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COMUNIDAD

D4.1
Colombian applications requirements

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

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Project Summary

The COMUNIDAD project, coordinated by Lesprojekt, leverages Copernicus satellite data, the European Global Navigation Satellite System (EGNSS), Artificial Intelligence (AI), Big Data technologies, and numerical modeling to facilitate technology transfer and capacity-building in Latin America. Focusing on Chile and Colombia, the project aims to enhance agricultural and forestry management by developing infrastructure and a foundational platform for applications that improve precision, efficiency, and sustainability. This initiative contributes to socio-economic development in South America while promoting environmental sustainability through an open-source development approach.

Lesprojekt, as the project leader, capitalizes on its extensive experience in applying

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technology to agriculture and forestry to guide a consortium of experts. By integrating Copernicus services, EGNSS, and other spatial datasets, the project generates actionable insights to support informed decision-making for diverse stakeholders, including farmers, advisors, policymakers, and land managers. These insights encompass critical information on crop health, land use, and forestry conservation, enabling improved land management practices and increased agricultural productivity.

Through the COMUNIDAD project, knowledge and expertise are shared via the development of technological components, infrastructure, and training materials. This ensures the effective transfer of innovative practices to local stakeholders and fosters capacity building.

By uniting European expertise with local collaboration, the COMUNIDAD project strives to revolutionize agricultural and forestry management in South America. The integration of advanced technologies with strategic data analysis is poised to drive progress across various sectors, contributing to environmental sustainability and socio-economic growth in the region.

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Executive Summary

The COMUNIDAD project focuses on improving agricultural and environmental management in Colombia and Chile by leveraging cutting-edge technologies such as Copernicus satellite data, the European Global Navigation Satellite System (EGNSS), Artificial Intelligence (AI), and Big Data analytics. This project aims to create innovative downstream services that enhance productivity, sustainability, and resilience in key sectors like agriculture and forestry. By integrating advanced data processing, real-time monitoring, and predictive modeling, the project addresses critical challenges related to land use, environmental risk management, and sustainable practices.

In Colombia, the project focuses on optimizing coffee crop management and mitigating environmental risks like landslides. The use of satellite data will enable farmers and land managers to make data-driven decisions, improving the efficiency of resource usage and increasing crop resilience to climate variability. The project will also support policy recommendations and the development of agroclimatic indicators, helping local stakeholders adapt to changing environmental conditions.

By fostering collaboration between European and Latin American institutions, the COMUNIDAD project aims to transfer technological knowledge and tools, driving innovation and sustainable growth in the region. Ultimately, this initiative will empower local communities and stakeholders to embrace advanced technologies for better decision-making, contributing to long-term environmental and economic sustainability.

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Introduction

The COMUNIDAD project is a collaborative initiative that aims to enhance agricultural and environmental management in Latin America, with a particular focus on Colombia and Chile implementation. By leveraging cutting-edge technologies such as Copernicus satellite data, the European Global Navigation Satellite System (EGNSS), Big Data analytics, and Artificial Intelligence (AI), the project addresses critical challenges in land use, environmental risk management, and agricultural sustainability. The project is structured to foster the transfer of knowledge and technology from Europe to Latin America, supporting sustainable practices and the resilience of key economic sectors, particularly agriculture and forestry.

In Colombia, the project centres on the optimization of coffee production, a vital sector for the national economy. Coffee cultivation in Colombia faces significant challenges due to the mountainous terrain, irregular topography, and increasing vulnerability to environmental risks, such as landslides, deforestation, and climate variability. Through the COMUNIDAD initiative, advanced technologies are being deployed to address these challenges, providing farmers, land managers, and policymakers with tools to improve decision-making and promote long-term sustainability.

One of the core aspects of the project in Colombia is the integration of Copernicus Earth Observation data with real-time GNSS (Global Navigation Satellite System) measurements, providing precise and timely information on land conditions, crop health, and environmental risks. The data collected is processed using AI-driven models and Big Data platforms to generate actionable intelligence for improving farm management practices, optimising land use, and increasing agricultural productivity.

The project will also focus on developing tools for topographic precision mapping in coffee-growing areas, which is crucial for understanding the complex terrain and mitigating risks related to soil erosion and water distribution. By implementing Digital Elevation Models (DEMs) and other geospatial analysis tools, the project will enable precise planting line planning, soil conservation, and water management, ultimately enhancing the efficiency and sustainability of coffee cultivation in Colombia.

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Another key component of the project is the management of environmental risks such as landslides and wildfires. By integrating satellite data with historical climate records and predictive models, the project aims to develop risk maps that highlight vulnerable areas. This will provide local authorities and farmers with early warning systems and decision-support tools to implement proactive risk mitigation strategies. The project also plans to introduce agro climatic indicators to help predict weather patterns and improve climate resilience for farmers.

In addition to technological advancements, COMUNIDAD emphasizes stakeholder engagement and capacity building. The project will work closely with local communities, cooperatives, agricultural institutions, and government agencies to ensure that the tools developed are tailored to the needs of Colombian farmers and land managers. Workshops, training sessions, and continuous technical support will be provided to ensure that stakeholders can effectively use the technologies introduced. This collaborative approach will foster knowledge transfer, enabling local participants to integrate these advanced technologies into their agricultural practices for long-term sustainability.

By addressing both technological and human dimensions, the COMUNIDAD project aims to improve not only the productivity and sustainability of Colombia's coffee sector but also to strengthen the country's capacity to adapt to environmental changes and mitigate risks. The long-term vision of the project is to create a model for sustainable agricultural practices that can be replicated across other regions and sectors, contributing to Colombia's economic resilience and environmental conservation.

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1. Use cases in Colombian Pilot

Mapping site-level in Coffee crops using microtopography with Real Time Kinematic Global Navigation Satellite Systems (RTK GNSS)

Overview:

This Section focuses on improving agricultural efficiency in Colombia's coffee-growing regions by utilising RTK GNSS to produce precise topographic maps. These maps allow farmers to plan and manage their crops more effectively, particularly in challenging mountainous terrain. By leveraging microtopography, farmers can make data-driven decisions that optimise crop placement, reduce soil erosion, and enhance water management. The goal is to integrate advanced geospatial technologies into daily agricultural practices to improve crop productivity and sustainability.

Applications:

Precision Topography Mapping: This use case employs RTK GNSS technology to generate high-resolution Digital Elevation Models (DEM), providing detailed insights into the topography of coffee farms. These models help farmers understand terrain variability, slope gradients, and elevation, allowing them to make more informed decisions regarding land use.

Crops Planning: By using the topographic data generated, this use case focuses on optimizing planting layouts. The goal is to align planting lines with the natural contours of the land, minimizing erosion and improving water distribution. This improves both crop yields and land sustainability.

Pipeline

Inputs:

Data:

- Real-time GNSS Data (RTK GNSS): Generates highly accurate point clouds

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for microtopography mapping, enabling precise characterization of terrain features relevant to soil stability and erosion risk.

- Generates highly accurate point clouds for microtopography mapping.

- Satellite Imagery (Sentinel-1, Sentinel-2):
    - Complements GNSS data by providing multispectral and synthetic aperture radar (SAR) imagery for topographic analysis, terrain classification, and soil moisture estimation.
    - Uses Sentinel-1 SAR for high-resolution elevation and slope analysis, and Sentinel-2 multispectral imagery to assess vegetation health and soil conditions.
- Digital Elevation Models (DEM):
    - Created from GNSS and satellite data, these models provide detailed slope and elevation variations, essential for assessing soil erosion potential and water distribution patterns.
- Local Soil Surveys (Cenicafé):
    - Offer detailed soil classification, texture, composition, and fertility data, supporting crop management and land-use planning.

