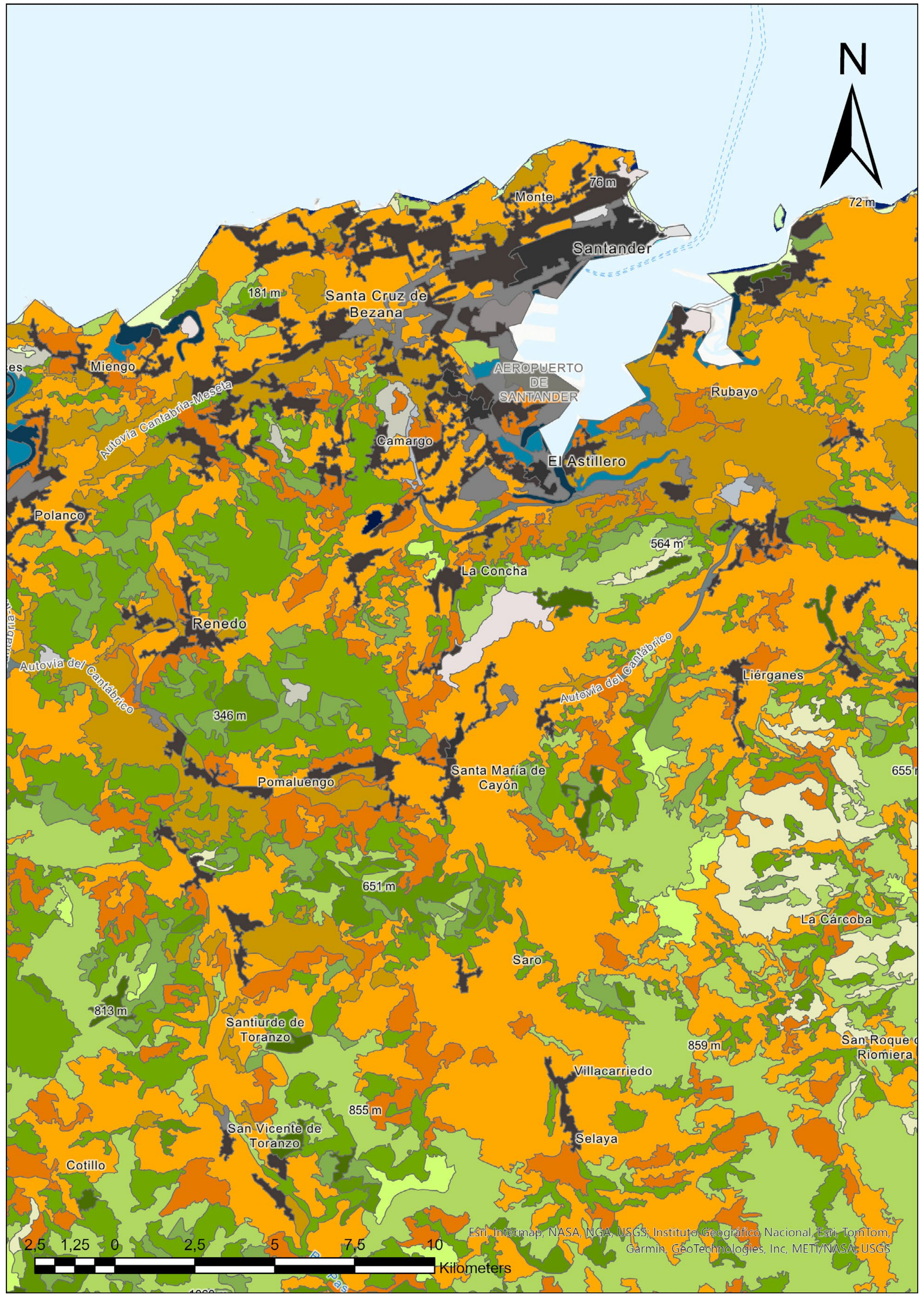
. Only the main river sections are included, while little or no information is provided for first order tributaries

. Last updated in 2018

. An arbitrary buffer distance from the watercourse is reported, not representing the actual variability of the riparian width

Possible improvements:

. Include hydro-geomorphological criteria to delineate the riparian zone and extend the information to smaller river reaches using synthetic river networks tools (e.g., NetMap)



View of the lower Pas and Miera River basins, Cantabria, North of Spain.

CLC

Frequency: 6 years

Temporal extent: 1990 - present

Geometric accuracy: 100m

Geographic extent: Europe

Link to the product: CLC

CLC Classes:

- Continuous urban fabric
- Discontinuous urban fabric
- Industrial or commercial units
- Road and rail networks and associated land
- Port areas
- Airports
- Mineral extraction sites
- Dump sites
- Construction sites
- Green urban areas
- Sport and leisure facilities
- Non-irrigated arable land
- Permanently irrigated land
- Vineyards
- Fruit trees and berry plantations
- Olive groves
- Pastures
- Annual crops associated with permanent crops
- Complex cultivation patterns
- Land principally occupied by agriculture, with significant areas of natural vegetation
- Broad-leaved forest
- Coniferous forest
- Mixed forest
- Natural grassland
- Moors and heathland
- Sclerophyllous vegetation
- Transitional woodland-scrub
- Beaches, dunes, sands
- Bare rocks
- Sparsely vegetated areas
- Burnt areas
- Inland marshes
- Peat bogs
- Salt marshes
- Intertidal flats
- Water courses
- Water bodies
- Coastal lagoons
- Estuaries
- Sea and ocean

Strengths:

. Information on land cover and land use at different levels of detail (up to 64 thematic classes)

. Spatial coverage at the European level

. It provides metrics useful for reporting on European Directives

. Useful for model validation

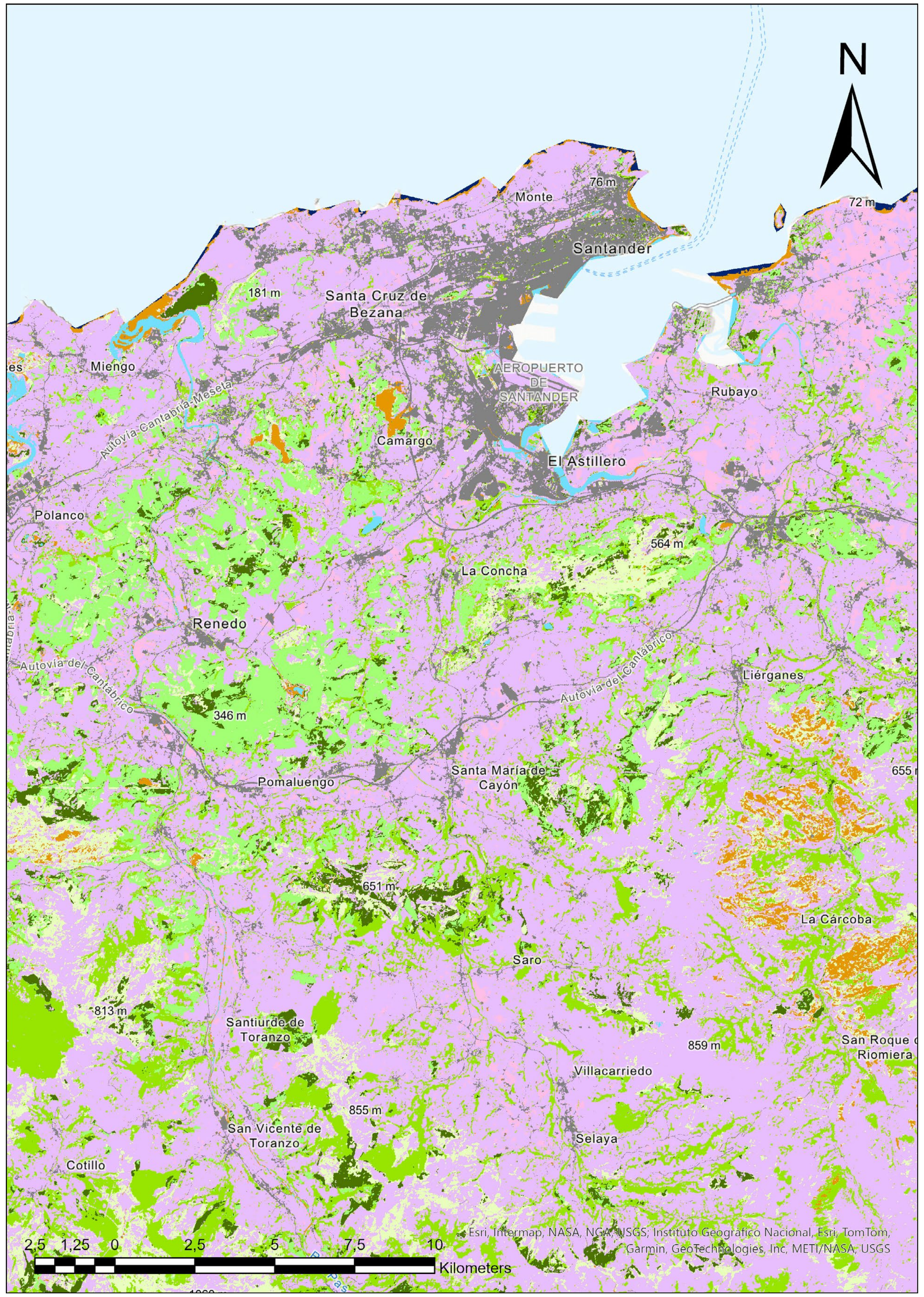
Weaknesses:

. Last updated in 2018

. Spatial resolution (100m) doesn't allow to monitor changes at the local scale

Possible improvements:

. Increasing the spatial resolution



View of the lower Pas and Miera River basins, Cantabria, North of Spain.

CLC+

Frequency: 3 years

Temporal extent: 2018 - present

Geometric accuracy: 10m

Geographic extent: Europe

Link to the product: CLC+

CLC Classes:

- Sealed
- Woody needle leaved trees
- Woody broadleaved deciduous trees
- Woody broadleaved evergreen trees
- Low-growing woody plants
- Permanent herbaceous
- Periodically herbaceous
- Non and sparsely vegetated
- Water
- Coastal seawater buffer
- Outside area

Strengths:

. Spatial coverage at the European level

. It provides metrics useful for reporting on European Directives

. Last updated in 2023

. Better spatial resolution (10m) compared to CLC (100m)

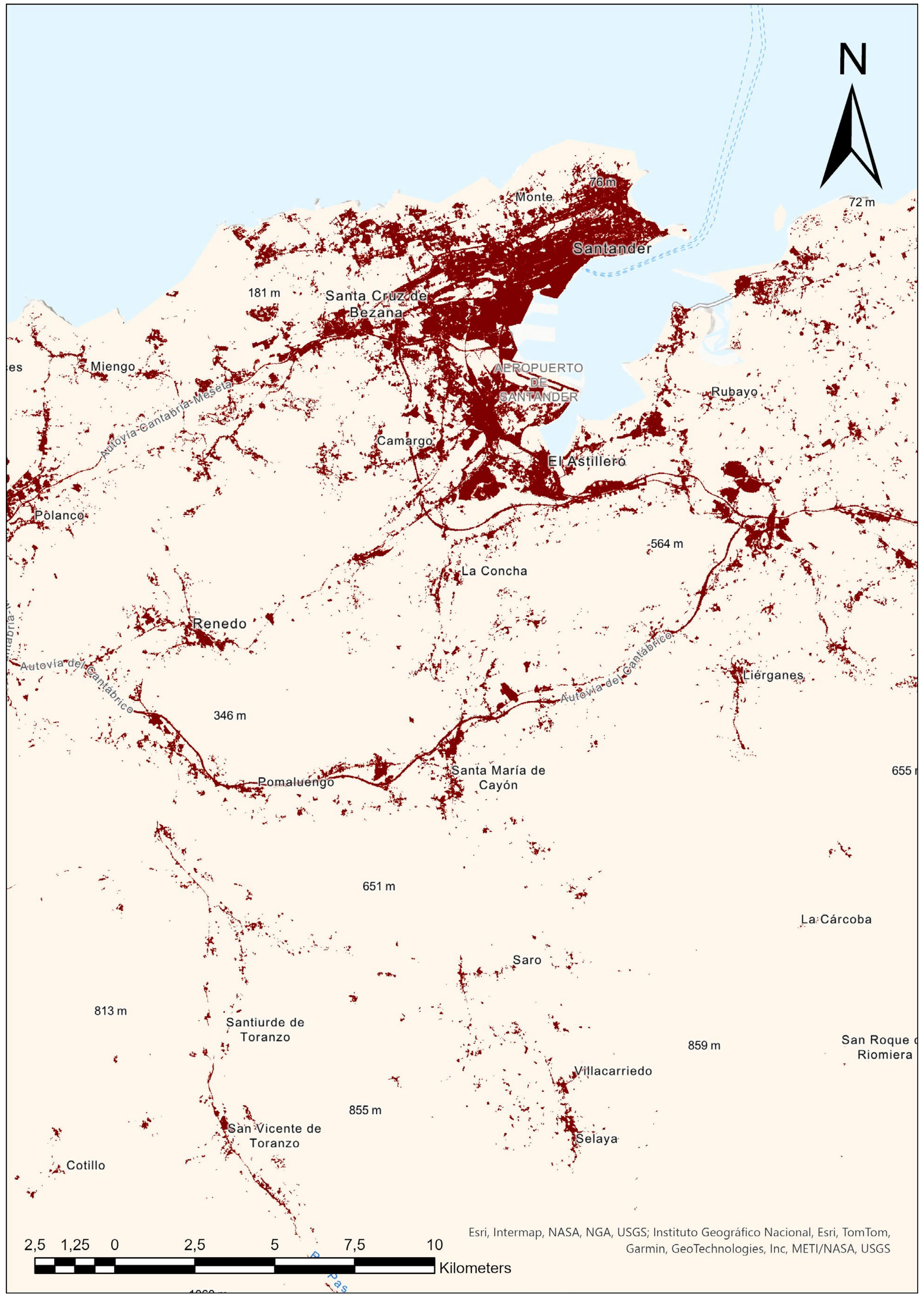
. Useful to detect changes at the local scale

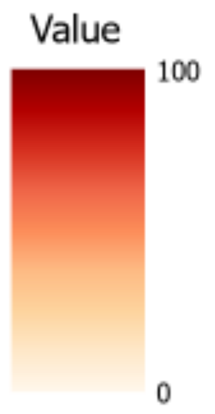
Weaknesses:

. Only 11 broad land cover classes

Possible improvements:

. Increasing the number and type of land cover classes





View of the lower Pas and Miera River basins, Cantabria, North of Spain.

