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MONITORING FORESTS IN REMOTE AREAS BY IOT BASED MEASURING SYSTEMS: THE REMOTREES PROJECT.

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Abstract:

Forests ecosystems play a fundamental role in mitigating global warming and associated increasing climatic variability through the feedback of their carbon and water cycles on the global climate system, while being increasingly exposed to dieback and natural disturbances triggered by extreme climate events. The absence of a comprehensive in situ forest monitoring network, particularly in remote regions characterized by strong logistic limitations, poses challenges in tracking forest responses to climate change. Recent strides in IoT technology, satellite IoT connectivity and energy harvesting systems present promising opportunities for the development of novel devices and set-ups for field observations in forest environments.

On that note, the EU-funded RemoTrees project (Horizon Europe Research and Innovation Programme under Grant Agreement No. 101086287) aims to design and build an innovative, autonomous in-situ monitoring system suitable for remote forest areas also under extreme physical conditions and able to provide data via satellite communication to a dedicated platform. In this framework, RemoTrees will provide observations of Essential Climate Variables (ECVs) and other key variables including fraction of absorbed photosynthetically active radiation (fAPAR), multispectral measurements of incident, canopy reflected and transmitted solar radiation, tree stem radial growth and motions, sap flow, soil temperature and moisture, besides air temperature and humidity below and above the forest canopy. The resulting data set will be integrated with Earth Observations for the development of use cases on the impact of climate change on forests, demonstrating its usability as a reference for remote sensing products calibration and validation as well as the interoperability and synchronization between in-situ and remote sensing systems according to GEOSS requirements.

1. Introduction

Forests cover one-third of the land area and their impact on climate change mitigation and adaptation scenarios is enormous. Tree mortality due to climate stress is in this context a global-emerging threat (Anderegg et al. 2013; Senf et al. 2020). However, validated and integrated datasets to monitor forest degradation are currently missing, particularly in hard-to-reach areas such as boreal, high altitude, and tropical ecosystems

The overall goal of the RemoTrees project is to develop and test a new in-situ observation system based on Internet of Things (IoT) technology and satellite communication, specifically designed for hard-to-reach forest areas. The RemoTrees system will address the lack of in-situ data (Alton, 2020; Heiskanen et al. 2022; Samuel & Vargas, 2021) and complement Earth Observation (EO) efforts to monitor climate change effects on these ecosystems.

The recent introduction of an innovative IoT based device for the ecophysiological monitoring of trees (TreeTalker®, Valentini et al., 2019; Matasov et al., 2020) allows the monitoring of tree growth, stem water transport, spectra of canopy-transmitted light, and microclimate among other variables. The RemoTrees project will build on the experience gained with theTreeTalker® designing a new multi-sensor device, conceiving new sensor technologies and set ups. starting from an initial Technology Readiness Level (TRL) of the single sensors of 3-5 and aiming at a TRL of 6-7 by the end of the project.

The specific objectives of the Remotrees project are: 1)To design a unique IoT system enabled with satellite communication and based on affordable technologies capable of retrieving Essential Climate Variables (ECVs) and other key variables in environmental/ecological research in hard-to-reach forest areas also under extreme physical conditions; 2) To verify the ability of the designed system to reinforce the in-situ forest monitoring component in hard-to-reach areas which are currently undersampled; 3) To design and test a data platform integrating RemoTrees system data with dense EO time series demonstrating interoperability and synchronisation between in-situ and remote sensing systems according to GEOSS requirements; 4) To integrate the RemoTrees sites network in the Copernicus in-situ component e.g., Ground-Based Observations for Validation (GBOV) of Copernicus Global Land Products and other calibration and validation programs; 5) To analyse climate and ecosystem services case studies building on the RemoTrees system data to target climate change impacts on forests; 6) To provide an economic/social benefit analysis of the long-term sustainability of RemoTrees systems, adopting a business model approach which contemplates the participation of industrialists, research centres and public stakeholders.