Tools:

- Geospatial Analysis:
    - Tools for processing GNSS and satellite data for topographic maps and slope analyses.
- Real-time Data Integration:
    - Platforms to combine GNSS, satellite, and soil data into accurate DEMs.
- Agricultural Planning Systems:
    - Tools for designing optimized planting lines based on terrain and environmental data.

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Data Sources:

- GNSS Networks for real-time geolocation.
- Copernicus Open Access Hub for satellite imagery.
- SICA:
  - Sistema Integral de Control Agroalimentario (Private data pending approval)

Processes, Procedures, and Analyses:

Data Collection:

- Gather GNSS data for terrain point clouds.
- Collect satellite imagery for large-scale topographic analysis.

Data Preprocessing:

- Data Cleaning:
  - Remove inconsistencies in GNSS, satellite, and soil data.
- Data Standardization:
  - Convert all data into compatible formats for integration.
- Data Integration:
  - Combine GNSS, satellite, and soil data to generate DEMs reflecting microtopography.
- Resolution Adjustment:
  - Align data sources to ensure consistent spatial and temporal resolution.

Analysis:

- Topographic Mapping:
  - Create detailed maps showing slope and elevation variations.
- Slope Analysis:
  - Analyse DEMs to identify high-risk areas for erosion or poor planting.
- Planting Line Optimization:
  - Design optimal planting layouts that reduce erosion and maximise water distribution.

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Risk Management, Landslides and Fires Risk

Overview:

This section aims to integrate Copernicus data with local insights to address landslide and fires risk in Colombian, specifically the coffee region of Caldas. By leveraging satellite imagery and advanced data processing, we will develop a risk management framework tailored to the specific needs of these regions to enhance local capabilities in predicting, monitoring, and managing landslide and fire risks.

Applications:

Enhanced Risk Mapping: This use case integrates Copernicus satellite data with local geological and meteorological information to produce precise maps that identify high-risk areas for landslides and wildfires. The resulting maps will facilitate targeted interventions and optimised resource allocation, ultimately reducing the impact of these hazards on local communities.

Early Warning System: This use case focuses on establishing systems that provide timely alerts to communities about imminent landslide and fire threats. By leveraging continuous data analysis, these early warning systems ensure that local authorities and residents receive accurate, actionable information, allowing for swift action to mitigate potential impacts.

Pipeline:

Inputs:

Data:

- Satellite Imagery (Copernicus):
  - Sentinel-1 SAR: Surface displacement, ground deformation, and soil moisture analysis.
  - Sentinel-2 Optical: Vegetation health, land cover changes, and fire damage assessment.
  - Copernicus Emergency Management Service (EMS): Historical

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disaster records and risk assessment mapping.
        - Copernicus Global Land Service: Vegetation indices (NDVI, LAI) and soil moisture monitoring.
    - Local Geological and Meteorological Data:
        - Rainfall, humidity, and temperature variations (IDEAM).

Tools:

- Geospatial Risk Analysis:
    - Tools for processing and visualising risk data.
- Early Warning Platforms:
    - Systems for real-time data analysis and alert generation.

Data Sources:

- Copernicus Open Access Hub for satellite data.
- Local geological surveys and meteorological stations for contextual information.

Processes, Procedures, and Analyses:

Data Collection:

- Gather satellite imagery to monitor land use and vegetation.
- Collect geological and meteorological data to understand local risk factors.

Data Preprocessing:

- Data Cleaning:
    - Ensure accuracy and consistency of geological and meteorological data.
- Data Integration:
    - Combine satellite data with local datasets for comprehensive risk

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analysis.

Analysis:

- Risk Mapping:
  - Analyze integrated data to create detailed landslide and fire risk maps.
- Modelling:
  - Use predictive models to assess potential future risks based on current environmental conditions.

Alert System Implementation:

- Establish early warning systems that continuously monitor risk factors and trigger alerts.
- Provide actionable insights to local authorities and communities to facilitate timely responses to identified risks.

Hydrological Balance for Evaluation of the Impacts on Coffee Production

Overview:

This section focuses on assessing the hydrological balance and its impact on coffee production in Caldas, a region that relies heavily on coffee farming. Through the integration of satellite data, meteorological information, and hydrological models, this pilot will evaluate soil moisture, rainfall patterns, and climate variability, which are critical factors influencing coffee productivity. The aim is to provide coffee farmers, cooperatives, and local governments with actionable insights to mitigate the risks posed by water scarcity, excessive rainfall, and changing climate conditions.

Applications:

Evaluation of the Hydrological Balance and Soil Moisture in Coffee farms:

This use case leverages satellite data to monitor soil moisture levels and track water

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usage in coffee fields. By analyzing the hydrological balance, farmers can improve yield predictions based on long-term moisture trends.

Impact of Rainfall and Climate Variability on Coffee Productivity: This use case focuses on analyzing how changes in rainfall and climate variability affect coffee yields. By integrating historical climate data with satelital information, the project will help farmers and cooperatives understand the relationship between rainfall patterns and coffee production, enabling them to adapt their farming practices to changing environmental conditions. This will help mitigate risks associated with droughts, excessive rainfall, and seasonal variability.

Pipeline

Inputs:

Data:

- Satellite Imagery (Copernicus):
    - Sentinel-1 SAR: Soil moisture estimation and surface water detection.
    - Sentinel-2 Optical: Vegetation health, evapotranspiration estimation, and land cover classification.
    - Copernicus Global Land Service: Water cycle variables, including soil moisture and evapotranspiration.
    - ERA5 Climate Reanalysis Data (C3S): Historical and real-time climatic parameters, such as precipitation and temperature trends.
- Hydrological Data:
    - Local water sources, flow rates, and historical water usage in coffee production.
- Meteorological Data:
    - Historical weather patterns, particularly rainfall and temperature fluctuations.

Tools:

- Hydrological Modeling:

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- Tools to simulate water distribution, soil moisture levels, and water availability.

Data Sources:

- Copernicus Open Access Hub for satellite imagery.
- Local meteorological and hydrological stations for environmental data.

Processes, Procedures, and Analyses:

Data Collection:

- Collect satellite imagery to monitor soil moisture and land conditions.
- Gather hydrological data on water flows, availability, and usage.
- Obtain meteorological data on rainfall and temperature from local stations.

Data Preprocessing:

- Data Cleaning:
  - Ensure the accuracy and consistency of satellite, hydrological, and meteorological data.
- Data Integration:
  - Combine satellite imagery, hydrological, and meteorological data to generate a comprehensive view of the water cycle in coffee farms.

Analysis:

- Hydrological Balance Assessment:
  - Evaluate the balance between water availability and usage, focusing on soil moisture conditions..
- Impact of Climate Variability:
  - Analyze the effects of climate change, particularly rainfall variability,

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on coffee productivity, and identify patterns that can inform future farming decisions.

Environmental Footprint of Coffee Production

Overview:

This section focuses on assessing and minimizing the environmental footprint of coffee production by integrating satellite data and advanced data analytics, the project aims to provide a comprehensive understanding of how land use, water consumption, and emissions impact the environment. The goal is to equip farmers and cooperatives with tools to monitor, manage, and reduce their environmental impact while promoting sustainable practices in coffee farming.

Applications:

Environmental Impact Mapping: This use case aims to map the environmental footprint of coffee farms by integrating satellite imagery, emissions data, and field observations. By monitoring land use patterns, water resources, and energy consumption, the project will help identify areas where unsustainable practices are causing negative environmental effects. This will enable farm managers and policymakers to implement more sustainable practices, such as reducing deforestation, optimizing water usage, and lowering carbon emissions.