Imperviousness Density

Frequency: 3 years

Temporal extent: 2006 - present

Geometric accuracy: 10m

Geographic extent: Europe

Link to the product: Imperviousness density

Strengths:

. Spatial coverage at the European level

. Percentage-base metric with discrete levels per pixel (0 to 1)

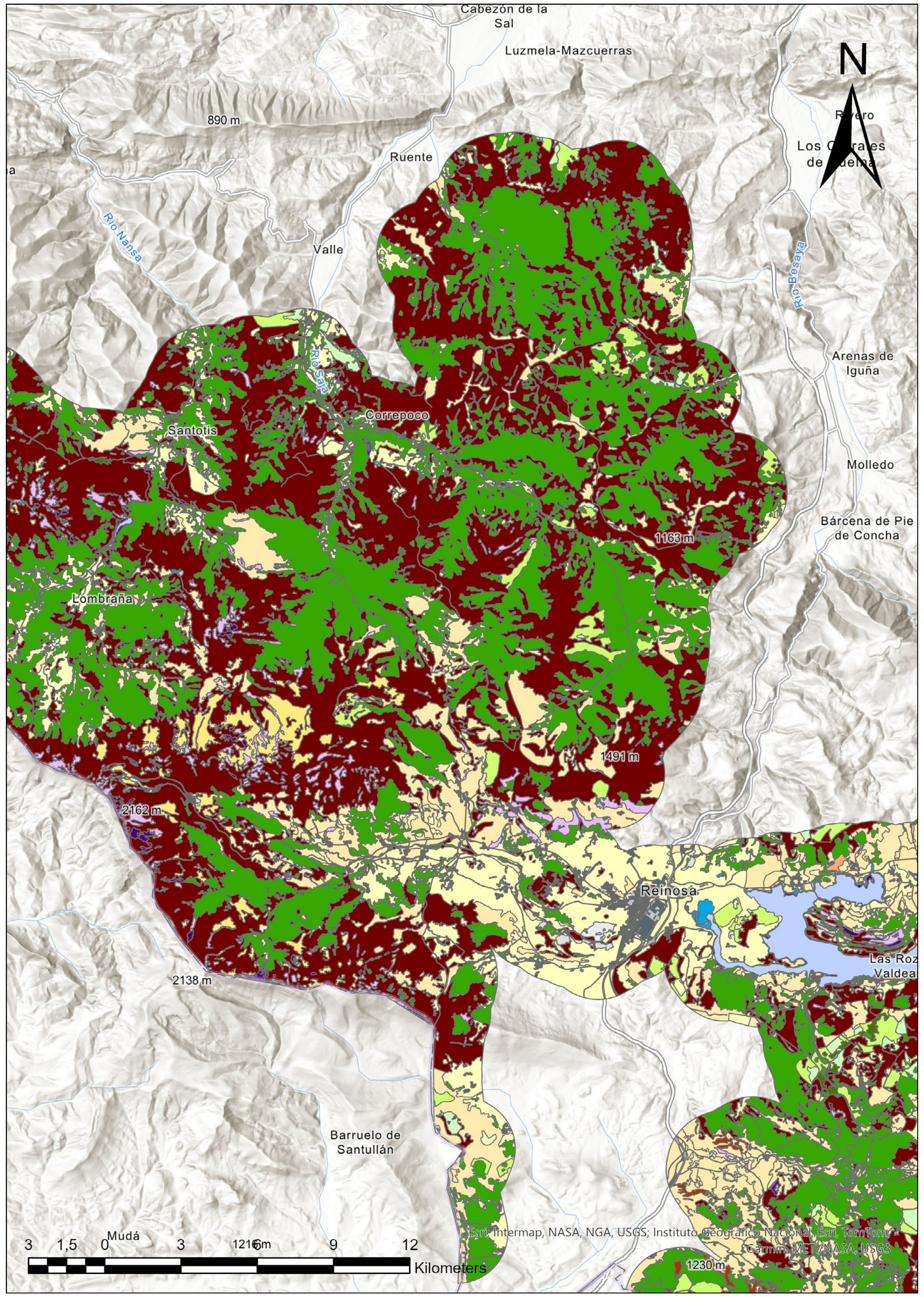
Weaknesses:

. Last updated in 2018

. Area of imperviousness potentially underestimated (33% according to Strand, 2022)

Possible improvements:

. Increasing the data frequency



View of the lower Pas and Miera River basins, Cantabria, North of Spain.

Very High Resolution Land cover/Land use datasets in selected Natura 2000 sites (N2K)

Frequency: 6 years

Temporal extent: 2006 - present

Geometric accuracy: 10m

Geographic extent: Europe

Link to the product: N2K

Strengths:

. 73 habitats from the Annex I of the Habitats Directive are included

. More specific classes than CLC

. High spatial resolution (10m)

. It addresses the Article 17 Habitats Directive for reporting

. Useful to detect changes at the local scale

Weaknesses:

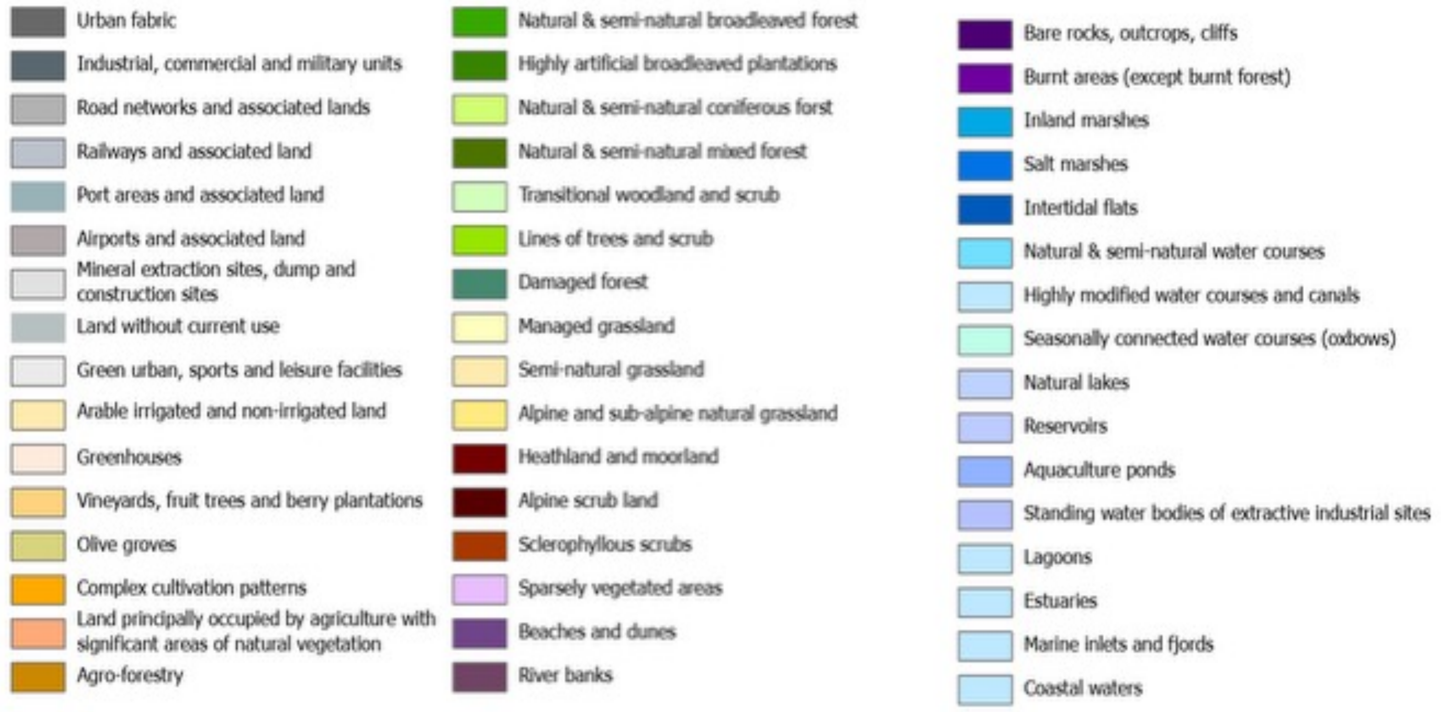
. Last updated in 2018

. Incomplete coverage across all EU member states

. Broad categories on forest habitats, including a lot of different tree species formation

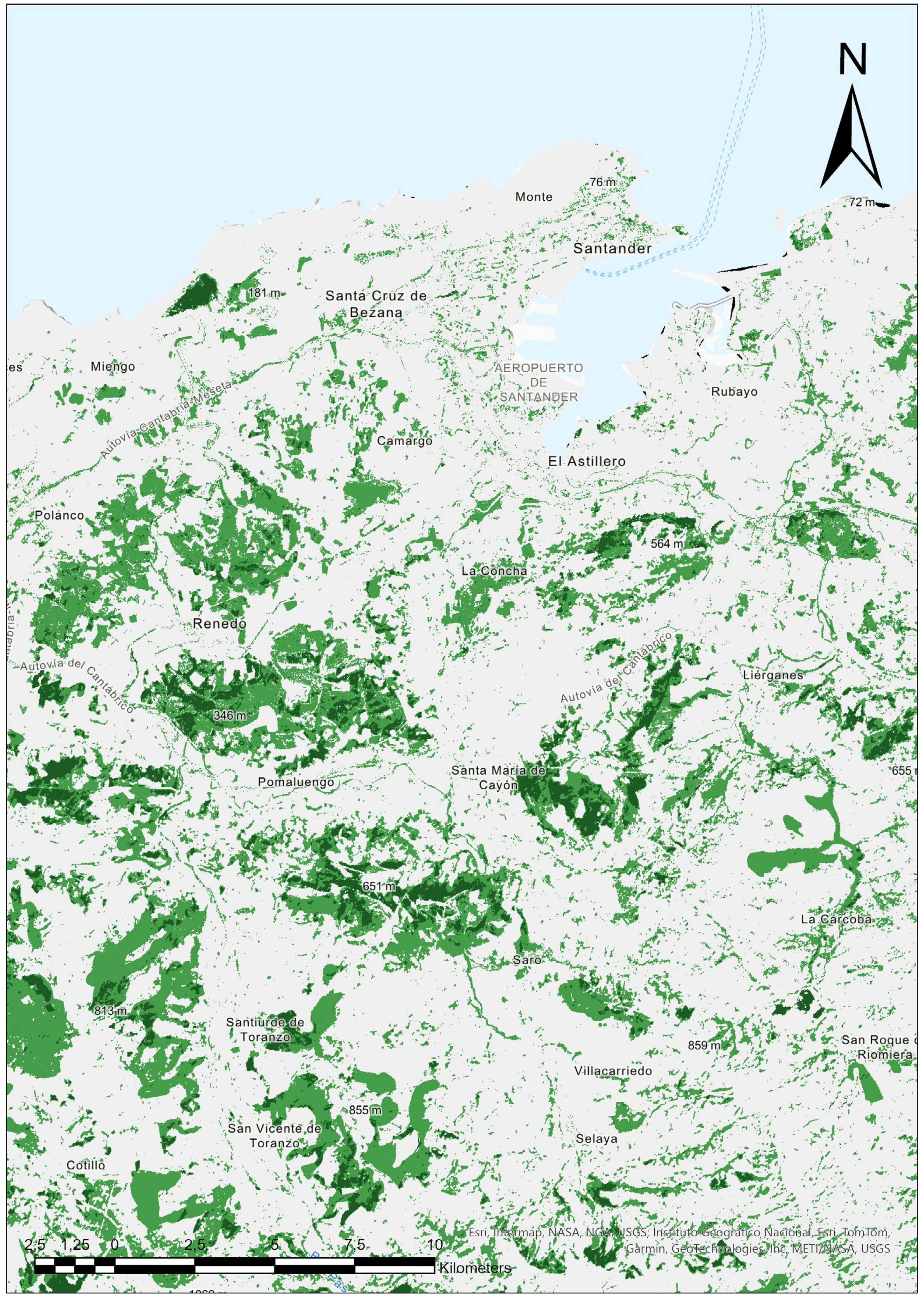
. It is unsuitable for full compliance with Article 17 reporting under the Habitats Directive, as it does not classify habitats at the resolution mandated by Annex I

Natura 2000 LC/LU Level 3



Possible improvements:

. Increasing the data frequency and the spatial coverage



View of the lower Pas and Miera River basins, Cantabria, North of Spain.

Dominant Leaf Type (DLT)

Frequency: one years

Temporal extent: 2018 - present

Geometric accuracy: 10m

Geographic extent: Europe

Link to the product: DLT

Dominant Leaf Type (DLT)

- No tree cover
- Broadleaved trees
- Coniferous trees

Strengths:

. Spatial coverage at the European level

. High spatial resolution (10 m)

. Complementary to other layers (e.g., Tree Cover Density)

. Updated every year

Weaknesses:

. Only two categories are included (broadleaved and coniferous trees), with no information about the species

. Last updated in 2021

Possible improvements:

. Including a mixed forest (with broadleaved and coniferous trees) category

View of the lower Pas and Miera River basins, Cantabria, North of Spain.

Small Woody Features

Frequency: 3 years

Temporal extent: 2015 - present

Geometric accuracy: 5m

Geographic extent: Europe

Link to the product: SWF

HRL Small Woody Features

Small Woody Feature

Strengths:

. Detailed coverage at European level

. High spatial resolution (10 m)

. Tree plantation and vineyards are distinguished

. Ambitious product that includes small structures with areas between 200 and 5000 m2

. Useful for studies on connectivity and ecological corridors

Weaknesses:

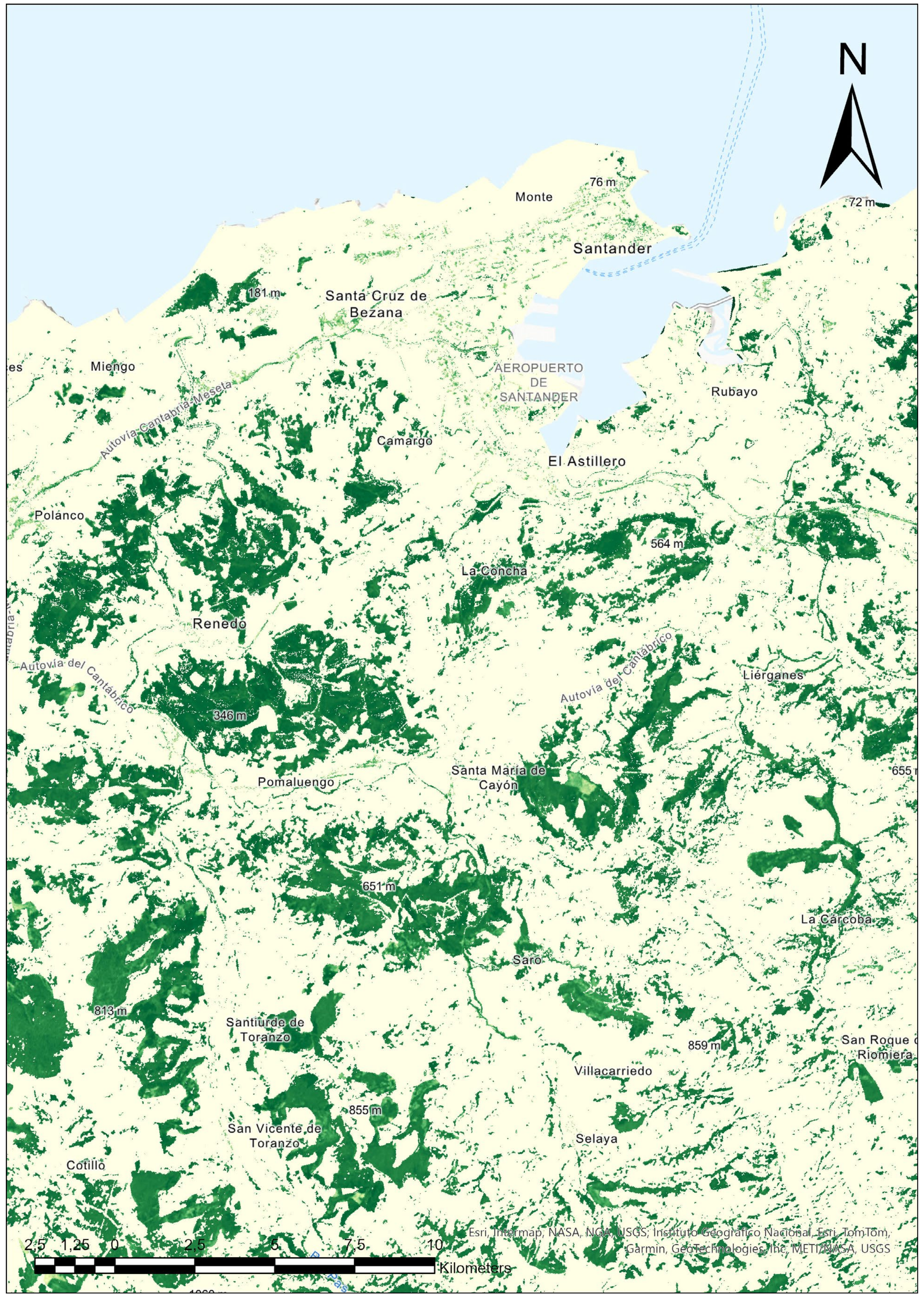
. Last updated in 2021

. Small structures with less than 200m2 are not included

Possible improvements:

. Promoting VHR scenes coming from lower number of sensors (Faucqueur et al., 2019)

. Increasing the number of thematic classes



View of the lower Pas and Miera River basins, Cantabria, North of Spain.