2. Methods

In order to achieve the above-mentioned objectives along a 4-year course, the Remotrees project is structured in different components and tasks

System design and lab testing: this entails a careful selection of the electronic components including costs analysis and devices assembling aimed at maximizing reliability in extreme environmental conditions and at reducing power consumption. Targeted variables include the following: a) stem radial growth, b) sap flow, c) stem water content, d) air temperature and relative humidity, e) soil temperature and humidity and f) canopy spectral data from at least 18 bands in the VIS/NIR range: incoming, transmitted and reflected radiation (fAPAR components) at Level 1 sites and canopy transmittance (incoming and transmitted light) at Level 2 sites. The devices will be designed to resist extreme temperatures and it will be enclosed in a waterproof coated case with waterproof plugs for the sensor probes (IP65 or higher). The firmware of RemoTrees devices will be developed including IoT communication system and optimization of satellite transmission hardware and software; the design of solar energy harvesting and battery systems will also be within the scope

The RemoTrees devices will be fully characterized (e.g. signal to noise ratio, temperature sensitivity, spectrometer bands spectral range, linearity with luminance level, short and long term signal stability etc.) and calibrated before the deployment in the field. Prototyping include an (alpha prototype (lab level) to be improved into beta and gamma prototypes before installation at level 1 and forest sites respectively.

Test of RemoTrees systems in hard-to-reach forest sites: preselected forest field sites are divided into Level 1 (5 sites) with good infrastructure where validation measurements with independent reference instruments will be carried out, and Level 2 (9 sites) which are hard-to-reach sites located in a) boreal/high altitude forests b) dry tropical forests and c) tropical rainforests. Identification and collection of site metadata and of auxiliary data relative to the field sites (e.g., location, vegetation type, climatic features, soil type, etc.) and to the monitored trees (e.g., stem diameter, height, health status, etc.) will be prepared as well as the definition of installation protocols and field experimental designs. Following installation at Level 1 sites, data collected from Remotrees system (Beta prototype) will be quality assessed against a benchmark based on available high-end instrumentation and state of the art techniques; Quality assessment will include satellite communication and energy harvesting systems. The necessary system improvements will be implemented in a new gamma prototype for installation at Level 2 sites, the data of which will undergo a final scrutiny for system performance and calibration stability.

Data integration within the RemoTrees platform: a FAIR principles compliant database resource will be implemented to accommodate the data produced by the RemoTrees sensors. The DBMS (DataBase Management System) will be based on PostgreSQL with the likely integration of Frost DB to be compliant with the OGC standard (SensorThings API). The schema of the database will extend the MIAPPE (Minimum Information About a Plant Phenotyping Experiment) standard (Papastoglou et al., 2020) to accommodate time-resolved RemoTrees data. A prototype API for accessing the data will be designed and implemented considering also the possible integration of the RemoTrees database with GEOSS and Copernicus. A set of data visualisation dashboards will be provided to monitor the data acquisition process of single and aggregated sensors. A prototype system for quality control and early diagnosis of malfunctioning devices hardware will be implemented. Due to the multivariate nature of the data stream this task will be performed by combining Statistical Process Control, Machine Learning and Deep Learning approaches. The measurements from each sensor will be screened using univariate and multivariate time series techniques that use past data to identify outliers, such as DeepAnT (Munir et al., 2019). Open-source analytical tools based on advanced machine learning algorithms will be developed to fill the gaps in time series building upon the current strategies used for eddy covariance data (Wutzler et al., 2018). The final product will be a robust and quality flagged time series of RemoTrees in-situ

Towards the integration of the RemoTrees data in the Copernicus in-situ component: the interoperability within the whole Remotrees data platform will be pursued by interfacing it with Copernicus Services and international validation programs, and in particular with the in-situ component and the Copernicus Land GBOV (Ground Based Observation for Validation) service as well as with international programs (Sentinel-2 & Sentinel-3 Validation Teams, CEOS WGCV LPV) to identify their needs and requirements in terms of in-situ data. Raw data collected by the RemoTrees sites network will be customized to meet the needs of the Copernicus services and upscaled to generate Land Products using Sentinel 2 products.

Climate and ecosystem services case studies: the necessary spatially detailed datasets for the development of the case studies will be collected and processed in the subsequent tasks: i) EO direct observations at the sites (ESA Sentinel & Earth Explorer missions, NASA Landsat, MODIS & GEDI missions), ii) EO-derived products (e.g. ECV and EBV like above-ground biomass (AGB), phenology, structural and biochemical properties); iii) gridded climate data (and if necessary downscaling of the data at the core sites. The pathways that ultimately lead to the death of a tree will be investigated using the detailed RemoTrees data on individual trees and the responses of tree health parameters to climatic factors. Additionally, potential recovery patterns from the impacts of extreme events will be evaluated. These findings will help to improve our understanding of tree resilience to withstand environmental pressures as well as of potential tipping points and will contribute to the development of monitoring approaches for early warning signals.

