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COMUNIDAD

D4.2
Advanced algorithm for snow coverage

Connecting Europe and Latin America
Transforming Today's Data into
Tomorrow's Solutions

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Project Summary

The COMUNIDAD project, led by Lesprojekt, utilises Copernicus satellite data and the European Global Navigation Satellite System (EGNSS), along with Artificial Intelligence (AI), Big Data technologies and numerical modelling to transfer technologies and know-how to Latin America. The COMUNIDAD project focuses on improving agricultural and forestry management in Chile and Colombia through infrastructure development and a basic platform for creating applications that enhance precision, efficiency, and sustainability. The South American region benefits from this initiative by contributing to its socio-economic growth. Technological advancements are expected to lead significantly to practical applications due to the open-source approach in development.

Lesprojekt, the project coordinator, draws on its expertise in technology applications in agriculture and forestry to guide the consortium. The project provides actionable insights by employing advanced techniques to incorporate Copernicus services, EGNSS and other spatial datasets. These insights help stakeholders, including farmers, advisors, policymakers, and land managers, make informed decisions that support sustainable practices. Essential data on crop health, land use, and forestry conservation are provided, enhancing land management practices and boosting agricultural productivity.

In the COMUNIDAD project, experiences and knowledge are transferred through developing and using technological components, infrastructure, and training materials.

The COMUNIDAD project aims to transform agricultural and forestry management in South America through technological innovation and international collaboration based on experiences and know-how from European partners and based on international cooperation with partners from Latin America. The integration of cutting-edge technologies with strategic data analysis is set to improve different domains and promote environmental sustainability in the region.

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Copyright Statement

Executive Summary

The primary objective of WP4 is to develop and deliver downstream services related to COPERNICUS, which will support decision-making processes in pilot regions of Chile and Colombia. These services, integrated with smart decision tools on the COMUNIDAD platform, will provide high-resolution Earth Observation data, climate services, IoT, and VGI solutions. Specific applications include tools for daily farm operations in Colombia, forest management in Chile, and agro-climatic indicators for risk mitigation and policy support.

Key components of the project in the Chilean Pilot include snow climatology estimation through remote sensing, leveraging Copernicus data to create snow cover maps using the Normalized Difference Snow Index (NDSI). The project also incorporates a System Dynamics approach to assess how snow cover affects economic activities such as agriculture and forestry. A particular focus in Chile is on forest management, especially in terms of native forest restoration and water resource management influenced by snow cover.

One of the Chilean use cases, centered on the Campos de Hielo Norte region in Aysén, focuses on glacier calving monitoring through satellite imagery and remote sensing. This system will support the management of national parks, improve tourist safety, and aid academic research. Another use case in Aysén addresses land use planning for agriculture and forestry, utilizing satellite data to optimize agricultural productivity and sustainable resource management.

These use cases aim to provide solutions to challenges like glacier calving events, inefficient land use, and wildfire management, offering real-time data and predictive models for better decision-making across different sectors, including tourism, agriculture, and environmental management. Key stakeholders include government agencies, local communities, and researchers, who will benefit from the enhanced data accessibility and actionable insights provided by the platform.

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Introduction

The primary goal of WP4 is to develop and provide COPERNICUS downstream services and related applications, which will be utilized directly by pilot users or indirectly through the smart decision tools developed for the pilots and operated via the COMUNIDAD Platform. These tools will be organized and tested in collaboration with project partners and local stakeholders in Chile and Colombia. Key activities include producing high-resolution downstream services to drive Earth Observation data, IoT, VGI, and climate services, developing services for daily farm activities in Colombia and forest management in Chile, and creating agro-climatic indicators for climate risk mitigation and policy recommendations. The project will also assess the impact of conventional and smart farming practices, and sustainable forestry, ensuring data products are validated for completeness, precision, and accuracy.

A critical methodology involves estimating snow/no-snow climatology using remote sensing optical and radar synergy. Copernicus data will generate seasonal snow composites at multiscale spatial resolutions, with the Normalised Difference Snow Index (NDSI) determining snow cover areas. Gaps in data due to cloud cover will be addressed using an algorithm based on stochastic processes to estimate obscured regions accurately. Additionally, a System Dynamics approach will link snow cover with economic activities such as agriculture and forestry, identifying feedback loops and evaluating policy suggestions through Dynamic Performance Management.

In Chile, WP4 will focus on forest management, particularly the recovery and restoration of native forests and the stress on natural areas. Agroclimatic variables will help land users manage crops more effectively, while understanding snow cover quality will impact water supply, productive activities, and the development of new small-scale hydrogenation projects. Collaboration with Chilean institutions like FIA and CONAF will be crucial for exploring deployment opportunities and technology transfer.

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1 Use cases of the Chilean Pilot

1.1 Use case – Campos de Hielo Norte: Snow Cover Identification and Glacier Monitoring

1.1.1 Overview

The Aysén region is home to 41.52% of the national glacier surface, which is equivalent to an estimated volume of 1236 km^3 of liquid water (According to the Dirección General de Aguas in its “Inventario Público de Glaciares”). This positions glaciers as a key factor for the economic development of the region, with a significant impact on activities such as forestry, agriculture and tourism.

In recent years, the unpredictability of glacial outbursts has been a constant challenge for both tourism operators and national park authorities. These events can cause sudden restrictions on access to popular tourist destinations, negatively affecting the local economy and generating serious safety risks for visitors. Over the past decade, the Chilean Ministry of the Environment and various research institutions have highlighted the importance of addressing these risks, especially in the context of climate change and increasing glacier retreat.

The management of these ice bodies by the authorities has been based mainly on sporadic manual monitoring. However, this approach is insufficient to detect and prevent hazards in a timely manner, which has led to the implementation of policies that are more reactive than preventive.

Against this backdrop, the COMUNIDAD project proposes an innovative solution based on the use of remote sensing technologies. Through real-time data analysis, this initiative seeks to optimize the prediction and management of glacial movements, offering a more effective tool to mitigate risks and ensure the safety of both communities and visitors.

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1.1.2 Proposed solution

The primary focus of this use case is to implement a comprehensive system for monitoring glacier calving in the Campos de Hielo Norte region of Aysén (Exploradores Glacier in the Northern Patagonian Ice Field), Chile.

The proposed system will use satellite imagery and remote sensing technologies to provide both real-time and historical data on glacier dynamics. This includes employing a Snow Cover Algorithm based on the Normalized Difference Snow Index (NDSI) to determine snow cover areas and track seasonal changes. Additionally, to account for cloud cover, a stochastic-based algorithm will fill in data gaps, ensuring comprehensive monitoring of the glacier's status.

The solution involves developing a real-time glacier monitoring system by integrating satellite data from the Copernicus Sentinel-1 and Sentinel-2 missions with local climatic data. The system will employ advanced algorithms to track glacier movements, predict calving events, and provide early warnings to mitigate risks.

