PEOPLE
Ecosystem Restoration

D19: EVOLUTION ROADMAP

March 2024

Prepared for:

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PIONEER EARTH OBSERVATION APPLICATIONS FOR THE ENVIRONMENT – ECOSYSTEM RESTORATION (PEOPLE-ER)

D19: EVOLUTION ROADMAP

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AMENDMENT RECORD

This report has been issued and amended as follows:

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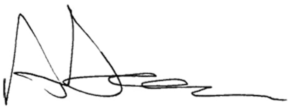
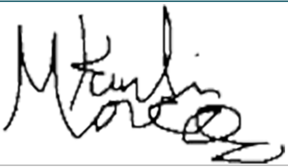
1	First version of D19 – Evolution Roadmap	20240325		
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1.0 INTRODUCTION

1.1 PEOPLE-ER PROJECT

Ecosystem Restoration (ER) is important to reverse biodiversity loss and is a critical element of nature-based solutions (NBS) for climate change mitigation and adaptation, food security, and disaster risk reduction. ER is needed on a large scale to achieve the United Nations (UN) sustainable development agenda and as part of the UN Decade on Ecosystem Restoration (2021−2030). At the Convention on Biological Diversity (CBD) COP 15 in Montreal in December 2022, nations adopted a target to “Ensure that by 2030 at least 30 per cent of areas of degraded terrestrial, inland water, and coastal and marine ecosystems are under effective restoration, in order to enhance biodiversity and ecosystem functions and services, ecological integrity and connectivity[1].

Effective planning, monitoring, and assessment of ER is required to evaluate ecosystem functions and to determine whether ER is having the desired impact. ER investments must be data-driven, requiring historical information on ecosystem disturbance and degradation, to enable planning of interventions, which are then monitored for their impact. There is a huge opportunity for satellite Earth Observation (EO) applications for ER, to meet the needs for regular, repeat measures of ER processes over long time periods covering large, often remote, areas.

To support ER investments, innovative methods are required to deliver high-quality EO-based products and indicators targeting high-priority forest, wetland, and biodiversity variables.

The Pioneer Earth Observation apPlications for the Environment (PEOPLE) ER project financed by the European Space Agency (ESA) is a trailblazer project to develop innovative high-quality EO-based application products, indicators, and methods, targeting ER research and development (R&D) priorities.

PEOPLE-ER is led by Hatfield Consultants – a science-driven service-oriented company that builds solutions to complex environmental challenges, with a depth of experience in ER projects in Canada and around the world. Hatfield is a trusted partner for the development of cutting-edge and practical EO technologies. The PEOPLE-ER consortium includes:

- VTT – the remote sensing team at VTT Technical Research Centre of Finland produces EO data processing chains for domestic and international users. The team is internationally known, particularly for its forest monitoring applications and the Forestry TEP cloud processing platform. VTT is ranked among the leading European Research and Technology Organisations (RTO).

- University of British Columbia, Faculty of Forestry – Dr. Nicholas Coops leads the Integrated Remote Sensing Studio (IRSS) and is a leading international research scientist in the application of EO technologies for forest ecosystem assessment and monitoring, including ER and the prioritization of methods and products for remote sensing essential biodiversity variables (RS-EBVs).

The Early Adopters are:

- **National Institute for Research and Development in Forestry (INCDS)** (Romania) – formally a member of the consortium, INCDS is the main organisation of research and development in

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[1] HYPERLINK "https://www.cbd.int/article/cop15-cbd-press-release-final-19dec2022"https://www.cbd.int/article/cop15-cbd-press-release-final-19dec2022

forestry from Romania. INCDS is in charge for the forest resources assessment and monitoring in Romania through National Forest Inventory. INCDS has also secured the support of two Romanian NGOs as documented in letters of support: Forestry Society Association and Fundatia Grupul Verde Oradea.