Tree Cover Density

Frequency: yearly

Temporal extent: 2018 - present

Geometric accuracy: 10m

Geographic extent: Europe

Link to the product: TCD

Tree Cover Density

Strengths:

. Spatial coverage at the European level

. High spatial resolution (10 m)

. Complementary to other layers (e.g., Dominant Tree Type)

. Continuous indicator (from 0 to 100%)

Weaknesses:

. Last updated in 2021

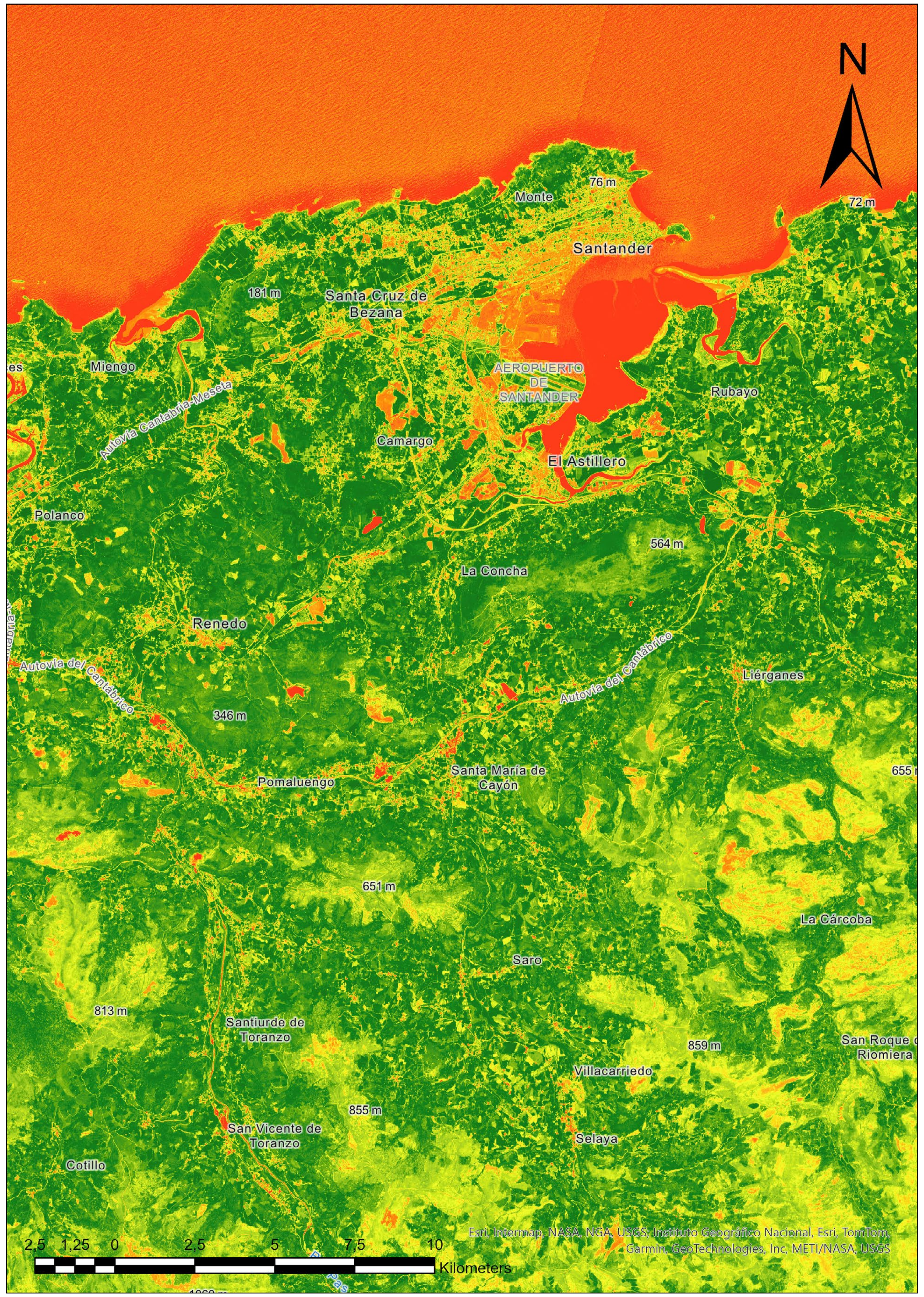
. Potential underestimation of tree cover density (Sarmento et al., 2015)

Possible improvements:

. Increasing the number of the thematic classes

4.

COPERNICUS PRODUCTS



View of the lower Pas and Miera River basins, Cantabria, North of Spain.

Normalized difference vegetation index (NDVI)

Frequency: 2-4 days

Temporal extent: 2017 - present

Geometric accuracy: 10m

Geographic extent: Europe

Link to the product: NDVI

Strengths:

. Spatial coverage at European level

. High spatial resolution (10 m)

. High data frequency (2-4 days)

. Complementary to other vegetation indices to characterize vegetation attributes and monitor ecosystem functioning

. A data quality flag is provided

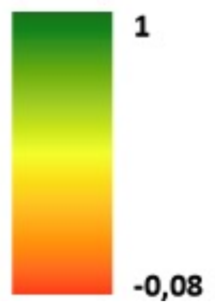
Weaknesses:

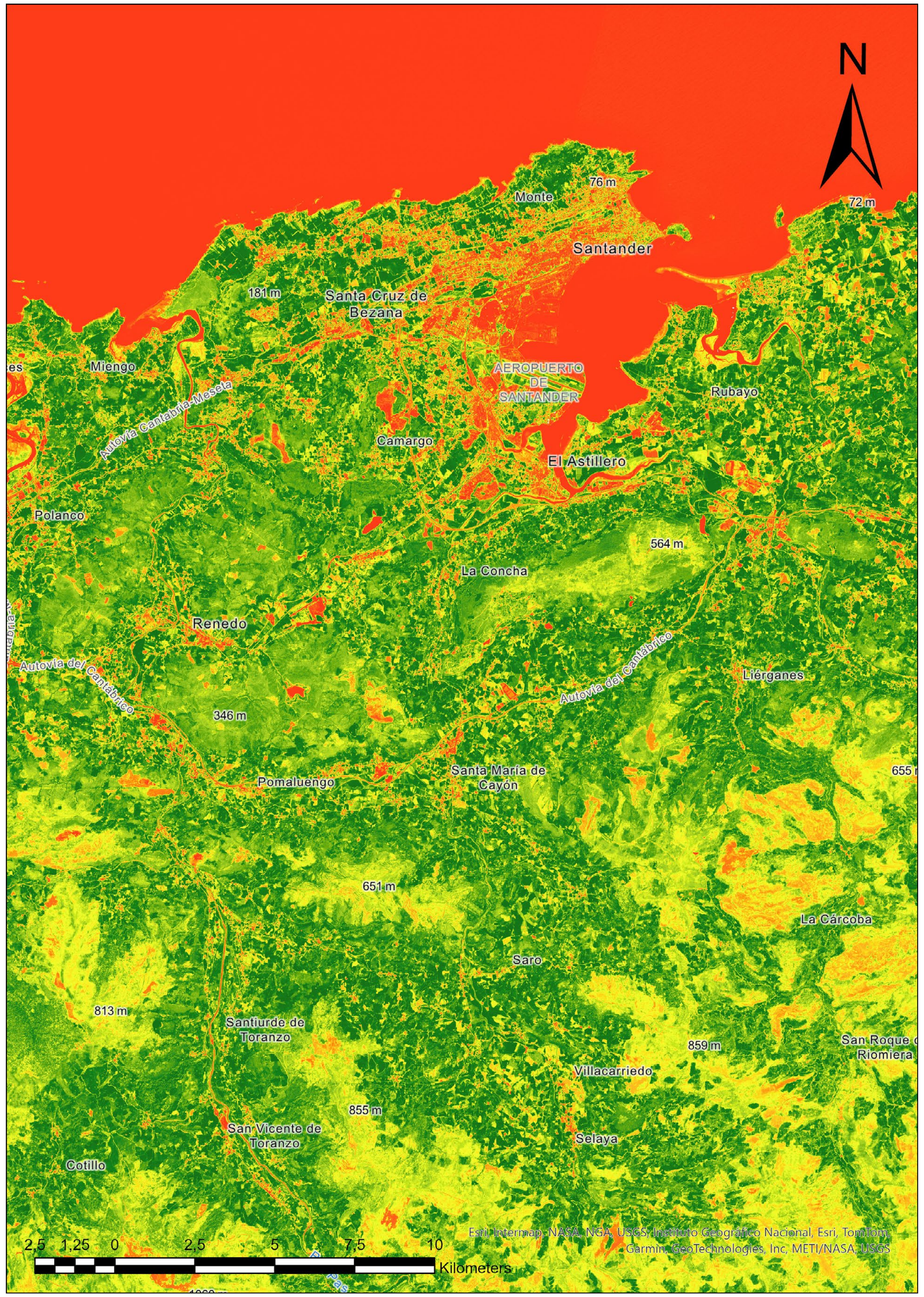
. Potential index saturation in dense vegetation (Tian *et al.*, 2025)

Possible improvements:

. Combination with other vegetation CLMS products for masking

NDVI Value





View of the lower Pas and Miera River basins, Cantabria, North of Spain.

Fraction of absorbed photosynthetically active radiation (FAPAR)

Frequency: 2-4 days

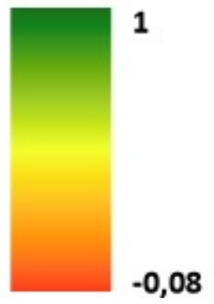
Temporal extent: 2017 - present

Geometric accuracy: 10m

Geographic extent: Europe

Link to the product: FAPAR

FAPAR Value



Strengths:

. Spatial coverage at European level

. High spatial resolution (10 m)

. High data frequency (2-4 days)

. Complementary to other vegetation indices to characterize vegetation attributes and functioning

. Useful for Primary Productivity modelling

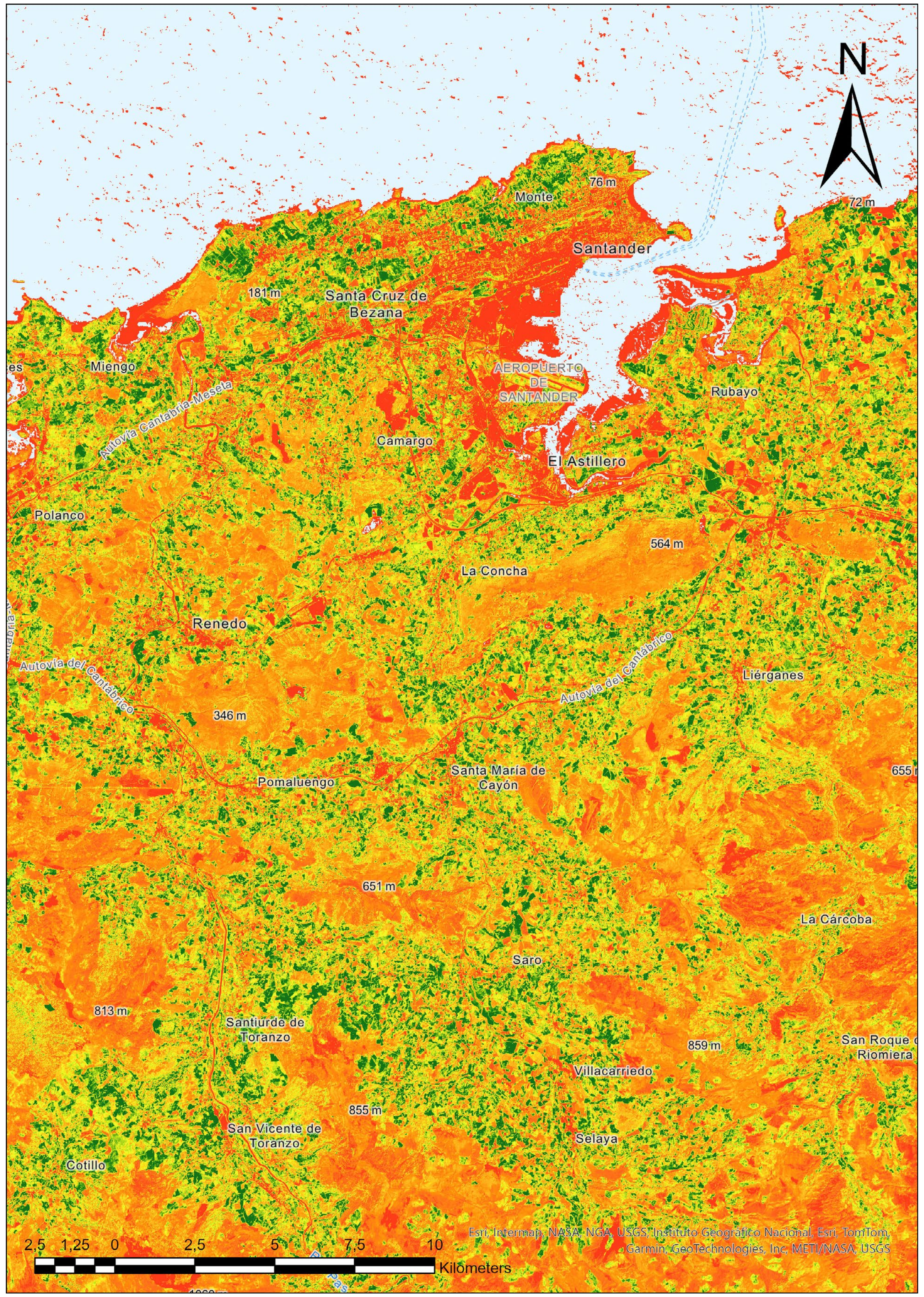
. A data quality flag is provided

Weaknesses:

. Only the green parts of the vegetation are considered

Possible improvements:

. Combination with other CLMS products for masking vegetation classes



View of the lower Pas and Miera River basins, Cantabria, North of Spain.