The data collected will enhance environmental management by supporting the National Forestry Corporation (CONAF) in its conservation efforts and ensuring visitor safety, support the tourism sector for looking possibly secure access routes to glaciers and provide valuable insights to academic institutions like the University of Aysén, enriching their research programs in forestry engineering and environmental sciences, while fostering local expertise in glaciology and climate studies.

1.1.2.1 Key Components of the Solution

- Snow Cover Algorithm using the NDSI to determine snow cover and its seasonal variations.
- Stochastic-based data interpolation to address cloud coverage issues, ensuring continuous monitoring of the glacier surface.
- Machine Learning models to predict potential calving events based on historical patterns and current environmental variables.

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1.1.2.2 *Expected Outcomes*

- Real-time hazard detection: Timely alerts for glacier calving events to enhance visitor safety and reduce accidents.
- Improved park management: Data-driven insights to support the planning and regulation of tourist activities in glacial areas.
- Academic and research support: Valuable datasets for researchers and academics to study glacier dynamics and climate change impacts in the region.
- Economic stability: By ensuring the safety and accessibility of key tourist destinations, the system will help maintain local economic activities tied to tourism.

1.1.3 Pipeline for Glacier Monitoring in Campos de Hielo Norte

Inputs

Data Sources

- Satellite Imagery
  - Copernicus Sentinel-1 (SAR – Synthetic Aperture Radar) for glacier movement monitoring.
  - Copernicus Sentinel-2 (multi-spectral imaging) for snow cover analysis using the Normalized Difference Snow Index (NDSI).
- Local Climate Data
  - Temperature, precipitation, and wind data from local weather stations (e.g., Dirección Meteorológica de Chile).
- Historical Records
  - Glacier movement patterns and calving events over the last decade.

Processes, Procedures, and Analyses

Data Collection

- Automated Satellite Imagery Retrieval: Automated download of Sentinel-1

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and Sentinel-2 data, focusing on the Exploradores Glacier and nearby glaciers in the Campo de Hielo Norte.

- Preprocessing
    - SAR imagery preprocessing to detect glacier displacement and possible stress zones indicating calving potential.
    - Snow cover determination using NDSI from Sentinel-2 images to track seasonal variations in snow and ice cover.

Data Analysis

- Glacier Calving Prediction
    - Machine learning models trained on historical calving data and climate patterns to predict potential calving events.
- Cloud Obscured Area Prediction
    - Integration of stochastic models to estimate snow cover in regions obscured by clouds, ensuring continuous monitoring.

Integration

- Multiscale Integration: Combining satellite data with local weather station data to improve predictive accuracy of glacier dynamics and related hazards.
- Snow Cover Algorithm: Utilizing the NDSI to generate snow cover maps and linking them with glacier movement data for better forecasting.

Visualization

- Dashboards & Maps
    - Interactive dashboards for real-time visualization of glacier movement, snow cover, and calving predictions.
    - Risk assessments mapped for tourist and environmental

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management purposes, including real-time alerts for potential hazards.

1.2 Use Case – Land Use Planning for Agricultural and Forestry Practices in Aysén Region (SilvoAgroPecuarias)

1.2.1 Overview

The region faces ongoing challenges related to inefficient land use practices, environmental degradation, and limited water resource management, all of which affect productivity and sustainability. The National Forestry Corporation (CONAF) and the Ministry of Agriculture have identified these issues as key concerns, requiring advanced solutions to support more effective land management.

This situation is clearly reflected in the evolution of the agricultural and livestock sectors at national and regional level. According to the "Censo Agropecuario 2021", there are approximately 26 million hectares worked in Chile, which contributed to a sectoral GDP of 8,566.77 billion Chilean pesos in 2023 (according to the Banco Central de Chile). Although the Aysén Region is the second nationally in terms of worked area, representing 12.38% of the total, its contribution to the sector's GDP in 2023 was barely 0.23%. This evidence shows an inefficient use of the extensions of worked land in the region.

According to the 2021 Agricultural Census, livestock farming is the predominant activity in the Aysén Region, representing 67.38% of agricultural production units, which makes it a fundamental pillar of the regional economy. However, in meetings with entities such as the Ministry of Agriculture, the National Agricultural Society (SNA), Agrotech and local stakeholders, it became evident that this sector is facing growing environmental and productivity challenges due to inefficient resource management, the impact of climate change and unsustainable grazing practices. These problems have generated multiple consequences, among them:

- Water pollution and overexploitation due to inefficient irrigation systems and

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inadequate management of livestock waste.

- Deterioration of grasslands caused by overgrazing, which accelerates soil erosion and biodiversity loss.
- Low adoption of regenerative grazing practices, which could improve the sustainability of the sector.
- Seasonal variations in snow cover, which affect water availability and complicate livestock planning.
- Lack of predictive tools to monitor drought and pasture health, increasing farmers' vulnerability to climate variability.

In terms of land use in Aysén, there is a predominant lack of diversification, with approximately 78% going to native forest and 10% to grasslands. In contrast, the O'Higgins Region, with only 3% of the hectares worked at the national level, generates around 21% of the sectoral GDP 2023, standing out for its broad diversification of land use, which includes native forest, pastures, fruit trees, cereals, grapevines, among others. The Aysén region struggles with inefficient land use practices due to limited data availability and reliance on manual observations, leading to suboptimal decision-making in agriculture and forestry. Additionally, seasonal variations in snow cover affect water availability, creating further challenges for farmers and foresters. Current approaches to land use planning and water management are insufficient to address these issues effectively.

The Aysén region faces inefficient land use practices due to limited data availability and reliance on manual observations, resulting in poor decision making in agriculture, livestock and forestry, highlighting the need to implement advanced technological solutions and sustainable management strategies to improve the productivity and resilience of the sector.

Against this backdrop, the COMUNIDAD project proposes an innovative solution based on the use of remote sensing technologies. Through real-time data analysis, this initiative seeks to complement current approaches to land use planning and water

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management to enhance their effectiveness.

1.2.2 Proposed solution

The primary focus of this use case is to develop a comprehensive system for optimizing agricultural and forestry land use in the Aysén region of Chile through satellite technology.

The proposed system will leverage satellite imagery from the Copernicus Sentinel-1 and Sentinel-2 missions, combined with local climate data, to provide detailed and real-time information on land cover, soil health, vegetation indices (NDVI, EVI, and LAI), assess crops, forest health, and snow cover. This data will be processed using predictive algorithms to support integrated watershed management and sustainable agricultural and forestry practices. Additionally, snow cover monitoring will be enhanced by employing the Normalized Difference Snow Index (NDSI) to better understand water availability during different seasons.

By implementing this system, the Aysén region can achieve more precise land use planning, enhance resource management, and improve the productivity and sustainability of both agricultural and forestry practices. This will also contribute to the goals of Chile's National Strategy for Watershed Management and the National Rural Development Policy by promoting balanced regional development and reducing economic disparities.