- **IUCN** (Vietnam) – established in 1948, IUCN is an international authority working on a wide range of themes related to nature conservation, forests, ecosystem management, protected areas, global policy and governance and rights.
- **African Parks** – a leading non-profit conservation organisation that takes on the complete responsibility for the rehabilitation and long-term management of protected areas across Africa in partnership with governments and local communities.
- **Society for Ecosystem Restoration in northern British Columbia (SERNbc) (Canada)** – a key enabler for ER in forested ecosystems affected by cumulative disturbances from forest operations, energy exploration, wildfires, and forest pests/diseases.
- **Natural Resources Institute (Luke) (Finland)** – as one of the biggest clusters of bioeconomy expertise in Europe, Luke develops knowledge-based solution models and services for renewable natural resources management and supports decision-making in society.

The following PEOPLE-ER Tools are defined:

1. **Spectral Recovery** – is an open source and multi-platform EO time series data analytics solution for restoration monitoring and assessment. It provides flexible methods for spectral recovery analysis by allowing users to select from a variety of spectral indices and recovery metrics as well as define reference or baseline conditions.
2. **K Nearest Neighbour** (k-NN) – is a tool for deriving forest structural variable maps by combining field reference data and EO datasets. It provides means to map ecosystem characteristics at any given timepoint before or during restoration.
3. **Satellite Wetland Inundation Flood Time-series Clustering (SWIFT-C)** is an open methodology that provides a set of data analytics tools to support large scale landscape assessment, leveraging the radar EO time-series.

These tools were identified following assessment of the current State of the Art (Deliverable 2a), Policy and Stakeholder Analysis (D2b), and Early Adopter Value Proposition (D3). The Tools are fully described in the Algorithm Theoretical Baseline Documents (D7).

1.2 SCOPE OF DELIVERABLE D19

Deliverable 19 (D19) comprises a roadmap that identifies:

1. A comprehensive Research and Development (R&D) agenda to tackle the critical areas of EO for ER; and
2. The necessary steps to further evolve the PEOPLE-ER tools to address identified limitations by the development team and Early Adopters.

2.0 COMMUNICATION AND USER ENGAGEMENT

The objective for communication and user engagement around the PEOPLE-ER tools is to raise awareness of the tools, use cases, and to expand the number and type of users to include ER and EO researchers and practitioners.

The communication and engagement component of the roadmap includes the following:

- **GEO-BON**: promoting and disseminating the tools and methods developed by the PEOPLE-ER project through GEO-BON events will raise awareness of the tools with a target user community. GEO-BON's annual conference provides a platform to reach a potential user base.
- **Society for Ecosystem Restoration:** through regional chapters there are opportunities for networking such as webinars and regional conferences.
- **ESA Blog Post**: through ESA Communications and in collaboration with Early Adopters.
- **Early Adopter led communications**: PEOPLE-ER Early Adopters to be engaged in communications and presentations with their stakeholders and community of practice.
- **ESA Stakeholders Expansion Facility (SEF):** The ESA SEF aims to sustain and expand the interaction with various stakeholders that took part in ESA EO Applications projects. As such continued user engagement through this program should be pursued to maintain the engagement of the Early Adopters as well as to further promote and evolve the tools produced by the PEOPLE-ER project.
- **Scientific publications**: write scientific publications on the following:
    - Spectral recovery tool – development and functionality of the tool for submission to Method in Ecology and Evolution.
    - Application of the spectral recovery tool in British Columbia
    - Application of the SWIFT-C methodology in Vietnam with IUCN Vietnam.
    - Application of a spectral recovery method in Central African Republic (CAR) with African Parks.

3.0 USER GUIDELINES AND TRAINING

The PEOPLE-ER tools and documentation produced are accessible and readily available to Early Adopters and the wider potential user community under **Findable, Accessible, Interoperable, and Reusable (FAIR)** principles.