Financial and business models for commercialization and exploitation of the RemoTrees system: in order to position RemoTrees system solutions within the analytics market for hard-to-reach forest areas and to analyse its profitability potential a Market and Competitor analysis will be carried out. A Costs and Benefit analysis, referred to the whole product life cycle with a forecasted projection in the middle-long term, will allow to individuate the most efficient, robust and profitable of the possible implementation solutions. Finally, a Business model for RemoTrees technology and related services will be developed, including three key elements: value proposition, configuration of the value creation and revenue model. The methodology to be used will be the Business Model Canvas (De Reuver et al. 2013).

3. Results and discussion

The RemoTrees project was conceived in response to the Horizon Europe Framework Programme topic: HORIZON-CL6-2022- GOVERNANCE-01-07 "New technologies for acquiring in-situ observation datasets to address climate change effects". It officially started on 1st December 2023 (Horizon Europe, Grant Agreement N. 101086287) and it has a duration of 4 years. The project, coordinated by Edmund Mach Foundation (Italy) features a consortium represented by Nature 4.0 srl (Italy), Helmholtz Zentrum Potsdam-GFZ (Germany), EOLAB S.L (Spain), Marburg University-MRU (Germany), National Institute for Laser, Plasma & Radiation Physics-INFLPR (Romania), National Research Council -CNR (Italy), and Deda Next srl (Italy).

In the first 8 months of the project, the main focus was first on the selection of sensor components, then on the preliminary sensors testing and assembling of the first (alpha) prototypes of the RemoTrees devices, which were released in due course in July 2024. (fig.1)

The RemoTrees (RT) system comprises three distinct devices: RemoTrees Trunk (RT-T), RemoTrees Radiation (RT-R), and RemoTrees Soil (RT-S). These devices are equipped with a variety of sensors designed to measure critical environmental and physiological parameters of trees (Table 1). All RT devices offer high versatility with three communication module options: NB-IoT, LoRaWAN, and GlobalStar. They are powered by a 32-bit ARM® Cortex®-based low-power microprocessor, which collects data from the sensors hourly and transmits it to a dedicated server.

Table 1: RemoTrees system targeted variables, sensor types and applied measurement principles

Parameter	**Sensor**	**Description**
Canopy radiation	Multi-band spectrometer	Multispectral digital sensor with 26 bands in the 400-960nm range
Sap flow density	Probe with 3 needles with NTC thermistors	Probe allowing the use of both the Heat Pulse Velocity (HPV) family methods and the Thermal Dissipation based methods for sap flow measurements.
Stem water content	Impedance Analyzer	Under development (operating range: 10 to 500 MHz)
Stem radial growth	Linear magnetic encoder (LME)	Tree Stem growth measured by point dendrometer with piston movements detected by LME technology
Microclimate	Digital thermo-hygrometer	Air temperature and relative humidity
Tree stem movements	Digital Accelerometer	Measurement of gravity components along 3 orthogonal axes
Soil water content	Capacitive sensor	Soil water content derived from changes in the capacitance of the transducer operated at 3 MHz

In parallel preparatory work for the following project phases was carried out including: the retrieval of a set of metadata (bioclimatic, soil, land cover and hydro-topographic) from gridded products for the field sites of level 1 and 2 by means of automated coded procedure and the conceptual design of the database and definition of methods for its implementation.

The RemoTrees website (remotrees.eu) launched in March 2024, containing a description of the project scientific background and activities, is since then being updated with news on the project

The RemoTrees IoT technology will be, to our best knowledge, the first to acquire in-situ data from hard-toreach forest areas and deliver them by satellite communication, supporting the integration with EO to address the impacts of climate change. The project outputs will enable the use of new tools for in-situ observations of climate variability and change, supporting further analysis of adaptation management scenarios. IoT technology and satellite communication will be used to deploy a cost-efficient approach for in-situ monitoring of Essential Climate variables (ECVs) and other key forest variables for EO product validation.