1.2.2.1 Key Components of the Solution

Vegetation and Pasture Analysis

- Use of NDVI, EVI, and LAI: To monitor pasture health, optimize rotational grazing, and support regenerative agricultural practices.
- Pasture Suitability Mapping: Identification of areas requiring reforestation, fertilization, or rotational grazing based on soil health and vegetation indices.

Water Balance and Snow Cover Monitoring

- Application of the Normalized Difference Snow Index (NDSI): To track seasonal snow cover variations and assess water availability for pasture irrigation and forestry.

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- Water Balance Monitoring: Integration of Copernicus data and local hydrological datasets to track watershed dynamics and identify drought-prone zones.

1.2.2.2 Expected Outcomes

Predictive Analytics and Decision Support

- Machine Learning Algorithms: To provide recommendations on optimal grazing patterns, irrigation scheduling, and land use planning based on historical and real-time data.
- Water Availability and Risk Mapping: GIS-based analysis of water distribution trends, identifying areas at risk of drought, overuse, or contamination.

Real-Time Monitoring and Climate Adaptation

- Integration of Satellite Imagery with Local Climate Data: To provide continuous updates on pasture conditions, snow cover, and water availability.
- Climate Risk Mitigation: AI-driven climate models to anticipate temperature and precipitation trends affecting livestock productivity and land use.

1.2.3 Pipeline for Land Use Planning

Inputs

Data Sources

- Satellite Imagery
  - Copernicus Sentinel-1 (SAR) for monitoring land use changes, soil moisture, and forest health.
  - Copernicus Sentinel-2 (multi-spectral imagery) for vegetation indices (NDVI, EVI, LAI) and snow cover analysis.
- Local Climate Data
  - Temperature, precipitation, and wind patterns from local weather stations (e.g., Dirección Meteorológica de Chile).

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- Historical Records
    - Data on land use, fire incidents, and climate patterns that impact agricultural and forestry activities.

Processes, Procedures, and Analyses

Data Collection

- Automated Data Retrieval
    - Automatically download satellite images from Sentinel-1 and Sentinel-2 at set intervals (daily, weekly, or monthly), focusing on the Aysén region.
    - Preprocess the data for further analysis, including correcting distortions and aligning images with local maps.

Data Analysis

- Predictive Analytics for Agricultural Practices
    - Use machine learning algorithms to analyze vegetation indices (NDVI, EVI, LAI) for optimizing agricultural decisions like planting and irrigation.
- Forestry Optimization
    - Analyze forest health using soil moisture data and predict potential risks like fires or land degradation.
- Snow Cover and Water Resource Planning
    - Apply snow cover algorithms to understand water availability for agricultural and forestry practices during different seasons.

Integration

- Combining Satellite and Climate Data
    - Integrate satellite imagery with local climate data (temperature,

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precipitation, wind) to enhance predictive accuracy for agricultural and forestry planning.

- Incorporate snow cover data for a holistic view of water resource management, especially important for land managers who rely on consistent water availability.

Visualization

- Dashboards and Maps
  - Create easy-to-use dashboards that visualize real-time data, such as vegetation health, snow cover, and fire risk maps.
  - Provide interactive maps for regional land use planning, showing areas with the highest agricultural or forestry potential.

1.3 Use Case: Forest Fire Prevention and Management in Aysen region Chile

1.3.1 Overview

The primary focus of this use case is to implement a comprehensive system for forest fire prevention and management in the Aysén region of Chilean Patagonia. The region is highly susceptible to forest fires due to prolonged drought conditions, changing climate patterns, and the presence of combustible vegetation. The devastating megafires of 2017, which affected large areas between Valparaíso and La Araucanía, have underscored the urgency of improving fire management strategies.

The development of innovative tools to implement both preventive and reactive strategies in the face of forest fires is of vital importance for the Aysén Region. According to National Forestry Corporation's (CONAF) Land Use and Vegetation Resources Cadastre, this region has the highest percentage of land use in forests, representing 24.52% of the approximately 18 million hectares destined for this purpose at the national level.

In relation to forest fires, the same cadastre reports that, between 2018 and 2024, the Aysén Region recorded a total of 194 fires that affected an area of 17.631 hectares. Some

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periods stand out for the disparity in the impact of fires. For example, in 2018-2019, with 40 fires recorded, the damaged area amounted to 15.712 hectares. In contrast, during 2020-2021, 48 fires were declared, affecting only 36,8 hectares. Finally, in 2021-2022, 35 fires were reported with a damaged area of 1.692 hectares.

The current approach to fire management is largely reactive, relying on manual observations and delayed responses, which are insufficient for timely hazard detection and prevention. These limitations increase the risk of uncontrolled fires, leading to significant ecological damage and economic losses in affected communities.

The disparity between the number of fires and the area affected shows that factors such as environmental conditions and accessibility to the area play a determining role in the magnitude of damage. It is therefore essential to develop tools to mitigate the impact of these elements and strengthen both prevention and response to forest fires.

1.3.2 Proposed solution

This system is designed to leverage satellite imagery from the Copernicus program, combined with local climate data, to identify high-risk areas and monitor fire hotspots in real time. By integrating predictive models, such as the McArthur Forest Fire Danger Index and the Canadian Fire Weather Index, the system aims to enhance wildfire risk assessments. The integration of the McArthur Forest Fire Danger Index and the Canadian Fire Weather Index into the wildfire risk assessment system for Chile presents a promising approach to enhancing fire prevention and management capabilities. These indices have been successfully applied in various regions with temperate and boreal climates; however, their direct application in Chile requires careful consideration and adaptation. The unique climatic conditions, environmental parameters, and vegetation types of Chile, particularly in the subantarctic region of Aysén, necessitate a thorough re-evaluation of the indices' parameters to ensure their relevance and accuracy in local contexts. Given the significant climatic differences, such as precipitation patterns, temperature variations, and vegetation fuel loads, it is essential to recalibrate the models to reflect the specific fire behavior dynamics in Chile.

The proposed solution leverages Copernicus satellite imagery in combination with local climate data to identify high-risk areas and monitor fire hotspots in real time. Predictive models, including the McArthur and Canadian indices, will serve as a foundation for risk

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assessments; however, adjustments will be made to incorporate region-specific variables. Advanced AI techniques will be utilized to analyze fire spread patterns, while drones and aerial platforms equipped with depth cameras will provide high-resolution data to improve early detection and damage assessment capabilities. Although similar models have been applied in neighboring Argentina, their direct implementation in Chile requires further research and validation. The project will therefore focus on evaluating the necessary parameter adjustments, ensuring that the indices accurately represent the region's fire risk. This process will involve close collaboration with local experts and stakeholders to refine the models and optimize them for the unique ecological and meteorological conditions present in Aysén and other high-risk areas of Chile.