Spectral Recovery:

- Codebase is available on GitHub: https://github.com/PEOPLE-ER/Spectral-Recovery/
- Python Package Index (PyPI): https://pypi.org/project/spectral-recovery/
- Documentation including sample data and example notebooks is available on GitHub Pages: https://people-er.github.io/Spectral-Recovery/

Satellite Wetland Inundation Flood Time-series Clustering (SWIFT-C):

- Codebase is available on GitHub: https://github.com/PEOPLE-ER/Wetland-Function-Assessment
- Documentation including sample data and example notebooks is available on GitHub Pages: https://people-er.github.io/Wetland-Function-Assessment/

K-Nearest Neighbour:

- Codebase is available on GitHub: https://github.com/PEOPLE-ER/k-NN
- Documentation including sample data is available on GitHub Pages: https://people-er.github.io/k-NN/https://people-er.github.io/Spectral-Recovery/

Both the Spectral Recovery and k-NN tools are hosted on the Forestry Thematic Exploitation Platform (Forestry TEP) for users who want to access the tools as readily prepared services, using hosted (or user-uploaded) EO data – either via the graphic interface or the API of the platform: https://f-tep.com/. User Manuals on how to use the Forestry TEP platform as well as the individual tools are available to enable smooth onboarding of new users.

Training has been provided to Early Adopters and their associates (when desired) to develop capacity to use these tools. The PEOPLE-ER final meeting at the European Geoscience Union (EGU) conference in Vienna includes a demonstration of the Spectral Recovery tool using the application programming interface and Forestry TEP.

Hosting future open training events pertaining to the use of the Spectral Recovery, SWIFT-C, and k-NN tools would undoubtedly help increase the potential userbase and understanding of each tool.

Demonstrations of the Spectral Recovery and SWIFT-C tools in additional ecosystems and for different use cases is recommended to build evidence of the potential for the tools to support restoration, as well as identify areas for future improvement.

4.0 SPECTRAL RECOVERY

4.1 BRIEF SUMMARY OF THE CRITICAL NEED AND POTENTIAL USERS

The critical need is the computation of forest ecosystem recovery metrics using satellite EO data in a reproducible, scalable manner. More specifically, there is a need for an accessible solution that provides standardized metrics and information pertaining to change in vegetation conditions following ecosystem disturbances or restoration interventions, based on the calculation of spectral indices from an EO time series (annual cloud-free composite). Potential use cases include ecosystem restoration monitoring efforts for forested ecosystems or remote sensing research of forest recovery responses.

Users include:

- ecosystem restoration practitioners interested in monitoring restoration success or ecosystem recovery;
- remote sensing or GIS specialists studying ecosystem recovery responses;
- NGOs involved in ecosystem restoration and biodiversity conservation;
- levels of government that aim to assess landscape-scale or site-level conditions of vegetation; and
- International Finance Institutions (IFIs) that wish to have a reproducible tool and methodology with which to efficiently monitor their programs.

For the PEOPLE-ER project, the primary user was SERNbc (Society for Ecological Restoration in Northern British Columbia) who is collaborating with the Saik'uz First Nation and aims to implement, monitor, and improve the efficiency of ecosystem restoration projects in the Saik'uz traditional territory as well as more broadly in Northern British Columbia, Canada. The provincial government in British Columbia (BC GOV) is a secondary user that aims to increase the scale and ease of landscape-scale vegetation assessments across the province.

4.2 CURRENT STATE AND TESTING/DEMONSTRATIONS

The Spectral Recovery tool currently provides the ability to compute five recovery metrics for a restoration site over indices chosen from a catalogue of 100+ modern vegetation or burn-related spectral indices. Accompanying documentation provides information on spectral recovery analysis for forested ecosystems, ER practices, and tutorials for the software. The source code for the tool is publicly available on the GitHub repository and the software package has been distributed on the Python Package Index (PyPI) for download under the name spectral-recovery.

The spectral recovery tool supports various workflows by providing multiple interfaces for computing recovery metrics. An API and a command line interface (CLI) are both provided in the base spectral-recovery package distributed on PyPI. Additionally, the integration of spectral-recovery into the Forestry TEP platform provides users with a readily executable, cloud-based service, accessible via a graphical user interface (GUI) or an API. Support for multiple interfaces ensures that users of varying technical knowledge can use the spectral recovery tool to support ER activities through spectral recovery analysis.