Plant Phenology Index (PPI)

Frequency: 2-4 days

Temporal extent: 2017 - present

Geometric accuracy: 10m

Geographic extent: Europe

Link to the product: PPI

PPI Value

Strengths:

. Spatial coverage at the European level

. High spatial resolution (10 m)

. High data frequency (2-4 days)

. Complementary to other vegetation indices to characterize vegetation attributes and functioning

. It provides the best performance for deriving Seasonal Trajectories and Phenological and Productivity parameters

. Strong correlation with Gross Primary Productivity

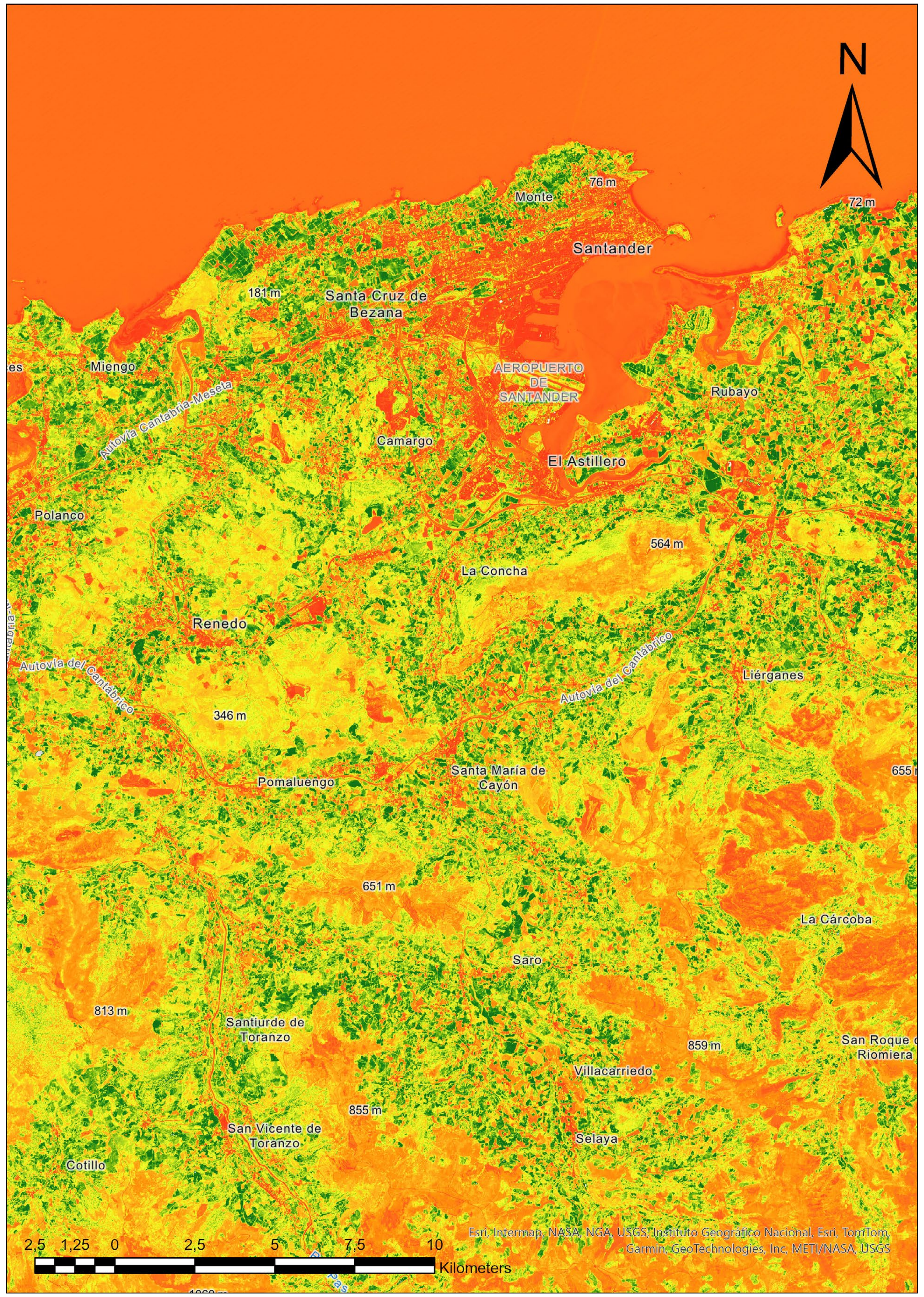
. A quality flag is provided

Weaknesses:

. No thematic masking

Possible improvements:

. Combination with other CLMS products for masking vegetation classes



View of the lower Pas and Miera River basins, Cantabria, North of Spain.

Leaf Area Index (LAI)

Frequency: 2-4 days

Temporal extent: 2017 - present

Geometric accuracy: 10m

Geographic extent: Europe

Link to the product: LAI

LAI Value

Strengths:

. Spatial coverage at the European level

. High spatial resolution (10 m)

. High data frequency (2-4 days)

. Complementary to other vegetation indices to characterize vegetation attributes and functioning

. It provides the best performance for deriving Seasonal Trajectories and Phenological and Productivity parameters

. Strong correlation with Gross Primary Productivity

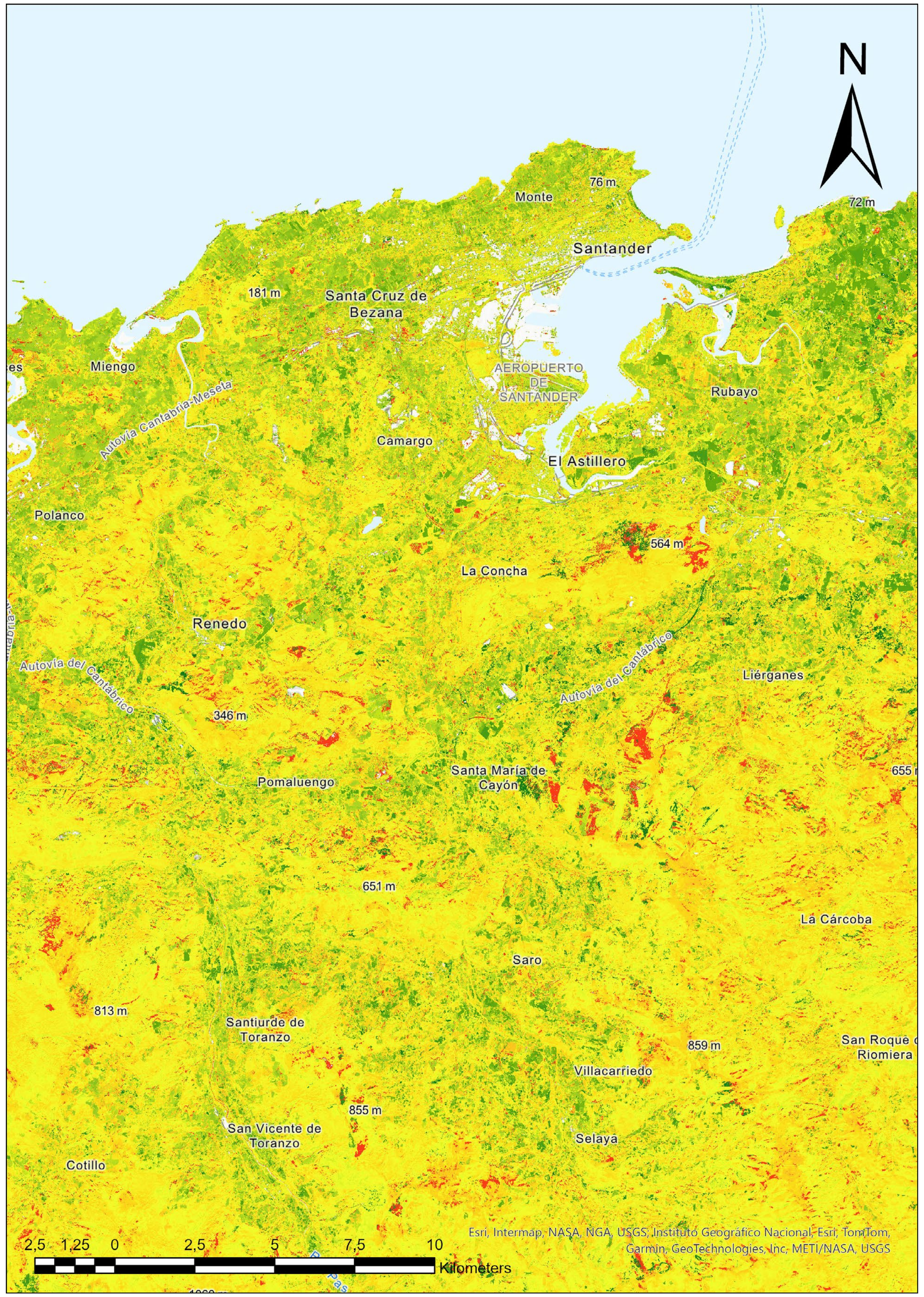
. A quality flag is provided

Weaknesses:

. No thematic masking

Possible improvements:

. Combination with other CLMS products for masking vegetation classes



View of the lower Pas and Miera River basins, Cantabria, North of Spain.

Plant Phenology Index Seasonal Trajectories: End of Season Date (EOSD)

Frequency: yearly

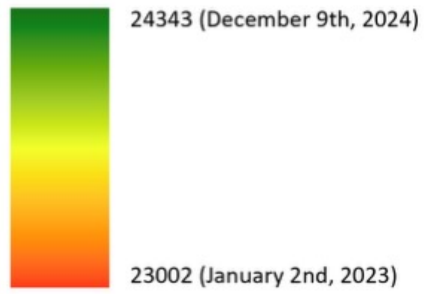
Temporal extent: 2016 - present

Geometric accuracy: 10m

Geographic extent: Europe

Link to the product: EOS

EOSD Value



Strengths:

. Spatial coverage at the European level

. High spatial resolution (10 m)

. Available every year, after the end of the vegetation growing season

. It provides useful information for the monitoring of the vegetation growth cycle

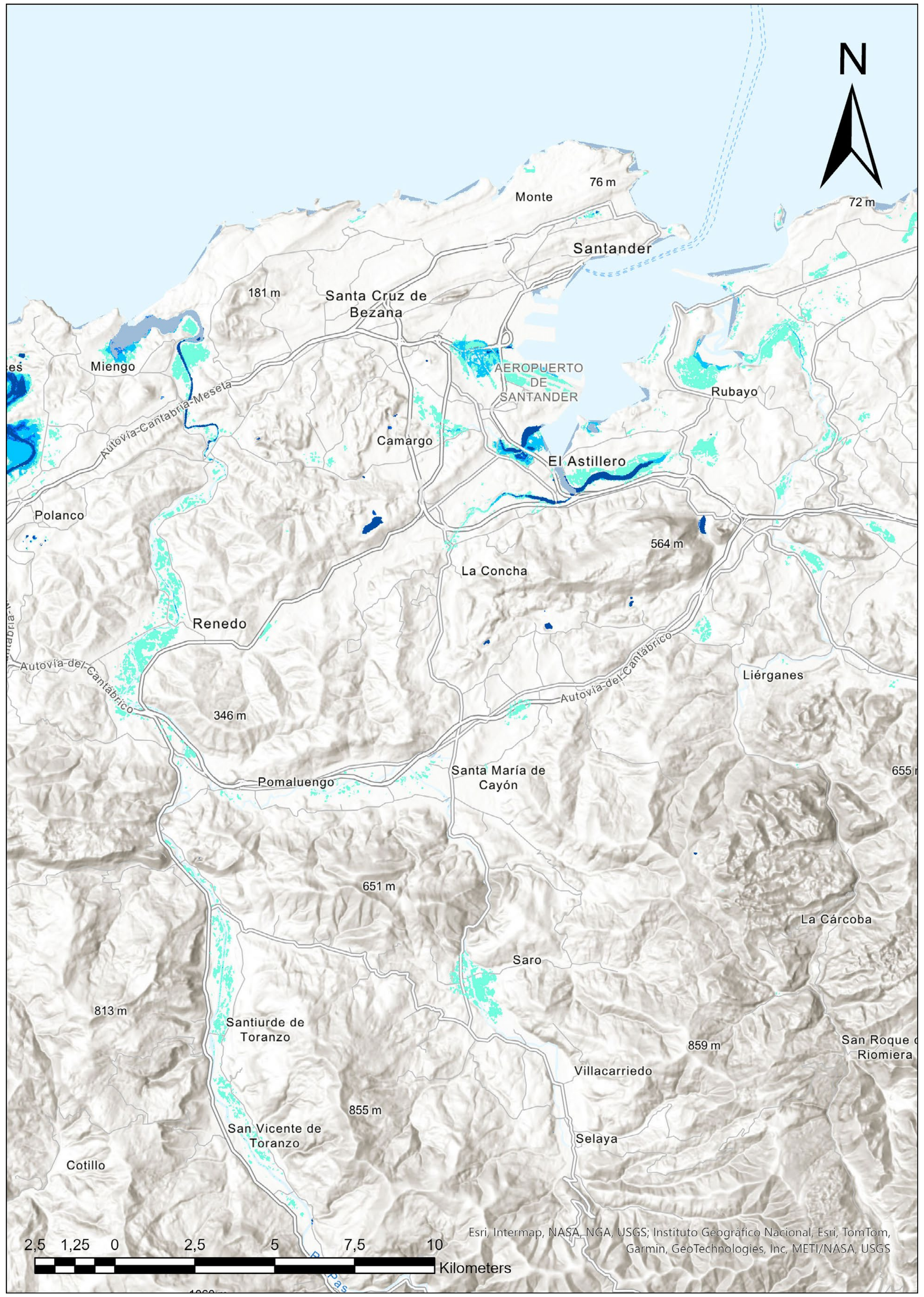
. A quality flag is provided

Weaknesses:

. No thematic masking

Possible improvements:

. Combination with other CLMS products for masking vegetation classes



View of the lower Pas and Miera River basins, Cantabria, North of Spain.

Water & Wetness

- Permanent water
- Temporary water
- Permanent wet areas
- Temporary wet areas
- Sea water

High Resolution Layer Water & Wetness

Frequency: 3 years

Temporal extent: 2015 - present

Geometric accuracy: 10m

Geographic extent: Europe

Link to the product: W&W

Strengths:

. Spatial coverage at the European level

. High spatial resolution (10 m)

. Intermittent wetlands and other temporal wet areas are detected

. Imagery from different seasons across the year is included, enabling a better permanent vs temporary classification

Weaknesses:

. Last updated in 2018

Possible improvements:

. Increasing the number and detail of the thematic classes

5.

THE USE OF REMOTE-SENSING DERIVED PRODUCTS FOR MONITORING FLUVIAL LANDSCAPES

5..

THE USE OF REMOTE-SENSING DERIVED PRODUCTS FOR MONITORING FLUVIAL LANDSCAPES

Global change drivers, such as climate change, land use change, pollution and invasive species are profoundly altering the habitats and the ecosystem functioning of rivers and riparian zones. Due to the complex and highly dynamic nature of aquatic and terrestrial ecosystems interacting in the fluvial landscape, together with their arrangement if a network-like structure, the characterization of their ecological status and response to environmental changes demands innovative tools to complement traditional in situ measurements. In this context, remote-sensing derived data provides critical information on fluvial landscape composition and functioning at large scales and continuous in space and time.

COPERNICUS products, and specifically, CLMS products, offer bio-physical data at high spatial (2-10 m) and temporal resolution (2-4 days) on land use and land cover, vegetation classes and functional status, and water bodies distribution and type (*i.e.*, seasonal character). The Riparian Zones product highlights because it is focused on adjacent areas of rivers, providing land use and land cover of 55 thematic classes, riparian forests included. However, this product is available for two reference years (2012 and 2018) and only includes the major and medium sized rivers, while little or no information is provided for secondary streams. Besides, the thematic resolution only differentiates between certain types of forest. These drawbacks can be overcome by combining Sentinel-2 spectral data, at a higher temporal resolution, and ground truth data to model the different elements of the fluvial landscape, including riparian terrestrial habitats (*i.e.*, Alder galleries) and water and sediments in floodplains and rivers sections, respectively, of a certain entity (>10-30 m width).

The use of remote-sensing derived products greatly improves our capacity to evaluate and monitor attributes and processes of fluvial ecosystems across space and time. Future improvements of remote-sensing application to ecosystem monitoring in fluvial landscapes includes increasing and enhancing ground-truth data, refining thematic resolution and advancing the characterization of the aquatic component in medium and small sized rivers.

6.

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CASES STUDIES

1.

INTRODUCTION

1.