1.3.2.1 Key Components of the Solution

- Satellite Data Integration: Utilize Sentinel-1 (SAR) and Sentinel-2 imagery to monitor vegetation health, land cover changes, and fire hotspots.
- Weather Monitoring: Incorporate local climate data (temperature, humidity, wind speed) to assess conditions that contribute to fire risk.
- Predictive Analytics: Apply AI models to identify high-risk areas based on historical fire patterns and current climatic variables.
- Real-Time Monitoring: Use drones and aerial platforms to capture detailed images of fire-affected areas, complementing satellite data for faster detection and response.
- Fuel Management: Implement controlled burns and other fuel reduction strategies to minimize the availability of combustible materials in high-risk zones.

1.3.2.2 Expected Outcomes

- Enhanced Early Warning Systems: Provide timely alerts for fire outbreaks, improving response times and reducing the risk of large-scale fires.
- Proactive Fire Management: Identify and prioritize high-risk areas for preventive actions, improving resource allocation for firefighting efforts.
- Community Preparedness: Increase public awareness and promote fire-safe

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practices through training workshops and educational programs.

- Environmental and Economic Benefits: Mitigate the destruction of ecosystems and reduce the financial impact of fire-related damages by preventing the spread of fires.
- Support for Policy and Research: Offer valuable data for government agencies and researchers to improve long-term fire management strategies and understand climate change impacts on fire risks.

1.3.3 Pipeline for Proactive Fire Management

Inputs

Data Sources

- Satellite Imagery
  - Copernicus Sentinel-1 (SAR) for monitoring land cover changes and fire risk indicators.
  - Copernicus Sentinel-2 (multi-spectral imaging) for detecting vegetation health and fire hotspots.
- Local Weather Data
  - Temperature, precipitation, and wind speed from weather stations to assess conditions that contribute to fire risk.
- Historical Fire Records
  - Fire incidents and patterns over the past years to train predictive models and improve risk assessments.

Processes, Procedures, and Analyses

Data Collection

- Automated Data Retrieval: Regular downloads of Sentinel-1 and Sentinel-2 data, focusing on areas identified as high risk in the Aysén region.

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- Drones and Aerial Platforms: Drones equipped with depth cameras to capture detailed images and support early detection of fire outbreaks, complementing satellite data.

Data Analysis

- Machine Learning Algorithms: AI-driven models to analyze climatic variables (temperature, wind, humidity) and vegetation indices (NDVI, EVI) to predict fire risk and detect early outbreaks.
- Fire Spread Simulation: Using historical fire patterns and real-time weather data, predictive models simulate potential fire spread scenarios to assist in preemptive firefighting efforts.

Integration

- Combining Satellite and Local Data: Integrate satellite imagery with local climate data for enhanced precision in identifying areas with the highest risk.
- Fire Danger Index Integration: Implement predictive models like the McArthur Forest Fire Danger Index and the Canadian Fire Weather Index to provide real-time risk assessments.

Fuel Management

- Controlled Burns and Fuel Reduction: Implement fuel management strategies in high-risk zones, based on ecological conditions, to minimize the availability of combustible materials.
- Post-Fire Recovery Monitoring: Monitor regrowth and recovery in post-fire zones to inform long-term land management strategies.

Visualization

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- Dashboards and Maps: Create interactive dashboards showing real-time fire risk maps, active fires, and weather conditions. These will provide early warnings and alert systems for local authorities and the public.
- Risk Assessment: Display dynamic maps to highlight areas of high fire risk and track the progress of fires in real time.

1.4 Overview of Use Cases and Snow Cover Algorithm

Use Case	Key Problem Addressed	Main Data Sources	Data Frequency	Target Users	Expected Outcomes
Campos de Hielo Norte Glacier Monitoring	Unpredictable glacier calving events affecting tourism safety and park management.	Sentinel-1 (SAR), Sentinel-2 (NDSI), local climate stations.	5–10 days (Sentinel-2), 6 days (Sentinel-1)	CONAF, tourism operators, researchers	Real-time data for hazard warnings, enhanced park safety, and improved research opportunities.
Land Use Planning for Agriculture and Forestry	Inefficient land use practices leading to environmental degradation and reduced agricultural productivity.	Sentinel-1 (SAR), Sentinel-2 (NDVI, LAI), local climate data	Weekly to monthly	Farmers, land managers, government agencies	Optimized resource management, improved crop yields, and sustainable forestry practices.
Forest Fire Prevention and Management	Increasing severity and frequency of forest fires due to prolonged droughts and climate change.	Sentinel-1, Sentinel-2 (fire risk indicators), local weather data	Real-time	CONAF, SENAPRED, local communities	Early fire detection and risk assessment, reduced economic and ecological damage, improved community preparedness.

In addition to addressing the various use cases mentioned above, a snow cover algorithm for data processing and generation of information on the state of snow cover

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in the territory is proposed and developed. This development has a direct impact on the previously mentioned use cases. Furthermore, it is not only expected to be implemented in these specific cases, but it is also expected to be applied in a transversal way, adapting to the analysis needs of the end user. The considerations taken into account for the development of this tool are presented in the following table.

Algorithm	Key Problem Addressed	Main Data Sources	Data Frequency	Target Users	Expected Outcomes
Snow Cover	Reduced snow cover affecting water availability for agriculture and forestry, with potential impacts on energy production.	Sentinel-2 (NDSI), local snow and climate data	5–10 days	Farmers, hydrologists, energy sector stakeholders	Accurate water resource predictions, optimized irrigation planning, and better agricultural/forestry decisions during critical seasons.

2 Users and target groups

2.1 Introduction

The Aysén region of Chile presents a unique landscape, both economically and environmentally, with its agricultural and forestry sectors playing a central role in sustaining local livelihoods. Characterized by small and medium-sized family farms as well as larger producers, the region's economic activities are deeply tied to natural resources. The agricultural and forestry sectors, while crucial, face ongoing challenges related to sustainability, resource management, and climate change, requiring innovative solutions to balance productivity with environmental stewardship. As such, technological tools capable of supporting decision-making in these sectors are becoming increasingly vital for ensuring long-term sustainability and economic growth.

The Aysén region, recognized for its vital agricultural and forestry sectors, holds significant potential for integrating advanced geospatial technologies to optimize resource management and land use planning. One notable initiative is the collaboration with government-led projects like IDE-Chile (Chile's Spatial Data Infrastructure -

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Infraestructura de Datos Espaciales de Chile. The implementation of GEONODOS (GEONODES) under IDE-Chile presents a key opportunity for advancing data-driven decision-making. These geoportals, which provide centralized access to regional geospatial resources, enhance the capacity of local stakeholders to visualize, analyze, and manage territorial data efficiently. The IDE-Aysén, specifically, aims to streamline the region’s geospatial data management, promoting transparency, digitalization, and the interoperability of territorial information. This system is designed to be accessible to a wide range of users, from governmental agencies to local communities, facilitating more informed decision-making processes across the board.