The tool currently supports scalable, reproducible, and interoperable computation of recovery metrics. By using the Dask and Xarray packages, recovery metric computations can be run in parallel locally or can be scaled further using compatible cloud computing platforms, like Microsoft's Planetary Computer Hub. The core functionality of the spectral-recovery package operates on data structures commonly used in cloud-native geospatial workflows like Xarray's DataArrays and GeoPandas' GeoDataFrames. Use of common packages promotes interoperability between the spectral-recovery package and other existing or future cloud-native geospatial tools for image compositing, restoration site delineation, recovery metric analysis, etc.

The Spectral Recovery tool demonstration in the Saik'uz traditional territory located in Northern British Columbia, Canada assessed the spectral recovery of forested areas that have previously been disturbed or degraded by wildfires or harvesting between the years of 2003 and 2018. The demonstration included the production of timeseries of spectral indices, including those such as NDVI (Normalized Difference Vegetation Index) and NBR (Normalized Burn Ratio), as well as the quantification of recovery progress both in the early stages of site recovery (5 years into the restoration window) through short-term recovery metrics (e.g., R80P and dNBR) and long-term recovery through Y2R. The analysis and demonstration showed variability in recovery progress across different restoration sites, allowing the identification of areas within the landscape that have spectrally recovered and those that might benefit from restoration or management interventions. These findings are beneficial for the early adopters, providing an indication of potential management priorities and demonstrating the tool's value for further restoration monitoring efforts.

4.3 CURRENT AND PLANNED USER ENGAGEMENT

Direct user engagement has focused on SERNbc, Government of BC, and Saik'uz First Nation in Canada, and INCDS in Romania. This included meetings to demonstrate the tool workflow, methodology, and outputs, as well as output interpretation and potential analyses that are enabled due to the tool.

Additional user engagement has included:

- Presentation at GEO-BON 2023
- Global webinar to introduce the tool, the theoretical concepts behind the tool's methodology, and demonstrate its applicability for monitoring efforts through Canadian and Romanian use cases.

Planned user engagement includes:

- An oral presentation and a splinter meeting tool demonstration to take place at the EGU Conference, 2024, to increase awareness of the tool and engage with potential users directly.
- Training or demonstration sessions within the Ministry of Forests in British Columbia.
- Publication in the peer reviewed journal Methods in Ecology and Evolution

Through the above efforts and availability of the Spectral Recovery tool in Github and PyPi, there have been **2948 downloads** of the tool as of March 2024.

4.4 PRIORITIES TO EVOLVE THE SOLUTION

An updated version of the Spectral Recovery package will be released in April 2024. Future evolutions of the Spectral Recovery tool should be user-focused, which will help ensure the tool continue to be useful for supporting ER research.

User interaction:

- User engagement and feedback will be facilitated through the GitHub repository's Issues and Discussion pages. This feedback, along with the resulting discussions, should identify which features and changes are most beneficial for users. Implementing these changes will create a more useful tool, helping promote spectral recovery analysis in ER research and practitioner workflows.

Tool development:

- **New recovery metrics for forested ecosystems** – should be integrated into the tool to ensure current, relevant research can be utilized by practitioners and researchers. Suggestions for new metrics by users or researchers should be facilitated through the GitHub Issue's page.

- **High-performance and cloud computing** – development of spectral recovery should continue to incorporate best practices to offer simple, scalable solutions to users. Methods for scaling data processing should continue to be abstracted away from users, when possible, while still allowing for customizability for those who prefer more oversight on their processing. By ensuring future tool evolutions support state-of-the-art research and computing practices, the spectral recovery tool will remain a crucial part of spectral recovery analysis research and practice within the ER community.

- **Forestry TEP** – After some final modifications and verifications, the Forestry TEP version of the tool should be included in the selection of basic tools available for all users in the platform.

- **openEO** – exploring the compatibility of the tool with openEO should be a priority, as it is being considered for adoption as a Community Standard under the Open Geospatial Consortium's (OGC) standards. This would enable users of the Spectral Recovery tool to work with different cloud environments in which the tool is currently unable to run; such as Google Earth Engine. In so doing, ensuring compatibility with openEO could increase the userbase of the tool, ensuring that its adoption is more widespread within the ER community.