INTRODUCTION

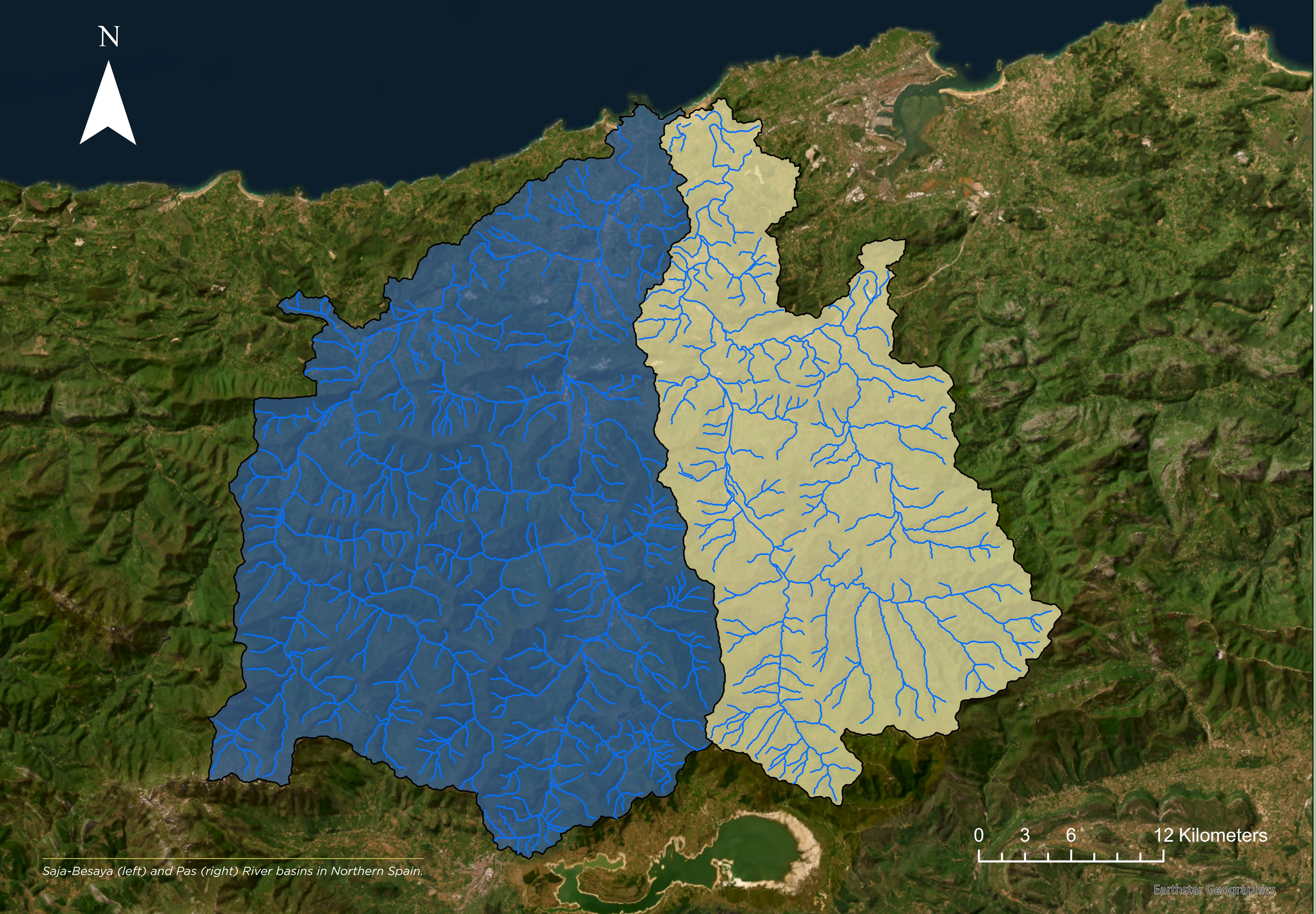
Cop.RIVER aims to promote the use of Earth Observation (EO) in applications and services related to the ecological status of riverscapes (i.e., rivers and their associated alluvial plains, floodplains, and riparian forests). The action will strengthen Copernicus user uptake by supporting regional and national authorities in the implementation of EU environmental policies, including the Biodiversity Strategy 2030, the Habitats and Birds Directives, and the Water Framework Directive.

This action has developed a toolkit including a selected set of standardized ecological indicators from both terrestrial and aquatic domains, a review of the applicability of COPENICUS products to calculate the indicators and a methodological benchmark for monitoring riparian and river ecological status. This toolkit will support independent decision-making to assist in water resource management, restoration, and conservation actions in these complex and valuable landscapes.

The toolkit was applied to two case studies located in Northern Spain: The Saja-Besaya and Pas River basins (Fig. 1). Both basins share the climatic setting and comprise similar vegetation formations in well-preserved areas, while land-use patterns and ecosystem conservation status differ notably, allowing us to explore the suitability of the toolkit in a range of environmental scenarios.

2

CASES STUDIES



Saja-Besaya (left) and Pas (right) River basins in Northern Spain.

Figure 1. *Saja-Besaya (left) and Pas (right) River basins in Northern Spain*

2.1

THE SAJA-BESAYA RIVER BASIN

The Saja River, originating in the Sierra del Cordel, spans 67 km and flows through the autonomous region of Cantabria, discharging into the San Martín de la Arena estuary. It is bordered by the Pas River to the east and the Nansa River to the west (CHCantábrico, n.d.-b.) The Besaya River, a major tributary of the Saja, runs 47 km from its source in Campoo de Enmedio, joining the Saja at Torrelavega (CHCantábrico, n.d.-a). Other important tributaries include the Argoza and Bayones Rivers (CHCantábrico, n.d.-b).

The estimated catchment area of the Saja-Besaya basin is 966 km^2, characterized by steep topography (Peñas et al., 2011). This basin includes the Saja-Besaya Natural Park, the largest in Cantabria, and two Sites of Community Importance (SCI); Valles Altos del Saja y Nansa y Alto Campoo and Río Saja (CHCantábrico, n.d.-b).

Geologically, the basin consists of clays, sandstones, siltstones, and calcareous rocks (DMA Cantabria, n.d.-b). In terms of land use, the most densely populated and urbanized areas are concentrated near the basin's outlet, while the headwater regions remain sparsely populated. Economic activities are primarily centered around the secondary sector, including industry and construction, with a significant contribution from the tertiary sector. Agricultural and livestock activities are minimal, reflecting the basin's transition away from primary sector reliance. Agricultural areas are found along riverbanks in lowland regions, while wooded areas dominate the steeper, more remote zones (DMA Cantabria, n.d.-b).

Within these wooded areas, mixed deciduous forests are the dominant vegetation type, both in riparian zones and upland regions. Oak groves (*Quercus robur*) are prevalent on south-facing slopes, while beech forests (*Fagus sylvatica*) dominate shadier slopes. Other notable species include holm oak (*Q. ilex*) and chestnut (*Castanea sativa*). Additionally, eucalyptus plantations are widespread throughout the basin (IHCantabria, 2020). The riparian vegetation is dominated by willow grove (*Salix atrocinerea*) and birch (*Betula celtiberica*), combined with alder (*A. glutinosa*), and it is particularly well preserved in the headwaters of the basin.

With increasing altitude and changing climatic conditions, vegetation gradually transitions from forested areas to scrubland formations. Natural meadows are irregularly distributed, occurring in both high mountain zones and coastal areas (IHCantabria, 2020).

The lower basin experiences the highest levels of anthropogenic disturbance, primarily due to urbanization and industrialization. Although infrequent, the pressures are substantial and include floodplain occupation, riverbank stabilization, and wastewater discharges from major urban and industrial centers. The basin also contains 20 dams, representing a significant environmental pressure (DMA Cantabria, n.d.-b). In terms of invasive species, *Reynoutria japonica* and *Cortaderia selloana* are the most widespread, particularly in the lower river sections and around Torrelavega, where human disturbance is greatest (IHCantabria, 2020).

Figure 2. The Saja River near Terán, Cantabria (Northern Spain).

2.2 The Pas River basin

The Pas River, originating from Castro Valnera, extends 61 km and flows through the autonomous region of Cantabria, discharging into the Mogro estuary. It is flanked by the Miera River to the east and the Saja River to the west. The main tributaries of the Pas are the Magdalena and Pisueña Rivers (CHCantábrico, n.d.-c).

The estimated catchment area of the Pas River basin is 649 km², characterized by steep mountainous terrain (DMA Cantabria, n.d.-a). The entire catchment, including the full course of the Pas and its tributary, the Pisueña, is designated as a Site of Community Importance (SCI) under the name Río Pas. At its estuary, an additional SCI—Dunas de Liencres y Estuario del Pas—is located at the river's mouth (CHCantábrico, n.d.-c).

The geology of the basin is predominantly composed of clays, sandstones, siltstones, and calcareous rocks (Derepasko et al., 2021). The climatic vegetation is characterized by Atlantic deciduous forest, mainly consisting of a mixture of oaks (*Quercus* spp.), chestnuts (*C. sativa*) and beeches (*F. sylvatica*), although pastures and shrublands dominate vegetation in the basin (80% cover, Álvarez-Cabria *et al.*, 2016). The riparian vegetation is dominated by alder (*A. glutinosa*) from sea level up to 700 m and by ash and hazelnut (*C. avellana*) at higher altitudes. In degraded areas, or where the soils are shallow and water level is highly variable, the alder is replaced by willow (*S. atrocinerea*). In modified river banks where agriculture and cattle activities are intensive, the dominant species are bramble (*Rubus* sp.), rose (*Rosa* sp.), hawthorn (*Crataegus monogyna*), blackthorn (*Prunus spinosa*), frequently combined with pastures (Benda et. al., 2011).

The most urbanized areas in the basin are concentrated in the lower reaches, while the upper reaches experience less anthropogenic pressure. The population primarily relies on the service industry sector, with the primary sector playing a relatively minor role compared to other river basins. Agricultural activity is most prominent in the upper basin, with scattered cultivated areas in the middle and lower sections (DMA Cantabria, n.d.-a). Forested areas follow a similar distribution, being more abundant in the upper areas of the basin (Natura Spain, n.d.-a).

The Pas basin contains relatively little infrastructure—such as dams or weirs—that significantly affects river flow (Derepasko *et al.*, 2021). However, riverbank stabilization affects approximately one-third of the river's course. Additionally, industrial activities in the middle reaches contribute further pressures (DMA Cantabria, n.d.-a).

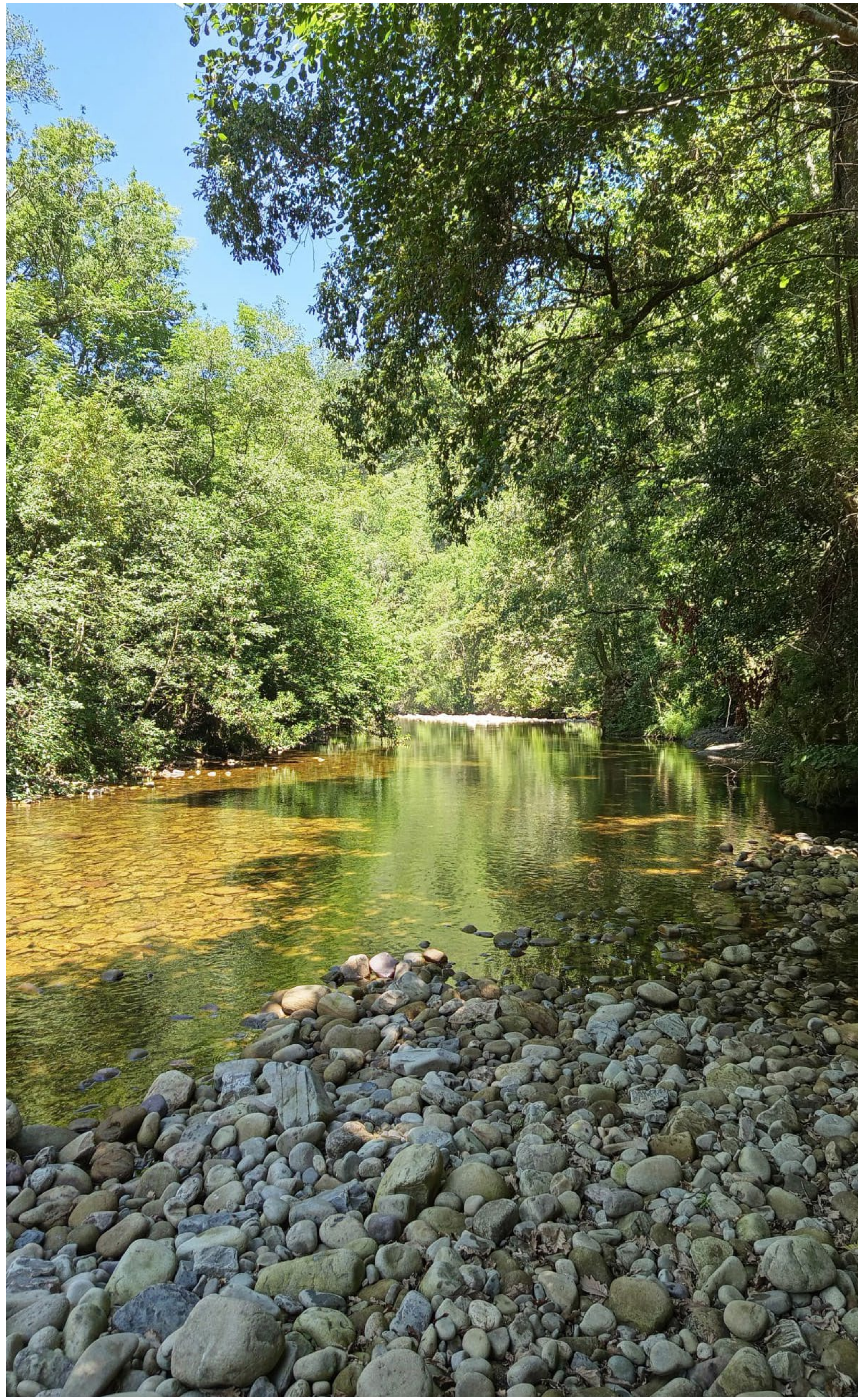


Figure 3. The Pas River near Renedo de Cabuérniga, Cantabria (Northern Spain).

3

REMOTE SENSING-BASED ECOLOGICAL INDICATORS

3.

REMOTE SENSING-BASED ECOLOGICAL INDICATORS

The toolkit includes a set of standardized ecological indicators based on remote sensing for both terrestrial and aquatic domains. In this study, we apply three indicators from each domain to two contrasting river basins to demonstrate their potential for characterizing and assessing the conservation status of fluvial landscapes within the Atlantic region.

3.1 Terrestrial domain

3.1.1 Land Use / Land Cover

This variable identifies land use and land cover types, distinguishing between anthropogenic areas (*e.g.*, cropland, buildings) and natural habitats (*e.g.*, forests, wetlands). The use of this variables is recommended by the River Habitat Survey (RHS; Environment Agency, 2003); a manual developed for conducting river habitat assessments in the UK and Ireland in preparation for the Water Framework Directive, included in EU directives; such as the Explanatory Notes & Guidelines for the 2007-2012 period for assessment and reporting under Article 17 of the Habitats Directive (ETC/BD, 2011) and in Spanish biodiversity legislation, where this parameter is essential for complying with the requirements of the Natural Heritage and Biodiversity Law.

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Two Copernicus products support its assessment:

- **Corine Land Cover (CLC):** A European dataset updated periodically (2000–2018), with 44 land cover classes and 25 ha minimum mapping unit. The 2018 version uses Sentinel-2 and Landsat-8 data with 10 m accuracy.
- **Riparian Zones:** Focused on riparian areas (2012 and 2018), using Very High-Resolution satellite data harmonized with CLC.