The regional IDE-Aysén initiative is closely aligned with broader national goals, as reflected in the work of the IDE-Aysén working group, which engages multiple stakeholders, including local governments, universities, and research institutions like the Nodo Ciencia Austral (Austral Scientific Node for Subantarctic Regions – Magallanes and Aysén). This platform presents a crucial tool for advancing scientific research and fostering collaboration in key areas, such as climate change, sustainable development, and biodiversity management. Moreover, the regional IDE fosters integration with local initiatives, allowing for the seamless exchange of geospatial information that can be leveraged in both public policy and private sector operations. Through continued collaboration between IDE-Aysén and the broader IDE-Chile framework, there is substantial potential for building a more connected, informed, and sustainable approach to territorial management in the Aysén region.

In a broader spectrum, the pilot developed in Chile aims to collaborate closely with national and local actors, as previously mentioned. Given the geopolitical dynamics of the southern austral macrozone, it is common to encounter multiple initiatives and evident over-intervention in the territory, which creates expectations among individuals and organizations. Therefore, coordinating with groups such as those involved in the IDE-Aysén working group and its members facilitates a more effective engagement with users, enhancing the potential use of the platform being developed.

In light of this, the development of a tailored digital platform for Aysén's farmers and foresters is essential. This platform must integrate advanced technologies such as remote sensing, predictive analytics, and real-time data to address key regional needs. By incorporating environmental indicators like snow cover, precipitation patterns, and wind data, the platform can assist land managers in optimizing their resource use and

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improving resilience against climate variability. Equally important is the platform's accessibility, as it should cater to a range of digital literacy levels among users, from tech-savvy individuals to those less familiar with digital tools. With the majority of households having internet access, a mobile-friendly and user-centered design will be crucial in ensuring widespread adoption and impact.

The application must be tailored to the specific needs of farmers and foresters in the Aysén region of Chile. Aysén's agricultural landscape is characterized by small to medium-sized family farms, alongside larger producers, as noted by ODEPA. To maximize its effectiveness, the platform must consider the following key regional characteristics:

2.2 Key Regional Characteristics

- **Economic Impact**: The silvoagricultural sector in Aysén, which includes both agriculture and forestry activities, represents approximately 1.7% of the region's GDP. On the other hand, the fishing industry, a key economic driver for the region, contributes a significant 35.5%. From 2022 to 2023, this sector saw remarkable growth, with its value increasing by 11.4%, rising from $11.65 billion to $12.98 billion. This growth can be attributed to the region's thriving fishing industry, particularly in areas such as salmon farming, which continues to experience rising global demand and production.
- **Environmental Considerations**: The silvoagricultural sector in Aysén is responsible for approximately 34% of the region's total greenhouse gas (GHG) emissions, highlighting the critical need for more sustainable agricultural and forestry practices. However, Aysén's extensive forest cover also plays a significant role in carbon sequestration, making the region a net carbon sink. The forests in Aysén absorb more carbon dioxide than they emit, positioning the region as a crucial contributor to carbon capture efforts both for Chile and globally. This dual role emphasizes the importance of balancing emissions with enhanced forest management practices to maximize Aysén's potential as a carbon sink, while simultaneously reducing its GHG emissions through sustainable land use.
- **Population and Rural Dynamics**: In Aysén, rural dynamics present a complex and varied picture, with the region's rural population making up about 20.4% according

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to INE, although the OECD estimates it as high as 44% due to different metrics and definitions of "rurality." This rural population is predominantly dependent on agriculture and forestry, making it a critical target for development initiatives. However, given the vast distances and challenging terrestrial access across the region, reaching individuals directly is often difficult. As a result, the focus will shift toward organized groups such as agricultural associations, community leaders, and participants in initiatives like the IDE-Aysén working group. Additionally, specialized offices within the region's 10 municipalities and professionals working in government services—particularly those identified by key institutions like the Foundation for Agricultural Innovation (FIA) and the National Forestry Corporation (CONAF)—will be prioritized in the platform's initial rollout. This strategic engagement will enhance the impact of the platform, making it more accessible and useful to key stakeholders in the region.

- **Agricultural and Forestry Activities**: Key agricultural crops in Aysén include cherries, red apples, and blueberries, with the latter becoming increasingly significant in both domestic and international markets due to rising demand. The forestry sector, focused on species such as evergreen forest, lenga, and Magellanic coihue, covers a considerable portion of the region. Agricultural activities occupy 0.1% of the national territory, whereas forestry spans a vast 29.8%. Livestock farming also plays an important role, with Aysén contributing 1.9% of national beef production and 4.5% to sheep farming.
- **Apiculture**: Apiculture in the Aysén region represents a small but valuable part of Chile's beekeeping sector. The region hosts approximately 0.9% of the nation's apiaries, 0.2% of the hives, and 1.2% of the beekeepers. Despite its modest scale, this contribution is important due to the region's unique environmental conditions, which provide favorable circumstances for beekeeping. Beekeeping in Chile is part of a broader initiative to improve honey production and promote sustainable apiculture practices, helping beekeepers increase both productivity and income. Programs supporting modern beekeeping techniques and sustainable management have positioned Chile, including regions like Aysén, as key players in the global honey market.
- **Irrigation and Exports**: The General Carrera sector in Aysén primarily utilizes drip irrigation systems, which have proven effective in reducing water usage while

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enhancing crop quality and yield. This technology is particularly important in regions where water conservation is critical for sustainable agricultural practices. Aysén's exports reflect a diverse agricultural economy, contributing 8.6% to Chile's national dairy production. Additionally, while the region's contribution to fresh fruit and flower exports is smaller, at 0.1% and 0.5% respectively, these sectors remain vital for local economic growth. Drip irrigation helps optimize the productivity of these agricultural activities by ensuring efficient water management, particularly for high-value crops like fruits.

The platform being developed for the Aysén region must be designed with a deep understanding of the area's unique agricultural and forestry characteristics. Aysén's economy relies significantly on small to medium-sized family farms, forestry activities, and a thriving fishing industry. However, it faces challenges such as high greenhouse gas emissions from silvoagricultural activities, vast distances, and limited terrestrial access. To address these issues, the platform must cater to the specific needs of key stakeholders—farmers, foresters, and local organizations—by integrating environmental data and ensuring accessibility through organized groups like IDE-Aysén and key governmental institutions.

2.3 Primary Objectives and Features

- **For Agricultural Users**: The platform should support farmers in agricultural planning, resource management, and risk mitigation by integrating key environmental indicators like snow cover, frost, precipitation, and wind. These indicators are crucial in the Aysén region, where agriculture heavily depends on accurate weather data to inform planting, irrigation, and harvesting decisions. The platform will initially focus on groups that work with the Foundation for Agricultural Innovation (FIA), such as producer associations in Chile Chico and near the Exploradores Glacier, El Fraile sector and Ñirehuao, etc. It will also prioritize women farmers and rural youth organized through local chambers of commerce and initiatives like IDE-Aysén.
- **Snow Cover Monitoring**: Monitoring snow cover in Aysén is crucial due to its significant impact on water availability, agricultural planning, and local economies. As snow cover diminishes, the region's reliance on meltwater from glaciers, such as the Exploradores Glacier, becomes more pronounced. In recent

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years, studies have shown a decreasing trend in snow cover in the Aysén River Basin, which could affect the availability of water for agriculture during the dry season. This declining snow cover, combined with rising temperatures and changing precipitation patterns, signals potential challenges for water management in the region. Seasonal streamflows have also been decreasing, which may further stress agricultural and energy production activities, both of which rely on consistent water availability.