Sustainable Practices Monitoring: This use case focuses on evaluating the sustainability of agricultural practices by analyzing satellite data and tracking land use changes. Farm managers can identify unsustainable practices and make necessary interventions. Insights will be generated to ensure that farms comply with sustainability goals, allowing for adjustments to be made when necessary.

Pipeline

Inputs:

Data:

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- Satellite Imagery (Copernicus):
  - Sentinel-2 Optical: Land use monitoring, vegetation health, and deforestation tracking.
  - Copernicus Global Land Service: Biomass, soil organic carbon, and vegetation indices (NDVI, LAI) for assessing carbon sequestration.
  - Copernicus Atmosphere Monitoring Service (CAMS): Air quality and greenhouse gas emissions data to estimate carbon footprint trends.
- Emissions Data (Ceficafé):
  - Energy Use Records: Fuel consumption for transportation, processing, and drying operations.
  - Fertilizer Application Data: Quantification of nitrogen-based fertilizers and their contribution to greenhouse gas emissions.
  - Deforestation and Land Use Change Reports: Monitoring the impact of coffee cultivation on forested areas.

Tools:

- Environmental Analysis:
  - Tools for assessing the environmental footprint through satellite and emissions data.
- Sustainability Monitoring:
  - Platforms to track sustainable practices and environmental impact.

Data Sources:

- Copernicus Open Access Hub for satellite imagery.
- Local emissions data from coffee farms to monitor carbon output.

Processes, Procedures, and Analyses:

Data Collection:

- Use satellite imagery to map land use and assess deforestation.
- Collect emissions data from local sources to assess the carbon footprint of

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farming activities.

Data Preprocessing:

- Data Cleaning:
  - Remove inconsistencies from satellite and emissions data for accurate environmental assessment.
- Data Integration:
  - Combine satellite and emissions data to form a comprehensive environmental footprint model.

Analysis:

- Descriptive and Predictive Models:
  - Evaluate land use patterns, environmental impact, and sustainability through regression and clustering models. Predict future environmental impacts based on current practices.
- Sustainability Monitoring:
  - Track the effectiveness of sustainable practices using environmental data.

Deforestation Monitoring in Coffee Growing Areas

Overview:

This section focuses on identifying deforestation activities in coffee-growing regions through the development of a Deforestation Index. By utilizing satellite data, the project aims to provide coffee producers and environmental authorities with tools to detect deforestation and enable timely interventions that protect local ecosystems and promote sustainable land management practices. A secondary objective of this pilot is to enhance deforestation detection by applying computer vision algorithms to satellite imagery, aiming to improve the accuracy and efficiency of the identification process.

Applications:

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Identification of Deforestation in Coffee Growing Areas: This use case focuses on detecting deforestation in regions where coffee is cultivated. By combining satellite imagery with geospatial analysis, the project will create maps that highlight areas where illegal deforestation is occurring. As a secondary objective, computer vision techniques will be explored to automate and refine the detection process, enabling quicker, more accurate identification of deforested areas. This will enable stakeholders to intervene promptly and implement reforestation programs, helping to prevent further environmental degradation in coffee-producing zones.

Pipeline

Inputs:

Data:

- Satellite Imagery (Copernicus):
  - To monitor land cover changes and identify deforestation.

Tools:

- Deforestation Detection:
  - Platforms that analyze satellite imagery to identify land cover changes and highlight areas of deforestation. As a secondary approach, computer vision algorithms will be used to further refine the detection process.

Data Sources:

- Copernicus Open Access Hub for satellite data.
- GNSS networks for real-time location data and accurate field mapping.

Processes, Procedures, and Analyses:

Data Collection:

- Collect satellite imagery to detect deforestation activities in

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coffee-growing regions.

- Gather GNSS data for precise mapping and geolocation of fields.

Data Preprocessing:

- Data Cleaning:
  - Ensure satellite and GNSS data is accurate and consistent for analysis.
- Data Integration:
  - Combine satellite imagery and GNSS data to form a comprehensive Vegetation/Deforestation Index.

Analysis:

- Deforestation Detection:
  - Analyze changes in land cover to identify areas where deforestation is taking place and assess its impact on coffee-growing regions. The secondary objective is to test computer vision algorithms on the satellite imagery to improve the detection process, allowing for faster and more reliable identification of deforested areas.

Use case	**Objective**	**Key Data Sources**	**Algorithms**	**Applications**
Mapping Site-Level in Coffee Crops Using Microtopography with RTK GNSS	Generate high-precision topographic maps to optimize coffee crop planning and management.	RTK GNSS, Sentinel-1 SAR, Sentinel-2 Optical, DEM, Cenicafé soil surveys.	Digital Elevation Models (DEM), Slope Analysis, Interpolation Algorithms.	Precision topography mapping, optimized planting layouts.

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Risk Management, Landslides, and Fires	Develop risk maps and early warning systems for landslides and wildfires in coffee-growin g regions.	Sentinel-1 SAR, Sentinel-2 Optical, Copernicus EMS, Copernicus Global Land Service, IDEAM meteorologica l data.	Machine Learning (Random Forest, Gradient Boosting) for risk assessment, Logistic Regression for probability modeling, Change Detection Algorithms	Enhanced risk mapping, early warning systems.
Hydrological Balance for Evaluation of the Impacts on Coffee Production	Assess soil moisture, rainfall patterns, and climate variability affecting coffee production.	Sentinel-1 SAR, Sentinel-2 Optical, Copernicus Global Land Service, ERA5 Climate Data, IDEAM meteorologica l and hydrological data.	Hydrological Modeling (SWAT, Water Balance Models), Regression Analysis for precipitation impact, Time Series Analysis.	Soil moisture monitoring, impact analysis of rainfall and climate variability.
Environmental Footprint of Coffee Production	Quantify and reduce the environmental impact of coffee farming	Sentinel-2 Optical, Copernicus Global Land Service, CAMS,	IPCC Emissions Models, Carbon Sequestration Estimations.	Environmental impact mapping, sustainable practices

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	through emissions monitoring and land use assessments.	Cenicafé emissions data (fuel use, fertilizers, deforestation).		monitoring.
Deforestation Index in Coffee Crops	Monitor and detect deforestation activities in coffee-growin g areas.	Sentinel-2 Optical, NDVI, Cenicafé GIS data, GNSS plantation boundaries.	Supervised Classification (Random Forest, SVM), Change Detection Algorithms.	Deforestation detection.

2. Users and Target Groups

Introduction

The Colombian pilot, particularly focused on the department of Caldas, seeks to implement advanced technologies such as GNSS and satellite data in agricultural practices, specifically in coffee production. The region's reliance on agriculture, particularly coffee, as well as its unique geographical challenges, makes it an ideal focus for this pilot. The primary goal is to address the specific needs of local stakeholders, ranging from small coffee farmers to regional agricultural institutions. The project will directly impact key user groups, such as farmers, cooperatives, and local governments, improving their capacity for decision-making, resource allocation, and risk management.

Target Users

- **Small- and Medium-Sized Coffee Farmers:**

In Caldas, small- and medium-sized coffee farms dominate the agricultural

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landscape. According to recent data, 83.5% of the properties in Caldas are micro and smallholdings, with areas ranging from 0.5 to 10 hectares, with coffee being the principal crop. Specifically, farms ranging from 0 to 3 hectares are classified as small farmers, those from 3 to 5 hectares are considered medium-sized, while farms between 5 to 10 hectares are regarded as large. Properties larger than 10 hectares are typically owned by companies. These farmers are highly reliant on coffee as their primary income source and often face challenges related to terrain and resource management. They will be key users of the precision mapping and crop planning systems enabled by this pilot, which will allow them to optimize planting layouts, reduce soil erosion, and improve water usage.