Priority future tests and demonstrations of the tool should be used to assess the benefit of the spectral recovery analysis over a broader range of use-cases. These future use cases might include:

- Demonstrating the tool for restoration events in tropical forest regions such as the Amazon basin will demonstrate the tool's use in highly productive and dynamic environments, in which a multitude of ER efforts are focused.

- Demonstrating the tool in tropical montane forests where cloud cover and topography are challenges for remote sensing is another potential future use case. Demonstrating the tool's use in this kind of environment would be valuable as montane tropical forests contain many of the world's biodiversity hotspots.

- Demonstrating the tool in managed European Forests, might be of interest to the management community. Particularly in forests where multiple management interventions are underway. This might further display the potential of the tool for monitoring multiple different intervention types and comparing them based on reproducible metrics.

5.0 WETLAND FUNCTION CLASSIFICATION

5.1 BRIEF SUMMARY OF THE CRITICAL NEED AND POTENTIAL USERS

The critical need is to be able to identify the areas of seasonal flooding/inundation in wetlands, especially to identify the impact of restoration efforts by reconnection of wetlands to the natural hydrological system. The use case is catchments / river systems where natural, irregular inundation is a restoration priority. The users are restoration practitioners, NGOs, levels of government and IFIs working to implement and monitor policy changes and implementation of interventions or restoration activities.

The biological effects of irregular inundation is known to be a high-priority remote sensing biodiversity product, related to the "ecosystem disturbance and habitat structure" Remote Sensing Essential Biodiversity Variable (RS-EBV) (Skidmore et al., 2021). This is in part due to biological diversity and ecosystem services in seasonally flooded landscapes depending on the location and persistence of surface water (be it inland or coastal) and the nutrient exchange that occurs during these flood events.

In the PEOPLE-ER project, the primary user was IUCN Vietnam, who works closely with the Government of Vietnam and development agencies in the Mekong Delta to test new approaches to land and water management in the delta. This work culminated in Government Resolution 120 which provides the legal basis for transitioning from intensive rice production into flood-based agriculture. Since then, IUCN has supported the initiative to re-naturalize a substantial area within Vietnam's upper Mekong Delta – the Plain of Reeds (PoR) and the Greater Long Xuyen Quadrangle (G-LXQ).

5.2 CURRENT STATE AND TESTING/DEMONSTRATIONS

The SWIFT-C tool encompasses a series of five related Jupyter notebooks covering:

1. How to inspect an Area of Interest's Sentinel 1 time-series:
    - The purpose of this notebook is to show the user how to inspect Sentinel 1 time series for an area of interest. It covers topics such as: How to import required packages; Creating a Normalizing function; How to open Sentinel 1 images, apply the normalization, and visualize the imagery.
2. How segment a landscape based on S2 composites:
    - The purpose of this notebook is to show the user how to segment and area of interest into homogenous landscape units of analysis using Sentinel 2 composites. It covers topics such as: How to load import the required packages; How to load multi-date Sentinel 2 images; How to apply the Scharr Edge detection algorithm; How to visualize the edge layer; How to extract Landscape units of analysis; How to export landscape units.
3. How to compile time-series by units of analysis:
    - The purpose of this notebook is to show the user how to aggregate time series based on the landscape units of analysis that were calculated in the previous notebook. It covers topics such as: How to import required packages; How to load

Sentinel 1 data; How to read in polygons of landscape units; How to aggregate pixels by landscape units; How to export the resulting data frame.

4. How to cluster time-series and extract a reference:
   - The purpose of this notebook is to show the user how to embed your data into 2 dimensions using Principal Component Analysis (PCA) and t-Distributed Stochastic Neighbor Embedding (t-SNE), as well as conduct a cluster analysis on the data using a Hierarchical Density-Based Spatial Clustering of Applications with Noise (HDBSCAN) algorithm. This type of exploratory analysis can help a user better understand major temporal patterns that exist in the study area. The tutorial covers topics such as: How to import required packages; How to load time series; How to pre-process data; How to embed data with PCA and T-SNE; How to do cluster analysis with HDBSCAN; How to extract the average time series for each cluster identified.
5. How to classify time-series using Dynamic Time Warping (DTW):
   - The goal of this notebook is to show the user how one can use DTW to compare similarities between time series. This can be used in the context of classifying wetland typologies according to reference time series. Therefore, enabling the classification of a landscape based on different key floodplain typologies.