In this study, the 2018 Riparian Zones product was used to characterize the land use and land cover in the Saja-Besaya (Fig. 2) and Pas (Fig. 3) fluvial landscapes. Woodland and heathland dominate the headwaters, while urban and agricultural areas increase downstream. However, the product only covers main watercourses of the fluvial network and identify broad ecosystem types; e.g., the highest resolution for forest habitats is natural & semi-natural mixed forest vs. highly artificial mixed plantations. A methodological alternative to improve spatial coverage and habitat resolution is proposed by Pérez-Silos et al. (2019), where a large ground dataset of riparian formations is combined with modelling techniques based on remote sensing and environmental variables (e.g., climate, topography and geomorphology, land use/land cover and anthropogenic pressures such as embankments, etc.).

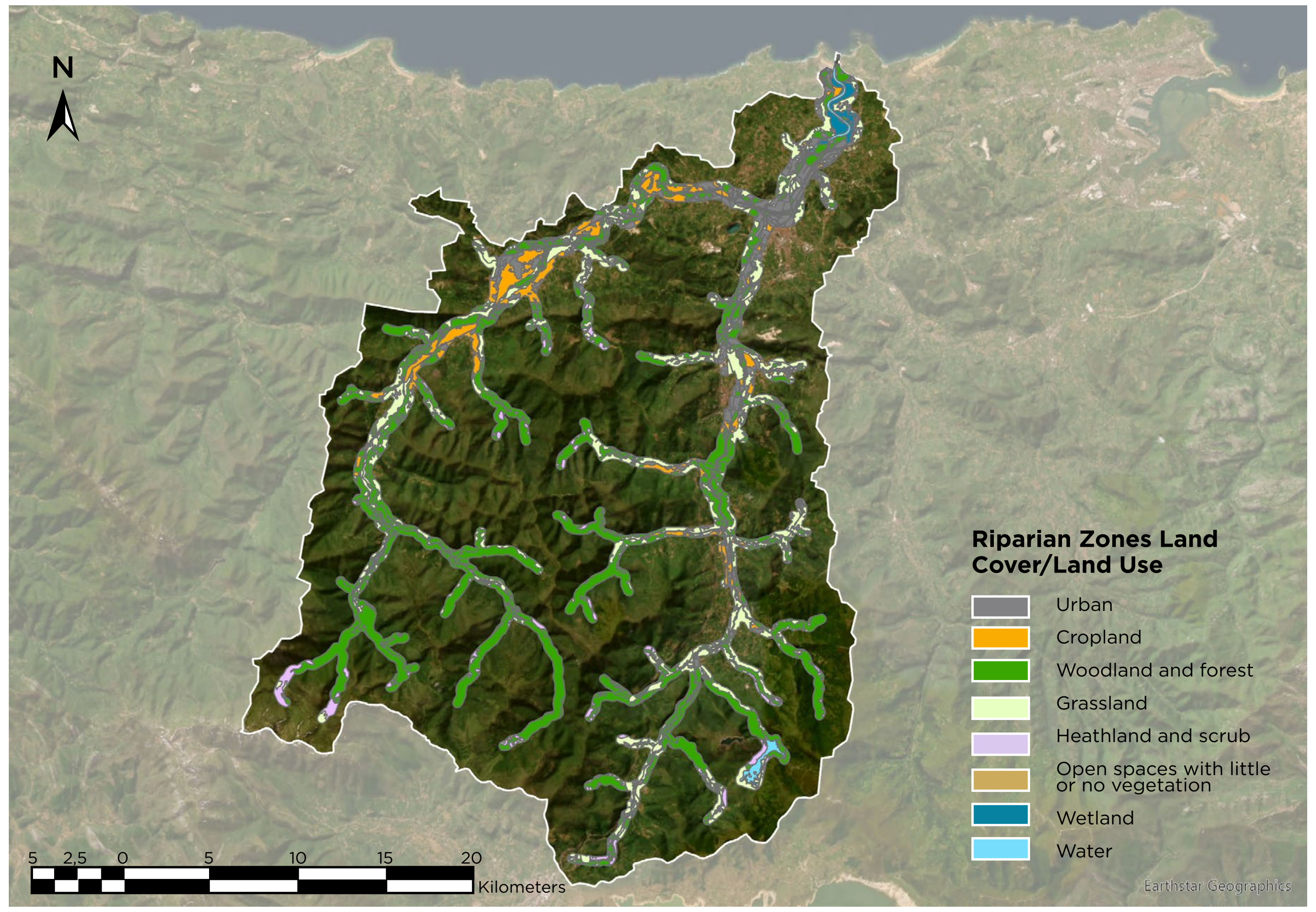


Figure 2. *Land use categories in the Saja-Besaya basin obtained from the Riparian Zones product.*

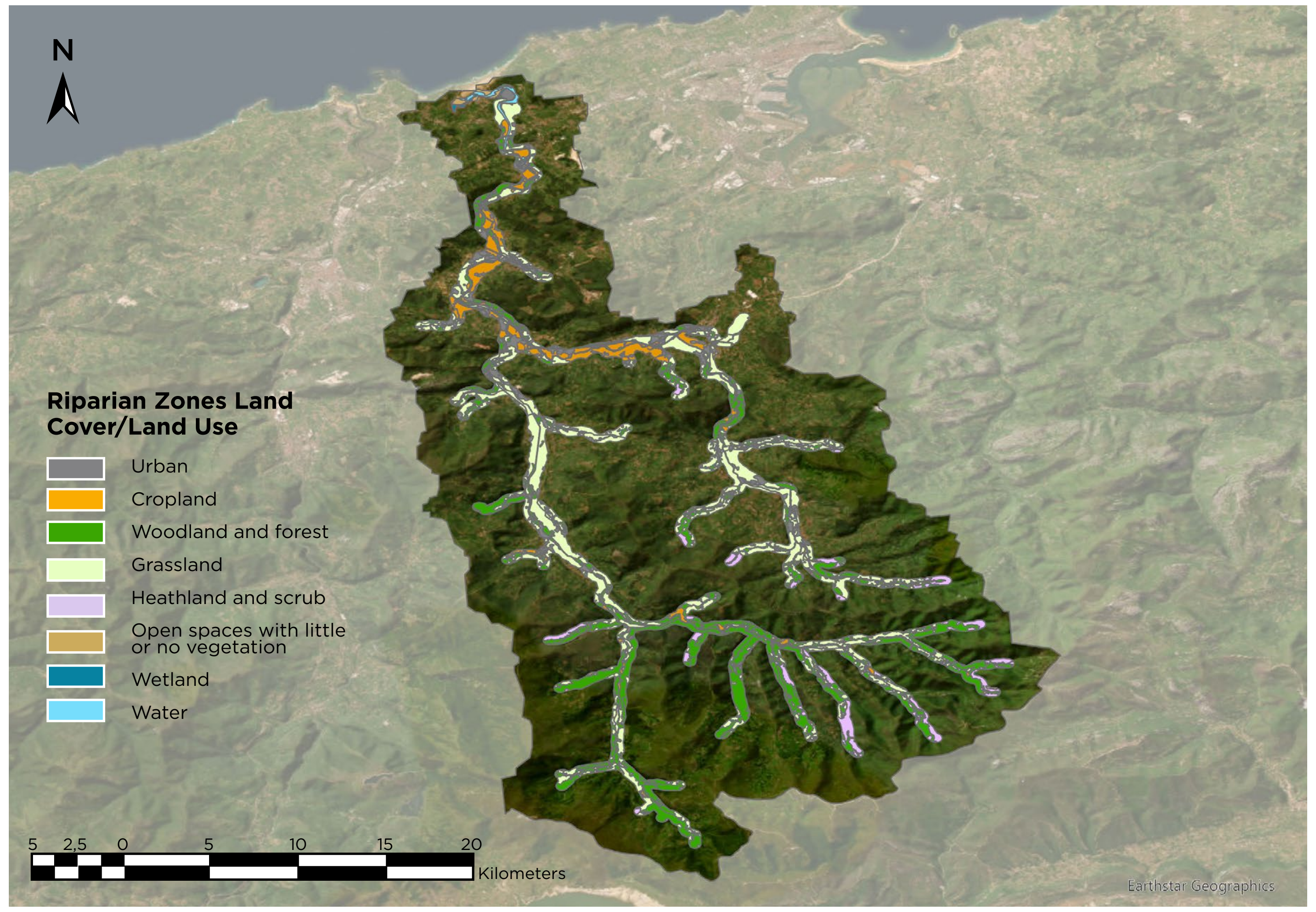


Figure 3. *Land use categories in the Pas basin obtained from the Riparian Zones product.*

3.1.2. Longitudinal connectivity

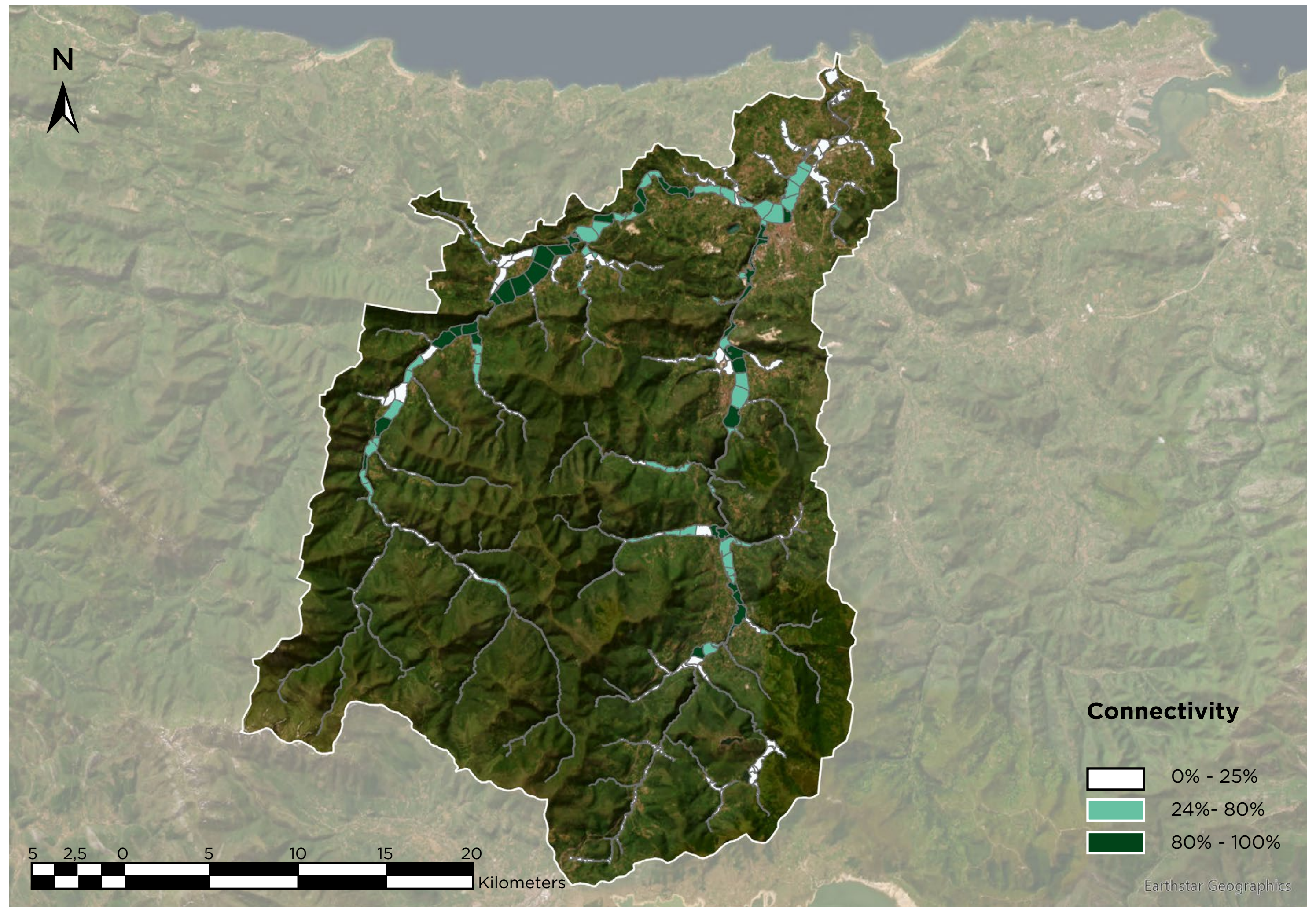
This variable, under the “Connectivity” category, identifies breaks in riparian forest or habitat continuity along riverbanks, indicating where vegetation is absent. It helps assess adjacent vegetation coverage and the potential extent of specific habitat types.

It is used in ecological assessments under the Water Framework Directive, such as the Riparian Quality Index (RQI; González del Tánago *et al.*, 2011) and the Morphological Quality Index (MQI), and also in habitat monitoring under the Habitats Directive. While the Water Framework Directive evaluates connectivity at the riparian zone level, the Habitats Directive focuses on individual habitat types.

To align with the Habitats Directive, our analysis targeted habitat type 91E0 (Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior*), one of the most common riparian habitats in the study area. Given the lack of available products at this habitat resolution level, we used the outputs of the habitat models described in Pérez-Silos *et al.* (2019). These models, based on ground truth data, predicted occupancy probabilities, which were converted into actual habitat presence by overlaying the probability data for each habitat type with concurrence layers, selecting the habitat type with the highest probability for each pixel (Pérez-Silos et al., 2019).

To assess the longitudinal connectivity of the 91E0 habitat, the river network was divided into functional river reaches using NetMap software (Pérez-Silos *et al.*, 2019), which were further subdivided into 10-meter sections. For each section, 100-meter buffers were created on both the left and right banks. The presence of the 91E0 habitat within each section was determined using data from the habitat distribution model. Longitudinal connectivity was assessed by counting the number of polygons within each functional segment that contained the habitat. This approach enabled the calculation of the percentage of each river segment where the riparian habitat formation is continuous.

Results showed a strong relationship between connectivity and habitat coverage in the Saja-Besaya (Fig. 6) and Pas (Fig. 7) basins, with connectivity values showing a highly fragmented pattern along both river networks. The analysis also revealed that high habitat coverage on one bank does not guarantee high connectivity, which may drop to 50% if the opposite bank lacks habitat. These results highlight the necessity of high-resolution data in both spatial detail and vegetation composition.