  - **Demographics:** Predominantly rural population, with farms averaging around 5 hectares in size. Farmers typically have limited access to advanced agricultural technology, which presents an opportunity for significant improvements through this pilot.
  - **Challenges:** The region's steep terrain complicates agricultural activities, while the lack of real-time environmental data makes it difficult to respond effectively to climate conditions. Furthermore, the high cost of technology and limited technical knowledge impede the adoption of precision farming techniques.
  - **Impact:** By providing access to GNSS-based precision agriculture tools and environmental data and satellite data, small and medium-sized farmers will be able to make informed decisions that improve yield efficiency, reduce labor costs, and enhance environmental sustainability. The project will help farmers mitigate risks, such as soil erosion and water inefficiencies, which are exacerbated by Caldas' mountainous terrain.

- **Agricultural Cooperatives and Associations**:
  Agricultural cooperatives play a crucial role in Caldas, where coffee production is predominantly small-scale. These cooperatives support approximately 9,000

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coffee growers in the region by providing access to markets, financial resources, and training opportunities. Cooperatives will be major users of the risk mapping and environmental monitoring systems introduced through the pilot. These tools will help cooperatives improve planning, reduce environmental risks, and enhance overall productivity.

- **Demographics:** Cooperatives are composed mainly of smallholder farmers who collaborate to achieve economies of scale. They play a vital role in consolidating resources for purchasing inputs, processing coffee, and gaining better access to markets.
- **Challenges:** Many cooperatives face difficulties in adopting new technologies due to limited access to capital and high implementation costs. Additionally, they struggle with managing environmental risks, such as landslides and deforestation, which impact the long-term viability of their members' farms.
- **Impact:** The integration of satellite data and environmental monitoring tools will allow cooperatives to better manage risks and provide tailored advice to their members. By leveraging real-time data, cooperatives will help farmers implement sustainable practices, improve productivity, and increase the quality of coffee production. They will benefit from detailed risk maps, enabling them to prevent natural disasters such as landslides.

- **Local Governments and Agricultural Institutions:**
Local authorities and agricultural research institutions, are critical stakeholders in Caldas. The local government is responsible for agricultural planning and environmental conservation. These institutions will benefit from the real-time risk monitoring systems and early warning tools developed in the pilot, which will allow them to make data-driven decisions to support the agricultural sector and respond to environmental challenges.

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- **Current Challenges:** One of the biggest problems facing local institutions in Caldas is the lack of capacity to monitor environmental risks in real time. The region's mountainous geography, combined with the effects of climate change, means that events such as landslides, floods and droughts are becoming increasingly frequent. However, institutions lack advanced tools to detect these phenomena in a timely manner, which limits their capacity for response and prevention. Currently, agricultural planning is affected by the lack of accurate and updated data. This makes it difficult to make strategic decisions and develop policies that can mitigate the impact of natural disasters. Local governments, while committed to improving the situation of farmers, also face budgetary constraints that limit their ability to implement large-scale solutions.
- **Impact on Local and Regional Management:** The implementation of these technological solutions will have a significant positive impact on the capacity of local governments and agricultural institutions to manage rural development. By improving agricultural planning and risk management, local governments will be able to optimize resource allocation and minimize losses due to climatic events. This will benefit not only coffee farmers, but also rural communities in general, who depend on the stability of the agricultural sector for their economic well-being.
- **Better coordination of resources:** Monitoring tools will allow local governments to better coordinate the resources needed to respond to weather emergencies. The ability to issue early warnings and forecast disasters such as landslides or floods will reduce human and economic losses.
- **More informed policies:** Real-time data will enable local governments to develop more accurate and evidence-based public policies, resulting in more efficient use of available resources and better preparedness for the effects of climate change.

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- **Optimizing human resource allocation:** With real-time data on worker location and activity, managers will be able to quickly reassign personnel to areas where they are needed most, ensuring that critical activities such as picking and transporting coffee are carried out efficiently.
- **Reduced downtime:** By monitoring the progress of workers and their location in the fields, managers can quickly identify bottlenecks or areas where workers may be idle due to poor logistical planning. This allows for immediate adjustments to the labor distribution strategy.
- **Better terrain management:** GNSS tools will help workers and managers better navigate the rugged and steep terrain of farms, optimizing access routes to harvesting areas. This will reduce the time and physical effort required to move between different areas of the farm, improving both productivity and worker satisfaction.
- **Improved long-term planning:** Data collected on worker movements and productivity can be analyzed to make more accurate predictions for future harvesting seasons. This will allow managers to better plan labor needs and adjust the hiring structure to improve efficiency in subsequent years.

- **CENICAFÉ as a Key Partner:**
  Cenicafé, the national coffee research center, will play a crucial role in strengthening institutional capacity in the agricultural sector. Its collaboration with the project will enhance the ability to monitor and manage environmental risks, fostering a robust integration between the public sector, farmers, and research institutions. This will not only facilitate innovation but also promote sustainable rural development that is resilient to climate change challenges.

  - **Institutional strengthening**: By improving the capacity of local institutions to monitor and manage environmental risks, collaboration between the public sector, farmers and research institutions such as Cenicafé will be strengthened. This will create a more robust ecosystem of agricultural

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support that will facilitate innovation and sustainable rural development.

  - **Environmental and Agronomic Monitoring:** Cenicafé has a long-standing commitment to environmental conservation and the sustainable management of coffee farms. Through its research, it has developed methods to monitor soil health, water resources, and biodiversity on coffee farms, which are essential for maintaining long-term productivity. The integration of these monitoring practices with the new technologies provided by the Colombian pilot, such as GNSS will greatly enhance the ability of farmers to manage their land more efficiently.
  - **Research and Innovation:** Cenicafé's participation in the project also presents an opportunity to push the boundaries of agricultural innovation. The data generated from real-time monitoring systems will contribute to ongoing research efforts in climate resilience and sustainable coffee production. Cenicafé will analyze the data collected through the pilot project to develop new insights into how coffee plants respond to different environmental conditions, allowing for the development of more resistant coffee varieties and improved farming practices

- **National Federation of Coffee Growers of Colombia (FNC):**
  The National Federation of Coffee Growers of Colombia is a key institution in supporting the country's coffee growing sector. Its participation in this project will ensure that the technological solutions developed are aligned with the needs of coffee growers at the national level. The FNC will provide technical expertise and strategic resources for the implementation of precision mapping and real-time monitoring tools, enabling coffee farmers to optimize their operations, improve sustainability, and increase resilience to climate variations. Its role will also include disseminating the results of the pilot to a wider audience of coffee producers, helping to drive the adoption of new technologies throughout Colombia.

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- **Technical and Logistical Support:** The FNC will provide technical expertise in coffee crop management, helping to tailor the developed tools to local conditions. Additionally, it will provide logistical support for the implementation of mapping and monitoring systems on farmers' coffee plantations.
- **Outreach and Training:** The FNC will be responsible for organizing workshops and training sessions for coffee growers, promoting the adoption of new technologies and enhancing the farmers' ability to use precision agriculture tools.
- **Improvements in Agricultural Management:** Through the integration of GNSS and Copernicus data, the FNC will help coffee growers optimize crop planning, improve water management, and enhance soil conservation.
- **Long-term Sustainability:** The FNC will work with other partners to foster sustainability and resilience in Colombian coffee production, promoting agricultural practices that minimize environmental impact and increase long-term productivity.
- **Project Benefits for FNC:** The FNC will gain access to advanced technologies and data, which will enhance its capacity to support coffee growers more effectively. The federation will benefit from improved tools for farm management, helping to create more resilient and sustainable coffee farming practices, which in turn strengthens its role as a key institution in Colombia's coffee sector.