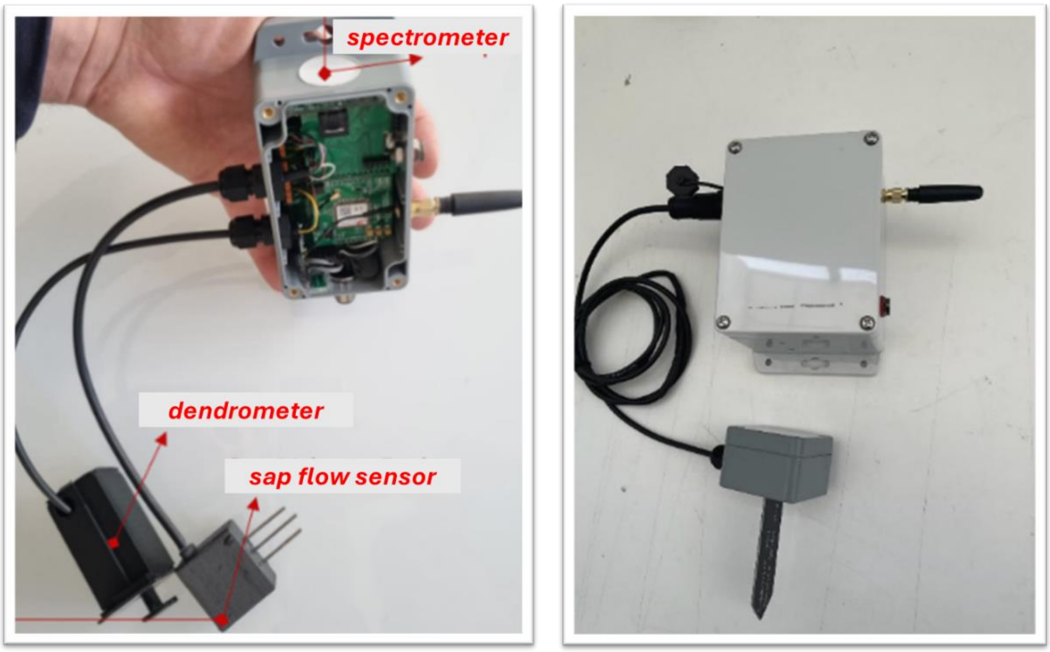

Figure 1: Alpha prototype pf the RT-T/RT-R (left) and of the RT-S (right).

The deployment of the RemoTrees system is based on a technology that requires limited resources (human, time, financial) for installation, maintenance, and recovery. It therefore enables widespread measurements at the single-tree level to complement data from other observation networks (e.g. ICOS, Fluxnet, ANAEE). On-site maintenance will be very limited, as the systems will be designed for standalone measurements in extreme environmental conditions.

The project will demonstrate that a larger network will be easily and quickly deployable at a European and even global scale, with a special focus on remote forest areas which are currently undersampled due to accessibility challenges (e.g. boreal, high altitude and tropical forest ecosystems).

The improved geographical coverage will provide detailed information on forest ecosystem responses to climate variability and change and is expected to better support future policies and decision making on climate adaptation and mitigation strategies. In addition, the real time transmission capability of the RemoTrees device will open unprecedented opportunities to provide useful risk management/prevention in the domain of ecosystem services.

As a flagship initiative of the European Green Deal, the European Commission has recently adopted the New EU Forest Strategy for 2030, which aims at facing the challenges of climate change. The ground-breaking nature of RemoTrees will strongly support the EU forest strategy and the GEO Global Forest Observations Initiative (GFOI), enhancing future activities in forest monitoring and Greenhouse Gas (GHG) accounting in developing countries. The proposed in-situ system, thanks to its low-cost and easy maintenance, will support Earth-Observation-based innovative governance efforts to protect forest resilience in the face of current climatic, ecological, economic, social, geo-political and health challenges

4. Conclusions

A new EU funded project, RemoTrees, is levereging on Internet of Thigs technology to design and implement a novel system able to monitor in quasi real time the ecophysiological parameters of trees and their physical environmnet. The system is conceived for deployment also in harsh climatic conditions and enabled also with satellite data tranmission opening the way to the monitoring of the most remote forests in the world from which in situ data are critically lacking.

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