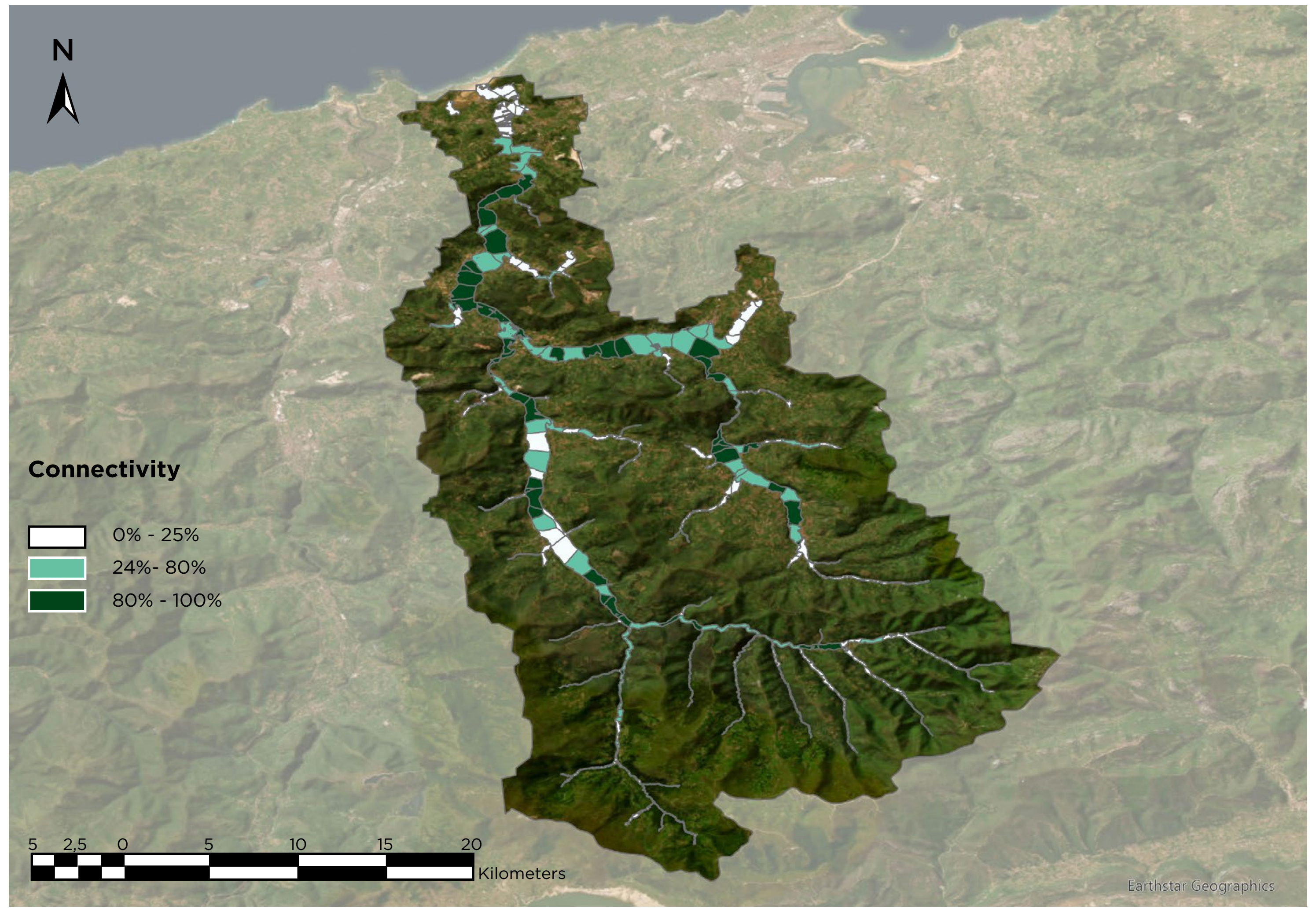


Figure 6. *Longitudinal connectivity of the 91E0 habitat in the Saja-Besaya basin.*

Figure 7. *Longitudinal connectivity of the 91E0 habitat in the Pas basin.*

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3.1.3. Vegetation Height

This variable, under the "Dendrometry" category, refers mainly to tree height and includes metrics like dominant, average, and modal height. This variable is particularly relevant for the reporting requirements of the Habitats Directive in the Explanatory Notes & Guidelines for the 2007–2012 reporting period under Article 17 of the Habitats Directive (ETC/BD, 2011) and proposed in the methodological frameworks of several European countries (Ercole *et al.*, 2016; Lara *et al.*, 2019). Furthermore, this variable may be useful in the development of conservation and restoration strategies. For example, vegetation height can serve as an easily measurable indicator of the effectiveness of Nature-based Solutions (NbS) implementation, such as riparian forest restoration actions (*e.g.*, Kettenhuber *et al.*, 2023).

To estimate vegetation height, we used the Normalized Digital Surface Model (NDSM), available as part of Spain's National Aerial Orthophotography Plan (PNOA). This model, derived from a point cloud, enables the calculation of the height of various structures, including vegetation and buildings. Here, the second PNOA coverage (2015-2016), with a mesh pitch of 2.5 m, was used.

In both the Saja-Besaya (Figure 8) and Pas (Figure 9) basins, higher mean vegetation height values are observed in the headwaters, while lower values are found closer to the river mouths.

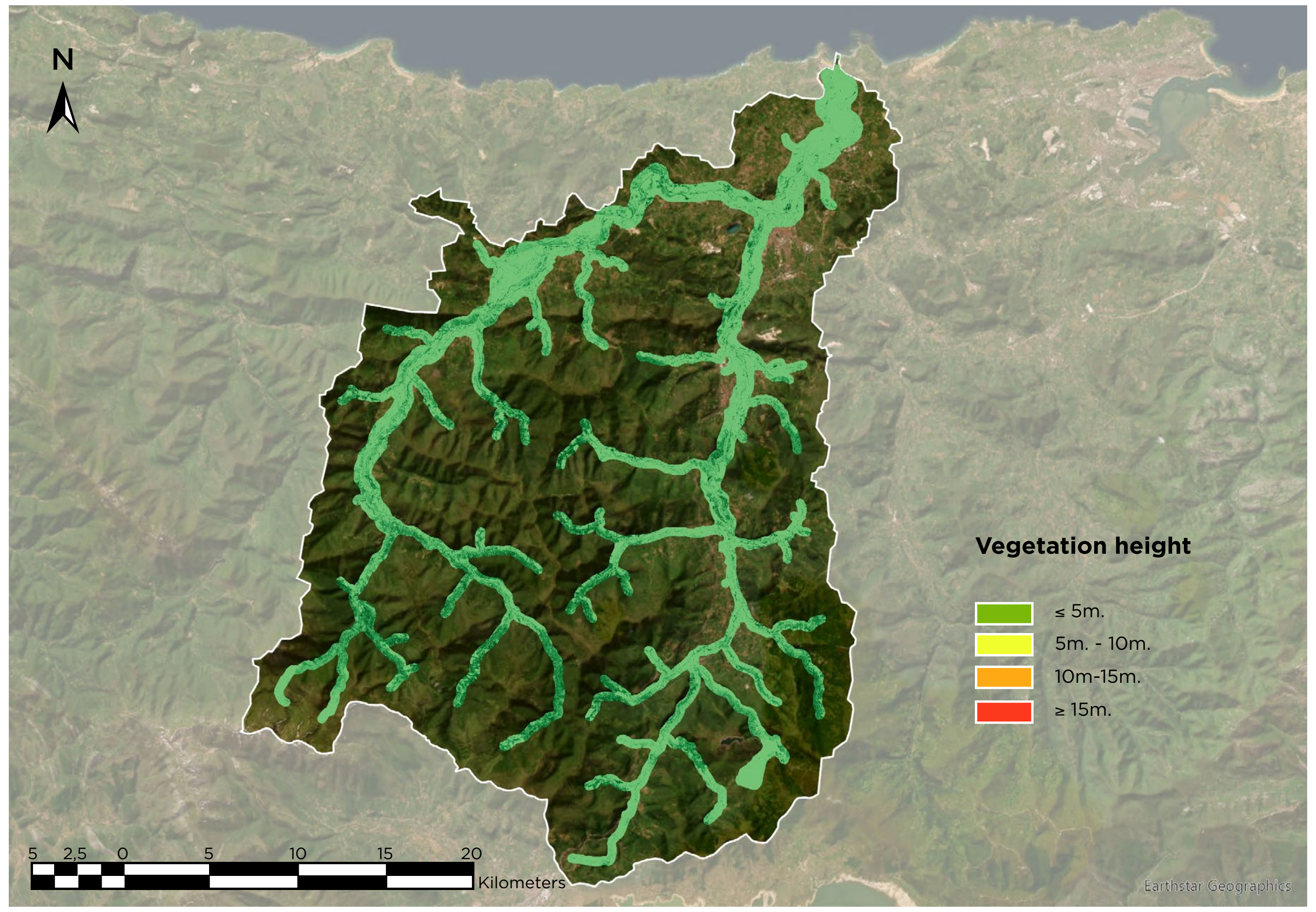

Figure 8. *Mean vegetation height in the Saja-Besaya basin.*

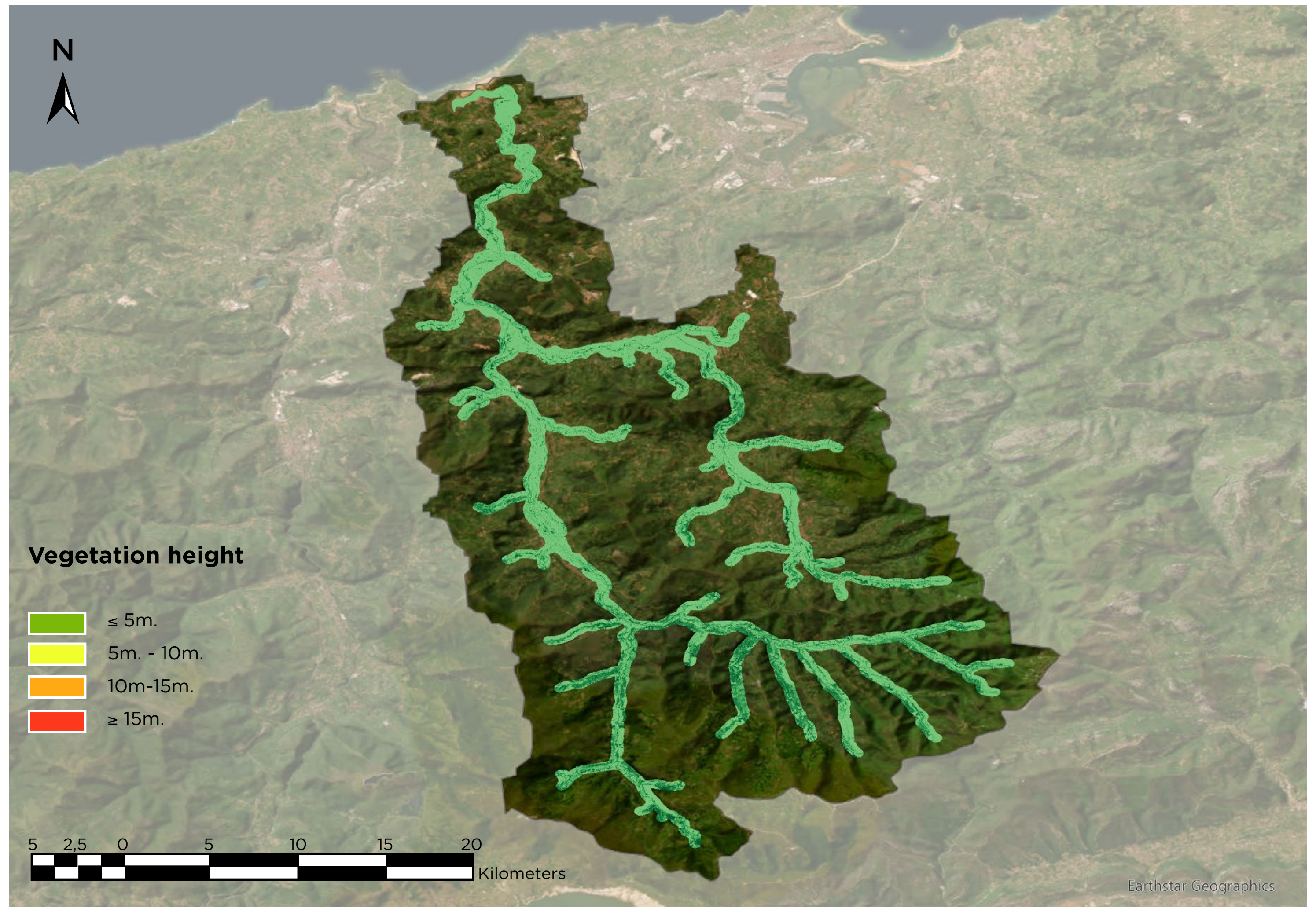

Figure 9. *Mean vegetation height in the Pas basin.*

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3.2 Aquatic domain

3.2.1. Eutrophication

This variable, included in the "Disturbances" category, represents a process closely associated with pollution, characterized by increased primary production within aquatic environments. It occurs when photosynthetic microorganisms, such as algae, proliferate beyond normal levels due to an excessive availability of nutrients. As these microorganisms multiply, they create an anoxic environment, often forming a dense layer that inhibits light penetration. This significantly alters the physical and chemical characteristics of the water, leading to severe ecological imbalances (Khan & Mohammad, 2013).

Evaluating the eutrophication is particularly relevant for assessing the conservation status of aquatic habitats under the Habitats Directive, as noted by Bundesamt für Naturschutz (2017). Its importance is also recognized in the EU-wide methodology for mapping and assessing ecosystem condition, as part of the EU Biodiversity Strategy for 2030. Indirectly, it addresses the requirements of the Water Framework Directive, which, although not explicitly mentioning eutrophication, mandates the evaluation of nutrient status and pollution caused by specific substances.

When calculating this parameter in water bodies, the first step is to accurately define the water-containing areas. To this end, a water mask was obtained using photo-interpreted training points representing various elements of the fluvial landscape—including deep and shallow water—alongside time series of spectral indices (IHCantabria, unpublished). In this case, chlorophyll-a concentration was used as a proxy to assess eutrophication. This approach, proposed by Fedonenko et al. (2022), utilizes the Surface Algal Bloom Index (SABI) to estimate chlorophyll-a concentration in water based on a combination of Sentinel-2 bands [(8a – b4)/(b2 + b3)]. Chlorophyll-a concentration is generally higher near the river banks and in narrow sections of the river (Fig. 12 y 13), although this pattern could be also determined by riparian vegetation over the water-containing area or by the presence of aquatic vegetation in the shallower areas of the river.

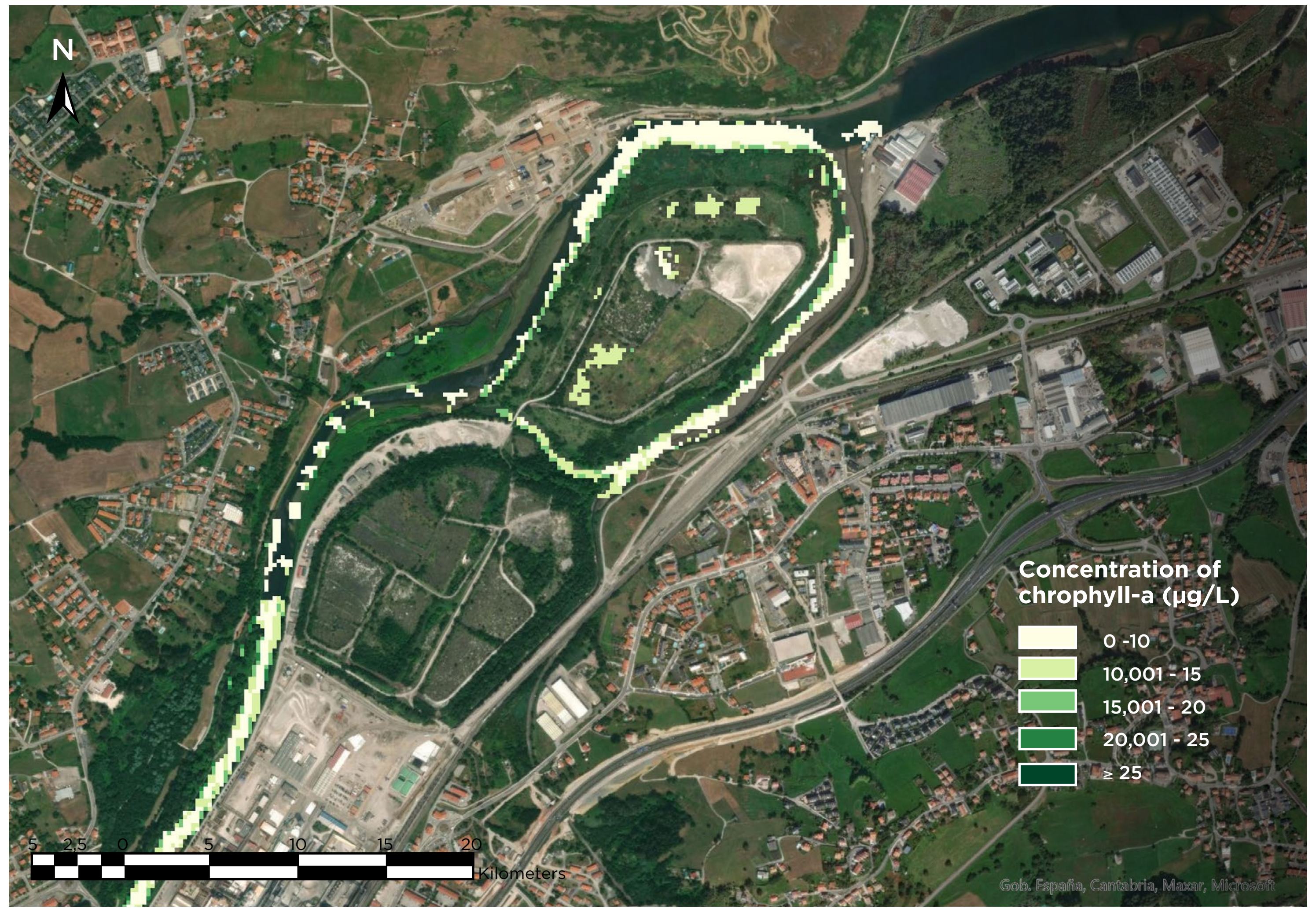

Figure 12. *Chlorophyll-a concentration following Fedonenko et al. (2022) in the Saja river, near Requejada.*