- **Risk Management Unit (RMU):**
  The Risk Management Unit is an essential partner in the management and mitigation of environmental risks affecting coffee farmers, particularly those related to landslides and extreme weather changes. Through its collaboration in this project, the UGR will implement real-time monitoring systems using GNSS and satellite data to generate early warnings and risk maps. This will allow coffee

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farmers and local authorities to react more effectively to potential disasters, minimizing losses and improving the long-term sustainability of coffee production in the region.

- **Real-Time Risk Monitoring:** The UGR will implement advanced monitoring systems using satellite and GNSS data, allowing coffee growers and local authorities to receive early warnings about potential landslides and other natural disasters.
- **Mapping Vulnerable Areas:** Through collaboration with the UGR, the project will generate detailed risk maps that help identify particularly vulnerable areas, enabling more effective planning and response to extreme weather events.
- **Early Warning Systems**: The UGR will facilitate the implementation of early warning systems, providing local coffee growers and communities with critical real-time information to make quick decisions and prevent economic and human losses.
- **Enhancing Climate Resilience:** The UGR will contribute to strengthening the resilience of coffee-growing communities, helping them better adapt to climate change and reduce risks through improved agricultural practices and proper land management.

- **Farmer Outreach and Training on Mobile Apps:**
To effectively reach small and medium-sized farmers, the dissemination of knowledge and training on mobile applications will be carried out by the extensionists of the National Coffee Growers Federation (FNC). The extensionists, who operate in 603 coffee-producing municipalities, serve as the primary channel for transmitting the technologies and knowledge developed by Cenicafé to farmers. Their role is highly valued due to their close relationship with producers and their ability to provide practical, on-the-ground assistance.

The training process will include:

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- **Workshops and Field Demonstrations:** Hands-on sessions where extensionists guide farmers in the installation, navigation, and use of mobile apps for precision agriculture and farm management.
- **Personalized Technical Assistance:** Extensionists will provide one-on-one support to address specific questions and challenges faced by farmers in adopting digital tools.
- **Printed and Digital Educational Materials:** Manuals, video tutorials, and FAQs will be made available to ensure farmers can continue learning independently.
- **Follow-up and Feedback Mechanism:** Regular visits and surveys will be conducted to assess adoption rates, gather feedback, and improve the usability of mobile applications.

3. Interaction Between Users and the Application and Web Portal

In the Colombian pilot, various user groups, including small and medium-sized farmers, cooperatives, local governments, agricultural institutions, and risk management agencies, will interact with the application and web platform designed to enhance coffee production sustainability, environmental monitoring, and disaster risk management. The platform will serve as the central hub for visualizing analysis results, monitoring environmental factors, and facilitating real-time decision-making through intuitive data visualizations and reports.

This section outlines how these users will interact with the application, how they will visualize different analyses from each chapter's pipeline, and the expected outcomes for these users.

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Small and Medium-Sized Farmers

Farmers are one of the primary target groups who will benefit from the precision agriculture and environmental sustainability tools provided through the web portal and mobile application. The user interface for farmers will emphasize ease of use and intuitive design, providing straightforward access to critical information such as topographic data, and environmental warnings.

- **Topographic Mapping and Crop Planning**: Farmers will access topographic maps generated by the RTK GNSS and satellite data through interactive 2D and 3D visualisations. These maps will include layers for slope gradient, elevation, and planting line suggestions, allowing farmers to adjust planting practices based on the topography.
  - **Visualisation Example:** A map with contour lines overlaid with slope data, enabling farmers to quickly identify optimal planting areas.
    - **Interaction:** Farmers will use a simple interface to toggle between different layers, such as elevation and risk areas for soil erosion, while receiving planting recommendations.
  - **Real-Time Alerts:** Farmers will receive real-time notifications via the mobile app regarding environmental conditions such as water availability and soil moisture. The app will notify users when certain thresholds are crossed, allowing immediate action.
    - **Interaction:** Simple push notifications for water usage optimization and potential weather risks, which can be adjusted based on individual preferences.
- **AI-Based Field Mapping for Coffee Plantations:** Coffee farmers and agricultural stakeholders will have access to AI-generated maps and reports created using satellite imagery (Sentinel-2) and GIS data. These visualizations will focus on terrain features and spatial information, offering valuable insights to support efficient land management and the planning of coffee plantations.
  - **Visualisation Example:** An interactive map allowing farmers to easily differentiate between areas for effective planning and management.

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- **Alert System:** The mobile app sends notifications to inform users about significant changes or conditions related to land use and environmental risks. These alerts aim to support timely decision-making and effective management of resources.
  - **Interaction:** Users receive general notifications about land changes, environmental conditions, and potential risk factors, with customizable settings to suit individual needs and preferences.

Cooperatives and Associations

Agricultural cooperatives will benefit from the platform's more advanced data processing features, enabling them to manage multiple farms collectively. They will be able to compare data across various farms, optimize resources, and disseminate best practices to their members.

- **Environmental Impact Mapping**: Cooperatives will utilize environmental impact maps showing real-time and historical data or water usage, deforestation, and carbon emissions. This will enable cooperatives to identify patterns of unsustainable practices.
  - **Visualization Example:** Dashboards that show aggregated environmental footprints of multiple farms, with trend graphs indicating the sustainability performance over time.
    - **Interaction:** Cooperatives can download reports and export data on environmental impact metrics, filtered by farm, region, or specific timeframe.

- **Risk Mapping and Predictive Models**: Risk maps showing areas prone to landslides or flooding will be available, enabling cooperatives to take preventive measures or advise members on which areas to avoid planting during high-risk seasons.
  - **Interaction:** An interactive map where cooperatives can input specific locations to receive predictions about potential environmental risks. Additionally, cooperatives can run what-if scenarios using historical data

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to simulate future risks.

Local Governments, Agricultural Institutions, and Risk Management Agencies

These institutions will leverage the platform's predictive models and risk monitoring tools to make policy decisions, improve resource allocation, and implement disaster management plans for coffee-growing regions. In particular, risk management agencies, such as UNGRD (National Unit for Disaster Risk Management) and local offices like CREPAD (Regional Emergency Committee for Disaster Prevention and Attention), will use the platform to monitor potential hazards and mitigate risks.

- **Landslide and Wildfire Risk Monitoring**: Local governments and risk management agencies can visualize risk maps with layers of satellite imagery, topographic data, and historical risk patterns. This will assist in early warning systems for natural disasters like landslides and fires.
    - **Visualization Example:** A heatmap indicating high-risk zones for landslides, with the ability to view different risk factors such as slope, soil composition, and rainfall intensity.
        - **Interaction:** Authorities and agencies can set automated alerts that notify them of any increases in risk based on weather data and real-time satellite observations. A decision-support tool will allow them to simulate the impact of mitigation measures.

- **Hydrological Balance and Climate Variability Analysis**: Government bodies and risk agencies can monitor the hydrological balance in coffee-growing regions by accessing models that display water availability, rainfall patterns, and soil moisture across different seasons.
        - **Interaction:** Interactive dashboards allow users to adjust input parameters, such as rainfall data, to see how changes in climate affect coffee productivity.

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- **Environmental Risk Alerts and Land Use Planning:** Governments will receive notifications of potential environmental risks impacting coffee cultivation, such as deforestation, uncontrolled expansion or encroachment on protected areas. This feature provides crucial data for timely policy adjustments and environmental conservation strategies.
    - **Interaction:**

      Automated alerts inform agencies of critical land use changes, allowing immediate intervention. The system allows officials to toggle between layers to view deforestation areas and generate reports supporting land conservation and climate resilience.