For the tourism sector, the melting of glaciers, particularly the Exploradores Glacier, presents unique challenges. While the glacier is a major attraction, its retreat and the associated risks have led to increased safety measures and even temporary closures of trekking routes. These disruptions not only affect the tourism industry but also emphasize the importance of accurate and timely snow and glacier monitoring for both environmental and economic planning. Collaboration with organizations like CONAF, MOP and SERNAGEOMIN will be key in integrating this data into sustainable development strategies, helping balance conservation efforts with the region's economic needs.

- **Forestry Sector Integration**: In the forestry sector, integrating advanced tools for monitoring forest health and tracking land-use changes is essential. The platform should offer capabilities to assess the impacts of climatic conditions on forest growth and productivity. Additionally, monitoring fire risks will be a key priority, with tools providing real-time alerts for high-risk zones. This will assist both **CONAF** and **SENAPRED** in managing and mitigating wildfire risks across Aysén, with the support of local emergency services and regional authorities. Forest fires, driven by climate change and land-use patterns, present a significant threat. Tools like Geographic Information Systems (GIS) are invaluable for predicting fire risks, tracking active fires, and supporting post-fire recovery efforts. This technology enables precise monitoring of forest conditions and helps to inform decision-making processes for sustainable forest management.

  Moreover, forestry management must extend beyond protected areas. Ministries, such as the **Ministerio de Bienes Nacionales**, play a crucial role in managing vast forested areas under state control. The platform can aid in predial management and land-use planning, helping authorities oversee these large tracts of forest more effectively. With over 1,800 agricultural and forestry production units across

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Aysén, the diversity of land-use situations demands sophisticated tools for managing resources and optimizing silvoagricultural practices.

- **Training and Capacity Building**: To ensure effective use of the platform, tailored training programs will be developed for areas like Coyhaique and Queulat National Park, where many forestry and agricultural projects are concentrated. Collaboration with IDE-Aysén will further enhance knowledge sharing and the use of geospatial data. Institutions such as the University of Aysén and local technical centers will also play a pivotal role in educating users on geospatial technologies, helping the region transition to more data-driven agricultural and forestry practices.

2.4 Overview Interaction in the Platform table

User Group	Analysis/Deliverable	Interaction	Visualization Format
Agricultural Users	Integration of environmental indicators (snow cover, frost, precipitation, wind) to optimize planning, irrigation, and harvesting.	Provides data access for farmers in collaboration with FIA, including producer associations and local rural communities, with a focus on women farmers and youth.	Real-time dashboards showing environmental indicators, risk assessments, and trends related to agriculture.
Snow Cover Monitoring	Monitor snow cover for water availability and agricultural planning. Analyze seasonal streamflows and predict water management challenges due to climate.	Government agencies and local authorities collaborate to integrate data into water resource planning for agriculture and energy sectors.	Interactive maps and charts for water availability, snow cover, and seasonal changes, accessible via the platform.
Tourism Sector	Monitoring glacier retreat and associated risks for tourism, with focus on the Exploradores Glacier and other major tourist spots.	Tourism operators and local government use the data to manage safety measures and inform tourists about closures or risks.	Visual maps showing glacier retreat, risk zones, and real-time alerts for tourist routes and activities.
Forestry Sector	Track forest health, land-use changes, and fire risks using Sentinel satellite data. Provide real-time alerts for high-risk zones.	Forestry managers, CONAF, and SENAPRED access the system for proactive fire prevention and post-fire recovery planning.	Fire risk maps, forest health indicators, and alert systems integrated into the GIS-based platform.

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3 Snow Cover Algorithm

3.1 Introduction

Environmental and spatial models are critical in understanding complex dynamics in geography. We focus on hierarchical models, Bayesian spatial predictions, and geostatistical analysis applied to obtain an enhanced algorithm for the prediction of the Snow Cover. These methodologies are essential for studying dynamic environmental systems, emphasizing the use of Bayesian inference and hierarchical modeling structures.

The methodological framework integrates spatial and temporal models to predict environmental patterns. The generalized linear spatial model (GLSM) is used as a foundation, combined with Bayesian hierarchical approaches to capture complex spatial dependencies.

For instance, a binomial distribution model is employed to estimate SC using environmental covariates. The core model is expressed as follows:

$$Y_i = Bin(M_i, p_i)$$

Where p_i represents the SC probability at location x_i .

The fundamental equation in this context is:

$$\log\left(\frac{p_i}{1-p_i}\right) = \beta_0 + \sum_j \beta_j X_{ij} + S(x_i)$$

where $S(x_i)$ is a spatially correlated random effect that accounts for unobserved spatial dependencies. This formulation allows us to model spatial autocorrelation between neighboring locations, essential for accurate prediction.

3.2 Bayesian Analysis and Hierarchical Models

Bayesian frameworks allow incorporating uncertainty in parameter estimation, which is particularly valuable in hierarchical models, where multiple layers (data, process, and parameter stages) interact. Hierarchical decomposition facilitates modeling complex

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spatiotemporal processes with significant uncertainty, allowing the integration of observed data with latent processes that evolve over time and space.

Bayesian geostatistical approaches have proven to be highly successful in mapping the SC. The use of Markov Chain Monte Carlo (MCMC) simulations ensures stability in parameter estimation, thereby enhancing the reliability of spatial predictions over time. Hierarchical models, as demonstrated by Wikle (2003), effectively address environmental phenomena, such as atmospheric changes, across multiple scales.

Hierarchical Bayesian models and GLSMs offer robust methods for analyzing spatiotemporal data, particularly in environmental science. The approaches outlined provide valuable insights into understanding environmental processes across scales. Future research should focus on refining these models to increase their accuracy in predictions, especially under changing climate conditions.

After a careful review of the literature, we considered the following algorithms:

3.2.1 Spatio-temporal interpolation

Spatio-temporal Kriging or smoothing splines can be suitable for predicting snow cover in cloud-affected areas, using data from clear areas and considering the spatio-temporal relationship.

> *Advantage*: They allow estimating values in cloudy pixels based on statistical relationships with nearby pixels both spatially and temporally.

3.2.2 Machine Learning-based models:

Random Forest or Support Vector Machines (SVM) can be used to predict SCA in cloudy areas. These machine learning algorithms are good at handling non-linear data sets and can be trained to identify patterns from clear areas.

> *Advantage*: Flexible and adaptable, they can incorporate multiple layers of data such as temperature, elevation, and previous sensor data to improve SCA prediction in the presence of clouds.