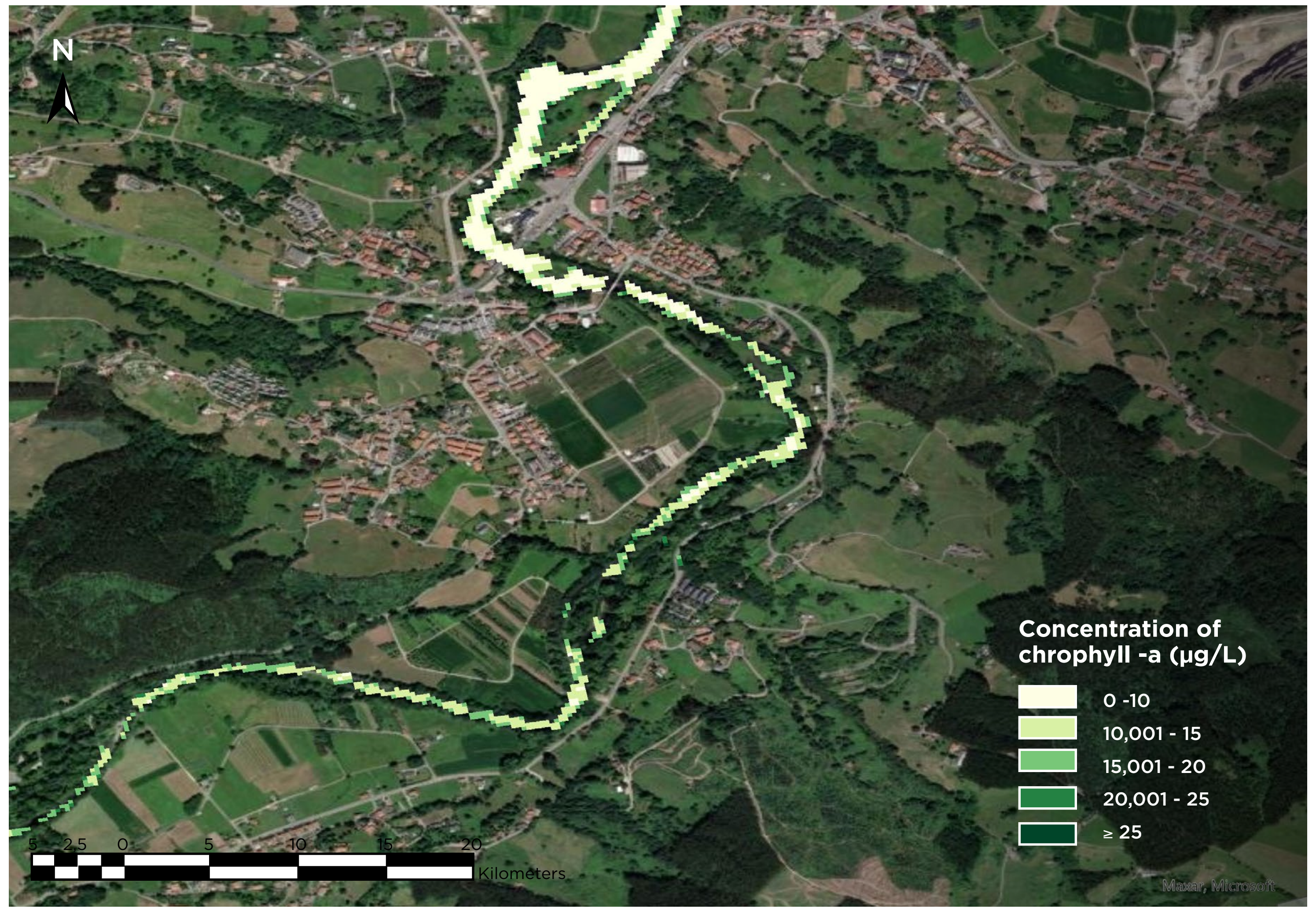

Figure 13. *Chlorophyll-a concentration following Fedonenko et al. (2022) in the Pas River, near Oruña de Piélagos.*

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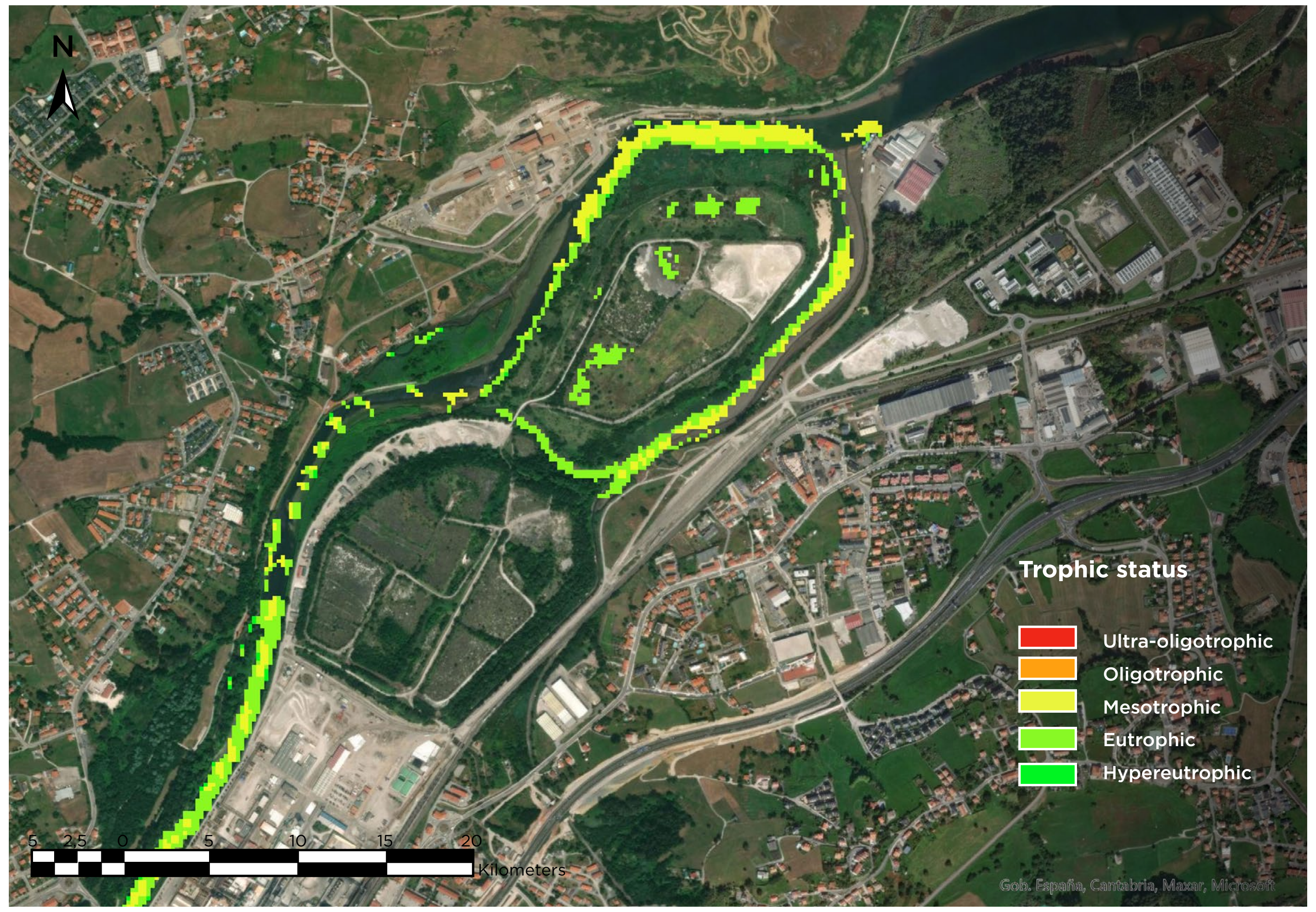
Chlorophyll-a values are then used to calculate the Trophic State Index (TSI), which classifies water bodies into different trophic status classes. Lower TSI values correspond to oligotrophic conditions, while higher values indicate eutrophic status.

The TSI, divided into five distinct classes, allows the visualization of the trophic status of rivers. The Saja (Fig. 14) and Pas (Fig. 15) rivers are predominantly classified as mesotrophic or eutrophic. Hypereutrophic conditions are only found in a few specific reaches of the rivers disperse over the entire fluvial network, and similarly to chlorophyll-a pattern, this occurs in isolated pixels close to the riverbanks.

This approach can provide relevant information to evaluate the eutrophication level in streams at a regional scale and along time; however, its application and accuracy depends on the river width (i.e., minimum width is required to match the spatial resolution of Sentinel-2 images) and the presence of the riparian and aquatic vegetation that could interfere with the reflectance signal of the water component.



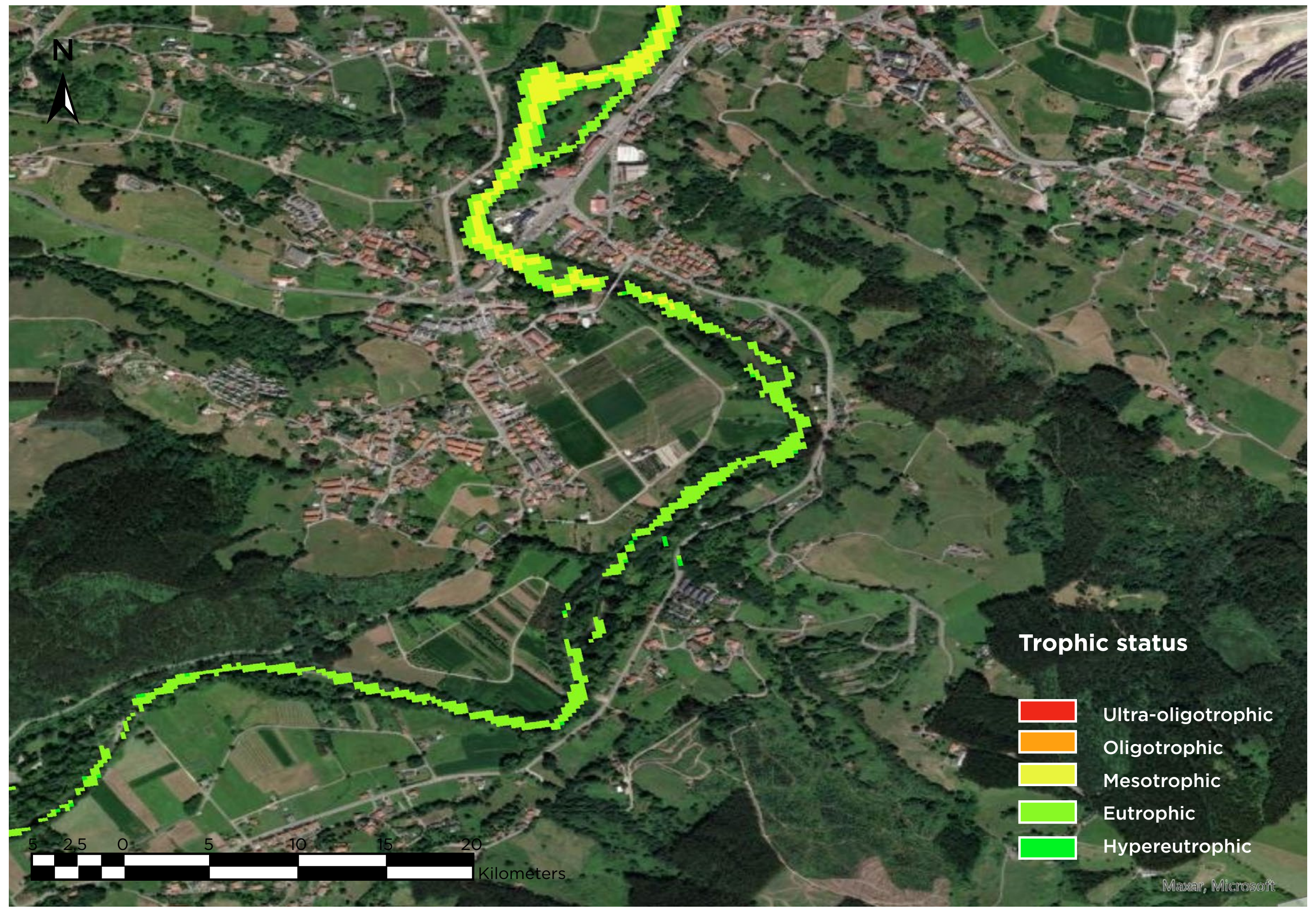


Figure 14. *Trophic status following Fedonenko et al. (2022) in the Saja river, near Requejada.*

Figure 15. *Trophic status following Fedonenko et al. (2022) in the Pas River, near Oruña de Piélagos.*

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3.3 The need for ground truth data for validating the selected indicators

To validate the results obtained for remote sensing indicators, it is essential to incorporate ground truth data from diverse sources. Ground truth data allows for the assessment of the accuracy and reliability of estimates derived from the CLMS products, the calculations based on Sentinel-2, and LiDAR metrics, by comparing them against in situ parameter values. In cases where discrepancies are identified, ground-truth data can be used to refine and enhance methodological approaches for improved precision.

For riparian vegetation-related data, the most accurate validation source consists of field observations conducted by botanists, who identify vegetation formations within riparian zones to the species or habitat level. These data allow to validate land cover classifications obtained from Copernicus products. For riparian forest dasometric data, the primary validation source in Spain is the National Forest Inventory, which provides a comprehensive set of parameters that can be extracted to validate and calibrate models derived from the PNOA project, thereby improving their accuracy.

Regarding aquatic ground data, the most relevant datasets for validation originate from the Monitoring Programmes (including surveillance and operational control) established to evaluate water status in accordance with national and European regulatory frameworks. This monitoring system, known as the Automatic Water Quality Information System (SAICA) in Spain, is managed by the General Directorate for Water Quality. SAICA operates through approximately 200 monitoring stations designed to detect various pollutants and other water quality parameters. The network continuously collects data across multiple river basins in Spain, facilitating the analysis of temporal trends in water quality indicators. Data gathered in specific scientific missions and programs also provide critical input for validating water quality assessments based on remote sensing products.

The need for ground truth data for validating the selected indicators

ACKNOWLEDGMENTS

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