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Detailed Interaction in the Platform

User Group	Analysis/Deliverable	Interaction	Visualization Format
Small and Medium Farmers	Topographic Mapping and Planting Line Recommendations	Toggle between slope gradient and elevation layers to view recommended planting areas.	2D and 3D contour maps, with slope and planting suggestions.
	Environmental Alerts	Receive notifications for water availability, weather risks.	Push notifications and simplified alert systems.
Cooperatives	Environmental Footprint Mapping	Download reports on carbon emissions and water usage for multiple farms.	Aggregated data dashboards with trends over time.
	Risk Mapping	Input regions to receive landslide risk projections and view scenarios.	Interactive maps with predictive overlays for risk factors.
Local Governments, Risk Agencies	Landslide and Fire Risk Monitoring	Access heatmaps showing risk areas and set automated alerts for high-risk zones.	Heatmaps, hazard zones with adjustable simulation settings.
	Deforestation monitoring	Alerts and reports on detected deforestation activities. Toggle between maps highlighting affected areas.	Interactive maps and detailed reports focused on deforestation patterns.
	Hydrological Balance Monitoring	Explore seasonal changes in water	Interactive dashboards with

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		availability and impact on crop yields.	rainfall and water usage charts.

4. Algorithms

The Colombian pilot focuses on five key areas of agricultural and environmental management, with each chapter employing advanced algorithms to process and analyze data. Below is a detailed description of the best algorithms selected for each chapter.

Mapping Site-Level in Coffee Crops Using Microtopography with RTK GNSS

Digital Elevation Model (DEM) Generation and Slope Analysis: The Digital Elevation Model (DEM) Generation and Slope Analysis algorithm is the most suitable for this pilot, which aims to map coffee crops using microtopography derived from RTK GNSS data. The algorithm enables the creation of precise topographic models and slope analyses that inform decisions regarding crop placement, erosion control, and water management in the steep terrains characteristic of Colombian coffee farms.

DEM Generation:

The algorithm creates a high-resolution Digital Elevation Model (DEM) from GNSS point cloud data. The input GNSS data contains geolocation points with elevation information obtained via Real-Time Kinematic Global Navigation Satellite Systems (RTK GNSS), which ensures centimeter-level accuracy.

The point cloud data is interpolated to produce a continuous elevation surface. Two common methods for interpolation in DEM generation are:

- **Inverse Distance Weighting (IDW):** Weights nearby points more heavily than distant ones, assuming that points closer to each other will have more similar elevation values.

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$$z(x,y) = \frac{\sum_{i=1}^{N} Z_i * \frac{1}{d_i^p}}{\sum_{i=1}^{N} \frac{1}{d_i^p}}$$

Where:

Z(x,y) is the interpolated elevation at the point (x,y)

Z_i is the elevation of the i-th point

d_i is the distance from the i-th point to the point (x,y)

p is the power parameter controlling the weighting based on distance.

- **Kriging:** A more advanced geostatistical technique that not only considers distance but also spatial correlation between points to create a more accurate surface.

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2$$

Where:

$\gamma(h)$ is the semivariance at distance h

$Z(x_i)$ is the elevation at point x_i

$Z(x_i + h)$ is the elevation at a point displaced by h

Slope Analysis:

Once the DEM is generated, a slope algorithm computes the gradient of the surface, defined as the rate of elevation change in the x and y directions. This information is crucial for identifying areas prone to erosion and for optimizing planting lines. The slope SSS is calculated using the following formula:

$$S = arctan\left(\sqrt{\left(\frac{\partial Z}{\partial X}\right)^2 + \left(\frac{\partial Z}{\partial Y}\right)^2}\right)$$

Where:

Z is the elevation.

X and Y are the horizontal distances in the east-west and north-south directions, respectively.

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Hydrological Balance for Coffee Production

Soil Moisture Estimation and Hydrological Balance Modeling Using Machine Learning: The best algorithm for Chapter 2, which focuses on assessing the hydrological balance in coffee production, combines Soil Moisture Estimation using Sentinel-1 SAR data with Hydrological Balance Modeling using traditional methods and advanced machine learning techniques. This algorithm helps farmers understand how soil moisture and water balance affect crop productivity, improving irrigation strategies, and predicting drought or water logging risks. The model leverages machine learning to estimate soil moisture and uses a hydrological equation to compute the water balance, with deep learning enhancing predictions over time.

The algorithm consists of two primary components:

Soil Moisture Estimation using Random Forest Regression: This component uses Sentinel-1 Synthetic Aperture Radar (SAR) data and machine learning techniques to estimate soil moisture. SAR data is sensitive to surface wetness, making it ideal for calculating moisture levels. The Random Forest Regressor, a robust machine learning algorithm, processes this SAR data alongside meteorological variables such as rainfall and temperature. The model outputs soil moisture levels across coffee farms, identifying areas that require irrigation or are at risk of drought.

Hydrological Balance Modeling using the Penman-Monteith Equation: Once soil moisture is estimated, the Penman-Monteith equation is used to compute evapotranspiration, which is a critical factor in determining the overall hydrological balance. This equation models the relationship between environmental factors (temperature, humidity, wind speed) and water loss through evaporation and plant transpiration. The soil moisture and evapotranspiration data are combined to create a hydrological balance model that predicts water availability over time.

Recurrent Neural Networks (RNNs) for Predictive Modeling: To forecast future soil moisture levels and water balance, an RNN is employed. The RNN uses sequential data on weather patterns and soil moisture to model temporal dependencies, allowing for

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more accurate predictions of water needs over time. This predictive model is crucial for managing irrigation in advance of dry or wet periods.

Key Components:

- **Penman-Monteith Equation**: Used to calculate evapotranspiration, a key element in hydrological balance modeling. The equation integrates various environmental factors:

$$ET = \frac{\Delta(R_n - G) + \rho_a c_\rho \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)}$$

  Where:
  ET = evapotranspiration
  R_n = net radiation
  G = soil heat flux
  ρ_a = air density
  c_ρ = specific heat of air
  e_s, e_a = saturation and actual vapor pressures
  r_a, r_s = aerodynamic and surface resistances

  This is the most widely accepted method for calculating evapotranspiration. By integrating multiple environmental variables into one equation, it provides a physically accurate measure of water loss from both the soil and plant surfaces. The equation plays a critical role in computing the hydrological balance.

- **Random Forest Regression**: A tree-based ensemble learning method that estimates soil moisture by correlating the backscatter coefficient from Sentinel-1 with environmental factors. It constructs multiple decision trees and averages their results for robust predictions. The model is trained on labeled data (soil moisture readings) and predicts soil moisture across new areas.

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$$\hat{y} = \frac{1}{T}\sum_{t=1}^{T} h_t(x)$$

Where:
$\hat{y}$ = predicted soil moisture
T = number of trees
$h_t(x)$= output from decision tree t
x = input data (SAR backscatter, weather conditions)

This technique builds multiple decision trees, each using random subsets of the data. For each tree, the model partitions the data by selecting features that best reduce variance (via Gini impurity or information gain). Once all trees are built, the final soil moisture estimate is the average output of all trees, which improves stability and accuracy.

- **Recurrent Neural Networks (RNNs)**: RNNs are essential for handling sequential data. In this context, they take historical soil moisture and weather data to predict future soil moisture levels. The RNN architecture incorporates memory of previous states, which allows it to model how moisture changes over time in response to weather:

$$h_t = \sigma(W_h h_{t-1} + W_x x_t$$

Where:
h_t = hidden state at time step t
h_{t-1} = hidden state from the previous time step
x_t = input at time t
W_h, W_x = learned weight matrices

The RNN's architecture allows it to model sequential dependencies by maintaining a hidden state that evolves over time. Each input (such as daily weather) updates the hidden state, which in turn affects future predictions. This is particularly useful for predicting soil moisture because it captures the impact

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of past weather events on future moisture levels.