3.2.3 Data fusion models:

Data fusion from different sensors (Sentinel-2 and MODIS): This approach combines

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images from different satellites that have different temporal and spatial resolutions. MODIS has a higher temporal frequency, so it can be used to "fill" data gaps when Sentinel-2 is blocked by clouds.

Advantage: Increases data availability, reducing the impact of clouds on predictions.

3.2.4 Neural network-based reconstruction methods:

Convolutional Neural Networks (CNN): Using convolutional neural networks, a model can be trained to "reconstruct" cloud-affected areas based on historical snow cover patterns.

Advantage: They are powerful for identifying complex patterns in images and can handle large volumes of data efficiently.

3.3 Comparison Table: Random Forest vs. Convolutional Neural Networks (CNN) for Snow Cover Prediction

Criteria	**Random Forest (RF)**	**Convolutional Neural Networks (CNN)**
Complexity	Lower computational complexity	High computational complexity
Data Requirements	Effective with smaller datasets	Requires large datasets for optimal performance
Training Time	Faster training time	Slower training due to the need for extensive parameter tuning
Interpretability	Highly interpretable; easier to understand feature importance	Less interpretable; features are learned implicitly
Handling of Missing Data	Robust handling of missing values using imputation techniques	Requires preprocessing steps to handle missing data
Performance in Cloudy Areas	Effective in filling gaps using spatiotemporal relationships	Can reconstruct cloud-affected areas with historical patterns
Flexibility	Can integrate various environmental covariates (e.g., temperature, elevation)	Primarily image-based; less flexible for additional variables
Suitability for Initial Implementation	Ideal for initial deployment due to simplicity and robustness	Suitable for advanced stages when more data and computational resources are available

While CNNs have shown strong capabilities in image reconstruction tasks, Random Forest was selected for the initial implementation due to its lower computational requirements, faster training time, and robust handling of smaller datasets. Additionally, Random Forest can integrate a wide range of environmental covariates, making it highly suitable for snow cover prediction in cloud-affected areas. CNNs may be considered for future enhancements when more data and resources are available.

Final Decision:

Since Sentinel-2 offers good spatial resolution but is susceptible to cloud cover, a combination of spatiotemporal interpolation and machine learning methods, such as Random Forest will be a good strategy to fill in the gaps in the data due to clouds.

3.4 Algorithm: Spatiotemporal Interpolation with Random Forest for Data Gap Filling

Input:

- Satellite imagery data with missing values due to clouds (D_{missing})
- Complete historical dataset without missing values (D_{complete})
- Spatiotemporal features (latitude, longitude, time)
- Environmental covariates (e.g., temperature, humidity, elevation, etc.)

Output:

Gap-filled dataset with predicted values for missing data points.

3.4.1 Step-by-Step Algorithm:

Step 1: Data Preprocessing:

- **Input Data**: Load the satellite imagery data D_{missing} and the complete historical dataset D_{complete}.
- **Feature Selection**: Extract spatiotemporal features (x, y, t) and environmental covariates (E) for both D_{missing} and D_{complete}.

Step 2: Spatiotemporal Interpolation

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- **Interpolation Setup**: For each pixel with missing data in D_{missing}: Identify neighboring pixels in space and time from D_{complete}.
- **Interpolation Calculation**: Use bilinear or cubic interpolation to estimate missing values based on nearby valid pixels over both space and time.
- **Initial Estimate**: Generate an initial estimate for missing values using this spatiotemporal interpolation method, resulting in D_{interpolated}.

Step 3: Random Forest Training:

- **Training Data Preparation**:

  From D_{complete}, create a training set with known values, using spatiotemporal features (x, y, t) and covariates (E).

- **Random Forest Model**:

  Train a Random Forest regression model using:

  Input: (x, y, t, E)

  Target: Corresponding pixel values (e.g., reflectance or NDSI).

- **Model Training**:

  Train the Random Forest model on the historical data D_{complete}, learning the relationships between spatiotemporal features and the target variable.

Step 4: Predict Missing Values:

- **Apply Trained Model**:

  For each missing data point in D_{missing}, use the trained Random Forest model to predict the missing value, using spatiotemporal features (x, y, t) and covariates (E) through the variogram..

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- **Combine Predictions**:

  Combine the predictions from Random Forest and the initial interpolated values D_{interpolated} to create the final gap-filled dataset D_{filled}.

  Use a weighted average of the interpolated and Random Forest predicted values for more robust estimation.

Step 5: Post-processing and Validation

- **Smoothing**:

  Apply spatial smoothing or filtering to reduce noise and ensure smooth transitions between predicted and actual values.

- **Validation**:

  Validate the accuracy of the filled data using cross-validation or comparing against a held-out test set from D_{complete}.

4 Overview of application requirements

Given the regional dynamics, the platform must cater to users with varying digital literacy, ranging from tech-savvy individuals to those with limited digital experience. With 91.8% of households having internet access (according to País Digital), the platform should prioritize mobile accessibility, as smartphones are frequently used in rural areas for internet connectivity.

4.1 Key Features for the Pilot Applications:

4.1.1 Agricultural Context

- **Data for Decision-Making:** Farmers will gain access to satellite-based environmental indicators such as snow cover, precipitation, wind patterns, and frost conditions. Using **Sentinel-1** (Synthetic Aperture Radar - SAR) and **Sentinel-2**(multi-spectral imagery) from the **Copernicus program**, the platform will deliver

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high-resolution data on a **10-meter scale**. Sentinel-2 provides images in multiple spectral bands, including the Red (Band 4), Near-Infrared (NIR, Band 8), and Shortwave Infrared (SWIR, Band 11), which are vital for vegetation and soil analysis.

- **Data Frequency:** The platform will utilize a combination of **Sentinel-1 SAR** data, which is available **every 6 days**, and **Sentinel-2** data, refreshed every **5-10 days**, depending on cloud coverage. This frequent data supply ensures up-to-date insights into agricultural conditions.
- **Risk Mitigation:** Machine learning algorithms will predict risks such as frost or drought, using the **Normalized Difference Vegetation Index (NDVI)** and **Evapotranspiration** data to optimize agricultural decisions and mitigate potential crop losses.
- **Sustainability: Real-time snow cover monitoring** will enable better irrigation planning by providing accurate water availability estimates. Integrating this with **soil moisture data** from **Sentinel-1** will further enhance water management, supporting sustainable agriculture in the region.

4.1.2 Forestry Context

- **Forest Management:** The platform will use **Sentinel-1 SAR** and **Sentinel-2** to track forest health, monitor land-use changes, and assess the effects of climate on forests. **Normalized Difference Moisture Index (NDMI)** and **Leaf Area Index (LAI)** from Sentinel-2 will help evaluate forest conditions and growth patterns.
- **Fire Risk Management:** Satellite data, combined with weather patterns and historical fire incident data, will generate real-time fire risk maps. This will aid **CONAF** and **SENAPRED** in proactive fire prevention. **Sentinel Ecosystem**, which offers higher temporal frequency for thermal imaging, can detect fire hotspots and help monitor burned areas.
- **Snow and Glacier Monitoring:** In collaboration with **CONAF**, the platform will use **Sentinel-1 SAR** to monitor glacier movement, including potential calving events in **Campos de Hielo Norte**. The **Normalized Difference Snow Index (NDSI)** will be employed to track snow coverage and quality, ensuring effective

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water management and assisting in tourism activities.