Risk Management for Landslides and Fires

For Risk Management in the context of Landslides and Fires, we need algorithms capable of predicting and assessing environmental hazards by integrating geospatial, topographical, and meteorological data. The most suitable algorithms for this chapter are Slope Stability Analysis for landslide risk. Each algorithm models the environmental risk based on real-time data inputs and predicts potential hazards, helping farmers and authorities take preemptive actions.

Slope Stability Analysis for Landslide Risk

The Slope Stability Model, particularly using the Factor of Safety (FoS) method, is a widely used technique for assessing the likelihood of landslides. This algorithm evaluates the balance between the forces that promote slope failure (driving forces) and the forces that resist slope failure (resisting forces). The Factor of Safety (FoS) is the ratio of the resisting forces to the driving forces acting on a slope:

$$FoS = \frac{R}{D}$$

Where:
R = resisting forces (typically the shear strength of the soil)
D = driving forces (typically the downslope gravitational force due to the weight of the soil or rock)

For a simple infinite slope model (commonly used in landslide risk assessments), the Factor of Safety can be calculated as:

$$FoS = \frac{c+\left(\gamma*z*cos^2(\theta)-u\right)*tan(\emptyset)}{\gamma*z*\text{sinsin}\,(\theta)\,*cos(\theta)}$$

Where:
c = cohesion of the soil (kPa)
γ = unit weight of the soil (kN/m³)

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z = depth of the soil or failure surface (m)
θ = slope angle (degrees)
u = pore water pressure (kPa), related to soil saturation
∅= internal friction angle of the soil (degrees)

The algorithm calculates FoS values across the study area, generating a landslide risk map. Areas with FoS<1 are highlighted as high-risk zones for landslides. These maps can be visualized on an interactive platform, allowing farmers and local authorities to monitor risk areas and implement mitigation measures.

Predictive Modeling and Monitoring

For both landslide risk and wildfire risk, predictive modeling and monitoring are critical to early warning systems. The implementation involves machine learning models trained on historical weather data and updates.

- **Random Forests or Gradient Boosting Machines (GBMs)** can be used to predict landslides by analyzing historical landslide data along with topographic and weather variables. These models are trained to recognize patterns that precede landslides, such as heavy rainfall on steep slopes with low soil cohesion.

- **Convolutional Neural Networks (CNNs)** combined with RNNs can be employed to predict the spread of wildfires based on satellite imagery and weather conditions. The CNN processes spatial data (e.g., vegetation maps), while the RNN models temporal changes in fire spread due to wind and weather fluctuations.

Environmental Footprint of Coffee Production

The Environmental Footprint of Coffee Production chapter focuses on monitoring the sustainability of agricultural practices by evaluating land use changes, carbon

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emissions, and resource utilization. The two key algorithms that best serve this objective are:

- ✔ Land Use Change Detection using Normalized Difference Vegetation Index (NDVI): This algorithm monitors changes in land cover, particularly deforestation and vegetation health, using satellite data.
- ✔ Estimation of Carbon Footprint using IPCC Guidelines for National Greenhouse Gas Inventories and Carbon Sequestration: This algorithm quantifies the carbon emissions from coffee production activities, including farming inputs, energy consumption, and deforestation, while also assessing the carbon storage capacity in soil and coffee plantations through biomass and soil organic carbon data. It offers a comprehensive view of both the environmental impact and the potential for carbon sequestration.

Normalized Difference Vegetation Index (NDVI): The NDVI algorithm is widely used for detecting changes in vegetation cover and land use. It relies on satellite imagery, primarily from Sentinel-2, to calculate an index that reflects the health and density of vegetation in a given area. This algorithm helps identify deforestation, monitor reforestation efforts, and assess the impact of agricultural expansion on forests. The NDVI is calculated using the following formula:

$$NDVI = \frac{(NIR-R)}{(NIR+R)}$$

Where:

- NIR = Near-Infrared band of the satellite image
- R = Red band of the satellite image

NDVI values range between -1 and 1, where:

- Positive values (closer to 1) indicate healthy, dense vegetation.
- Values near 0 represent sparse vegetation or bare soil.
- Negative values indicate water bodies or barren land.

Estimation of Carbon Footprint using IPCC Guidelines for National Greenhouse Gas

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Inventories and Carbon Sequestration Estimations: This algorithm calculates the total carbon footprint of coffee production, considering farming inputs, transportation, and processing. It follows the IPCC Guidelines for estimating CO_2, CH_4, and N_2O emissions, providing a standardized method to measure greenhouse gases across different stages of production. The algorithm also assesses carbon sequestration potential in soil and coffee plantations, using biomass and soil organic carbon data to estimate the land's ability to capture and store carbon.

To improve the accuracy of estimations, predictive models can forecast future land-use changes and emissions. Machine learning algorithms, like Support Vector Machines or Random Forest Classifiers, predict the expansion of coffee farms into forested areas, while time-series forecasting models, such as Long Short-Term Memory networks, help anticipate future emissions based on trends in energy use, farming inputs, and land-use changes. This supports long-term carbon reduction strategies.

Deforestation Risk Management

For deforestation monitoring and risk management, we utilize AI algorithms designed to detect changes in land use patterns. These algorithms integrate geospatial and spectral data, helping authorities and coffee producers identify and mitigate deforestation risks. The key algorithm for this application is Land Use Change Detection, which leverages real-time data inputs to enable timely interventions supporting land conservation and sustainable farming practices.

Deforestation Detection Using Satellite Imagery and AI

This application focuses on detecting deforestation activities in coffee-growing regions by analyzing changes in satellite imagery over time. Using advanced computer vision techniques, the system identifies areas where significant alterations in land cover have occurred. By leveraging machine learning models trained on historical satellite data, the approach ensures accurate detection and comprehensive monitoring.

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Key Methods and Features

1. **Change Detection Algorithms:** Advanced algorithms assess pixel-level differences between historical and recent satellite images to identify patterns indicative of deforestation. These algorithms focus on changes in spatial and textural features.

2. **Convolutional Neural Networks (CNNs) for Spatial Analysis:** CNNs extract and analyze spatial features, such as texture and color variations, directly from the satellite imagery. This allows for precise mapping of deforested zones by detecting subtle alterations in land patterns.

3. **Advanced Computer Vision Techniques:** Unsupervised learning models and change detection methods are applied to highlight regions with significant changes. These models evaluate differences in texture and spatial distribution, providing reliable insights into deforestation activities.

Monitoring Systems

Machine learning models, trained on historical satellite data, enable the detection of land-use changes as they occur. Alerts generated by the system notify stakeholders of deforestation activities, allowing for timely interventions and informed decision-making.

By deploying these algorithms, the project offers detailed monitoring of land-use changes in coffee-growing areas. This enables farmers, environmental authorities, and policymakers to take proactive, data-driven actions to mitigate deforestation, conserve ecosystems, and promote sustainable land management practices.

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5. Overview of Key Data Sources and Policies

The application requirements for the Colombian pilot address the critical data needs, update frequencies, and standards required to optimize coffee production and maintain environmental sustainability. Each use case relies on a combination of high-resolution satellite data, GNSS technology, and local environmental datasets, ensuring that stakeholders—including coffee farmers, agricultural cooperatives, and regulatory agencies—have access to accurate, actionable information for effective decision-making. The following subchapters provide an overview of key sources and policies for each use case.

Mapping Site-Level in Coffee Crops Using Microtopography with RTK GNSS

This application requires precise mapping of coffee-growing areas using RTK GNSS data and satellite imagery to assess slope, soil characteristics, and other topographical features. Digital Elevation Models (DEMs) will be generated to aid in optimal planting line planning, erosion control, and water distribution management.