4.1.3 Integration and User Interaction:

- **Mobile-Friendly Design:** The platform must be accessible via smartphones, ensuring a smooth user experience for stakeholders, including farmers, foresters, and local government bodies.
- **Data Visualization:** Interactive dashboards will display real-time satellite data, historical trends, and predictive analytics, allowing users to make informed decisions.

4.1.4 Key Data Sources and Standards:

- **Copernicus Sentinel-1** and **Sentinel-2**: Data will be provided at a **10-meter spatial resolution**, refreshed every 5-10 days for Sentinel-2 and every 6 days for Sentinel-1.
- **National Datasets:** Supplementary data from **Dirección Meteorológica de Chile** on temperature, wind, and precipitation will be integrated for real-time updates.
- IDE Chile utilizes a range of standards to ensure the quality, interoperability, and accessibility of geospatial data. Some of the key standards include:
    1. **ISO 19115-1**: Provides a schema for describing geographic information and services through metadata, offering insights into the quality, spatial and temporal aspects, and distribution of geospatial data.
    2. **ISO 19115-3**: Specifies how metadata defined in ISO 19115-1 should be encoded in XML for efficient data exchange.
    3. **ISO 19119**: Offers a framework for creating web services that allow users to access, visualize, and process geographic data. It defines how geospatial services should be described, ensuring they are discoverable and interoperable.
    4. **ISO 19128**: Establishes the standards for Web Map Services (WMS), enabling the retrieval of dynamic digital maps from geospatial servers.

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5. **ISO 19142**: Defines the Web Feature Service (WFS) for visualizing and sharing vector-based geographic information, allowing for interaction and feature manipulation directly on the web.
6. **ISO 19157**: Focuses on describing the quality of geographic data, ensuring that data producers and users have consistent metrics to assess and compare data quality.
7. **ISO 19110**: Provides methodologies for feature cataloging, ensuring that different datasets adhere to consistent structure and definitions of geographic features.
8. **ISO 19131**: Specifies the requirements for geographic data product specifications, ensuring uniformity across different datasets and services.
9. **WCS (Web Coverage Service)**: Enables users to access and query attribute values stored in raster datasets, providing the ability to retrieve information about environmental and earth observation data.
10. **CSW (Catalogue Service for the Web)**: A catalog service that allows users to publish and search metadata about geographic data and services, making geospatial resources easier to find and access.

- There are some **open-access databases and APIs** available in Chile for accessing information on climate networks, agroclimatic data, snow monitoring, glaciers, and various meteorological parameters like rainfall and wind, particularly relevant to the Aysén region:

    1. **Explorador Climático**: Developed by the Center for Climate and Resilience Science (CR2), this online tool provides access to historical and real-time climate data, including temperature, precipitation, and river flows. The data comes from institutions like the Chilean Meteorological Office and the General Directorate of Water. The platform supports advanced users by offering tools for statistical analysis and the ability to export data in various formats. https://explorador.cr2.cl
    2. **ODES (Observatory of Drought for Agriculture and Biodiversity)**: This

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platform allows users to visualize climate variables and drought indicators, offering near real-time data from a variety of meteorological stations. It is especially useful for monitoring drought conditions and agricultural impacts in regions like Aysén. https://odes-chile.org

3. **Agroclima INIA**: Focused on agroclimatic data, this platform provides access to meteorological station data from the National Institute of Agricultural Research (INIA) and the Chilean Meteorological Office. It includes information on rainfall, wind, temperature, and humidity, specifically tailored for agricultural applications in Aysén. https://recursos.riegoaysen.cl/clima/

4. **ARClim (Atlas of Climate Risks)**: Managed by Chile's Ministry of the Environment, ARClim offers gridded climate data and an API for accessing various environmental and meteorological parameters. It includes climate data interpolated for specific geographic units such as regions, glaciers, and watersheds, providing detailed insights into local climate risks. https://arclim.mma.gob.cl/atlas/index/

Conclusion

The conclusions derived from the WP4 objectives and activities reflect the significant efforts to integrate advanced technologies into environmental monitoring and land management. This work package focuses on developing COPERNICUS downstream services that leverage Earth Observation data to address critical challenges in agriculture, forestry, and climate risk mitigation. By combining satellite imagery, remote sensing, and climate models, the project aims to enhance data accuracy for real-time applications in regions like Aysén, Chile. These tools will facilitate better decision-making processes for stakeholders, optimize land use practices, and contribute to sustainable environmental management, all while promoting collaboration between local institutions and international partners.

Development of Downstream Services for Climate and Agriculture: WP4 focuses on creating COPERNICUS downstream services for climate monitoring and agricultural management, aimed at providing actionable data to pilot users in Chile and Colombia.

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These services will support daily farm activities and forest management, as well as contribute to climate risk mitigation and policy recommendations.

Integration of Remote Sensing for Snow and Glacier Monitoring: A key methodology involves using remote sensing techniques, combining optical and radar data to monitor snow and glacier dynamics. This includes estimating snow cover through the Normalized Difference Snow Index (NDSI) and applying algorithms to address data gaps caused by cloud cover.

Collaboration with Local Stakeholders: The project emphasizes collaboration with local stakeholders and institutions, particularly in Chile and Colombia. In Chile, partners like FIA and CONAF will assist in deploying technologies for forest management and sustainable land use, focusing on the recovery of native forests and effective water resource management.

Real-Time Monitoring and Economic Impact: The system for monitoring glacier calving in the Campo de Hielo Norte is designed to provide real-time data, supporting environmental management and enhancing safety for tourism and local communities. This will help mitigate the risks posed by sudden glacier calving, which affects both local economies and natural attractions.

Optimization of Agricultural and Forestry Practices: In the Aysén region, satellite-based land use planning aims to optimize agricultural and forestry activities by integrating precise data on snow cover, soil conditions, and climate variables. This approach will enhance sustainability and productivity, while also addressing environmental challenges like water resource management and land degradation.

Finally, to ensure broad accessibility and usability, the platform will be available through web-based dashboards optimized for both desktop and mobile browsers, catering to diverse user profiles ranging from government agencies and environmental organizations to farmers, foresters, and local communities. Recognizing the reliance on mobile devices in rural areas, the platform's mobile-friendly interface prioritizes smartphone access to overcome connectivity challenges. Interactive dashboards will provide intuitive visualization tools, including real-time maps, data overlays, and risk assessment models, allowing users to easily access and interpret critical geospatial information. In its initial phase, access will be extended to key stakeholder groups

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through partnerships with local institutions such as FIA and CONAF in Chile, ensuring the platform meets the specific needs of end users.

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