- Key data sources:
    - Sentinel-1 Satellite Data: Operating in Interferometric Wide Swath mode, Sentinel-1 provides 10-meter resolution SAR imagery, with a 6-day revisit interval, making it ideal for DEM generation and slope analysis in complex terrains.
    - RTK GNSS Networks: These provide high-precision real-time geolocation data, critical for microtopographic mapping at the field level.
    - Soil and Environmental Data: Baseline information on soil composition, moisture, and stability is sourced from IGAC and Cenicafé, enabling tailored recommendations for erosion prevention and planting line design.

- Required data frequency:
    - Real-time GNSS data during mapping
    - Updates every 6 days from Sentinel-1 satellite imagery.

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- Key standards and policies:
  - IGAC Resolution 068 of 2005: This resolution mandates that all topographic surveys must be georeferenced and referred to the MAGNA-SIRGAS Datum. This ensures the accuracy and consistency of the geographical location of the measured points.
  - Resolutions 471 and 529 of 2020: Issued by the Agustín Codazzi Geographic Institute (IGAC), these resolutions stipulate that all geographic information presented must comply with the Cartographic Projection System for Colombia - National Origin. This is crucial for the correct management and presentation of geographic data.
  - Colombian Technical Standard NTC 5043: This technical standard provides guidelines for the quality of geographic data, ensuring that the data used in specific applications, such as coffee crop mapping, are accurate and fit for purpose.

Hydrological Balance for Coffee Production

This use case focuses on monitoring soil moisture and water availability to optimize irrigation and understand the hydrological balance for coffee farms. By integrating Sentinel-1 SAR data, meteorological inputs, and hydrological modeling, this component evaluates water resource usage and predicts soil moisture conditions.

- Key data sources:
  - Sentinel-1 SAR Data: This satellite provides 10-meter resolution imagery, capturing updates every 6 days on soil moisture and surface water changes, which are essential for water management planning.
  - IDEAM's Meteorological Network: This network supplies real-time climate variables—such as rainfall, temperature, and humidity—that are integral to calculating evapotranspiration and water balance.
  - Hydrological Baselines from Cenicafé: Regional hydrological data offers essential insights into water flow, rainfall distribution, and irrigation needs, providing a robust framework for soil moisture modeling and water balance calculations.

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- Required data frequency:
    - Daily updates for meteorological data
    - Soil moisture updates every 6 days from Sentinel-1.
- Key standards and policies:
    - Resolution 2115 of 2007: This resolution from the Ministry of Environment, Housing, and Territorial Development establishes the criteria and quality standards for water intended for human consumption and agricultural use. It is crucial to ensure that the water used in coffee production meets the necessary quality standards to avoid negatively impacting the crop.
    - Colombian Technical Standard NTC 4113: This technical standard provides guidelines for water resource management in agriculture, including the measurement and monitoring of soil water availability and the implementation of sustainable water use practices in crops such as coffee.

Environmental Footprint of Coffee Production

This application assesses coffee production's environmental impact by calculating carbon emissions, monitoring land use changes, and evaluating resource utilization. Sentinel-2 satellite data supports analysis of land cover and vegetation changes, while emissions data is integrated to assess sustainability and guide resource management.

- Key data sources:
    - Sentinel-2 imagery (10 m resolution, with a revisit interval of 5 to 10 days) for land use and vegetation monitoring.
    - Emissions data from local farming records and environmental compliance reports
    - IGAC land classification datasets for land use change analysis.
- Required data frequency:
    - Emissions data updated every month and land use data updated every 5 to 10 days from Sentinel-2.
- Key standards and policies:
    - Resolution 2115 of 2007: This resolution from the Ministry of Environment, Housing, and Territorial Development establishes the criteria and quality

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    - Colombian Technical Standard NTC 4113: This technical standard provides guidelines for water resource management in agriculture, including the measurement and monitoring of soil water availability and the implementation of sustainable water use practices in crops such as coffee.

Deforestation Index in Coffee Crops

This use case focuses on detecting deforestation in coffee-growing areas, employing geospatial analysis and indices derived from Sentinel-2 data. These tools enable the early identification of unauthorized deforestation, supporting sustainable land management practices and forest conservation.

- Key data sources:
    - Sentinel-2 satellite data (10 m resolution, with a 5 to 10-day revisit interval) for real-time land-use monitoring.
    - IGAC and IDEAM datasets for land cover and forest management data; and historical deforestation data for trend analysis and preventive action planning.
- Required data frequency:
    - Biweekly updates from Sentinel-2
    - Guarterly reviews of deforestation data for trend analysis
- Key standards and policies:
    - CONPES 4021 of 2020: This policy aims to reduce deforestation by 30% by the year 2022 and achieve zero deforestation nationwide by the year 2030. It is fundamental for any project that seeks to monitor and reduce deforestation in coffee cultivation areas.
    - Decree 690 of 2021: This decree establishes guidelines for the sustainable management of natural resources and environmental protection, including the conservation of vegetation and the reduction of

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deforestation. It is crucial to ensure that agricultural practices in coffee crops are sustainable and environmentally friendly.

Conclusions

The proposed pilot and use cases in the COMUNIDAD project represent an innovative approach to addressing the challenges of agricultural management and environmental risk mitigation in Colombia's coffee-growing region. Each use case is designed to provide practical solutions tailored to the needs of farmers, cooperatives, and local institutions, though they are still in the planning and development stages.

The Microtopography Mapping for Crop Planning use case aims to generate high-precision maps using RTK GNSS and satellite data, enabling optimal planting line planning on steep terrain. This is expected to result in improved water distribution, reduced soil erosion, and greater efficiency in water resource use. Once implemented, this tool could significantly enhance crop productivity by adapting agricultural practices to the specific topographical features of each farm.

The Landslide and Fire Risk Management use case plans to integrate Copernicus data with predictive models to develop risk maps for landslides and fires, which is crucial in mountainous regions like Caldas. These risk maps and early warning systems are anticipated to strengthen the response capabilities of local authorities and producers, allowing for more proactive management of these events. This could help minimize damage caused by natural disasters, protecting both communities and agricultural infrastructure.

The Hydrological Balance and Coffee Production Impact Assessment use case aims to monitor water availability and balance in cultivation areas through the integration of satellite data and hydrological models. This is expected to provide valuable insights for optimizing irrigation practices and adapting to climatic variability, ensuring that farmers can better prepare for droughts or intense rainy seasons. Such insights could directly contribute to the stability of production and resilience against climate challenges.

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The Environmental Footprint Monitoring in Coffee Production use case proposes to create indices that assess the carbon footprint and environmental impact of coffee production using geospatial analysis tools. This would enable producers and cooperatives to identify unsustainable practices and make the necessary adjustments to reduce their environmental impact. Through this use case, the project aims to encourage a transition towards more sustainable practices, aligning agricultural production with environmental conservation goals.

The Deforestation Index in Cultivation Areas use case aims to detect deforestation activities using vegetation indices derived from satellite imagery. The tool provides environmental authorities and farmers with insights into land-use changes, enabling timely interventions to protect ecosystems and promote sustainable land management.

Overall, while these use cases are still under development, they demonstrate significant potential for improving agricultural and environmental management in Colombia. Each use case is designed to address specific challenges in the coffee sector, combining advanced data with local needs. The expected outcomes are aimed not only at enhancing productivity and sustainability but also at strengthening the resilience of rural communities to the impacts of climate change. This positions the COMUNIDAD project as a model that could be replicated in other regions, where the integration of technology and local knowledge can drive sustainable rural development.

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