The notebooks are shared with test-data (including output layers for some notebooks) so that the user can explore the tool themselves. The notebooks and documentation are hosted by GitHub and GitHub Pages, making them open and easy to access.

The wetland function workflow addresses identified challenges:

1. persistent cloud cover during the rainy season by using Senitnel-1 radar data to capture the timing and duration of the flood pulse;
2. lack of available landscape parcel/unit geospatial data by providing a segmentation process, based on multiple-date Sentinel-2 data;
3. timing of the flood pulse can change by several weeks from year-to-year, by using a classification function called DTW that measures the similarity between two time-series on a month to month basis, therefore inherently removing the potentially effects of seasonality of the data.

The PEOPLE-ER demonstration in the Upper Mekong Delta used the wetland function assessment tools/workflow to assess the impact of management interventions and initiative to re-naturalize a substantial area within Vietnam’s upper Mekong Delta. The demonstration aimed to assess the change in seasonal inundation between 2018-2022 to identify areas reconnected to the Mekong River annual ‘flood pulse’ and areas still protected by high dikes, which produce three rice crops a year.

The output of the demonstration was a classification of the three-rice crop area, isolated from the floodplain, and alternative land uses that allowed for the natural flood pulse. The PEOPLE-ER analysis showed that the transition away from three-rice crops can be reliably detected. IUCN Vietnam is seeking to expand use of the tool to additional provinces within the delta.

5.3 CURRENT AND PLANNED USER ENGAGEMENT

User Engagement of the SWIFT-C method has taken place in the following forms:

- Online meetings with the Early Adopter (IUCN-Vietnam) to familiarize them with the methodology of the tools and its outputs.
- Online meeting the Stimpson Center that operates the Mekong Dam Monitor online portal.
- Online meeting with the members of the USAID funded Climate Resilient Agriculture project in the Mekong Delta to raise awareness of the method and the potential for analysis to support the baseline assessment for this project.

Planned user engagement includes:

- Online training with An Giang University and the provincial Department of Agriculture and Rural Development (DARD) on the use of the methodology.

5.4 PRIORITIES TO EVOLVE THE SOLUTION

The following priorities are identified to evolve the SWIFT-C method:

- Improvements in the packaging of the tool, in line with the packaging of the Spectral Recovery tool (Python package shared in PyPI) would be recommended or developing a simple application with a GUI to simplify the process for non-coding users.
- Testing the methodology with other SAR sensors, including VHR SAR sensors. These might include TerraSAR-X, and ALOS PALSAR.
- Testing the methodology in other seasonally flooded landscapes such as the Várzea floodplains of the Amazon Basin or coastal mangrove ecosystems. Many of these areas are impacted by deforestation, human development, and agriculture. As such it would interesting to test the SWIFT-C tool in order to study whether conservation or restoration efforts such as the establishment of protected areas, sustainable use reserves, or sustainable management practices (Growth-Oriented Logging (Schöngart, 2008)) have influenced the return to a more natural floodplain typology in these landscapes.
- The SWIFT-C methodology has been developed and tested with the use of SAR time-series for the monitoring of flood typology interventions. However, this methodology could theoretically be used in forested and other dryland ecosystems optical and SAR time-series for applications where a process or feature of interest would present a unique temporal signature. Testing the methodology's applicability to other ecosystem types would increase its potential user base and could potentially be of great value to ecosystem assessment and monitoring in general. For example,
    - cluster and classify forest types based on the phenology of deciduous dry forests.
    - cluster and classify disturbances across a landscape, therefore enabling the detection of illegal mining or logging activities.

6.0 k-NN

6.1 BRIEF SUMMARY OF THE CRITICAL NEED AND POTENTIAL USERS

The critical need is to acquire information on ecosystem characteristics by efficient and reliable means at regular intervals to monitor and evaluate the ecological and climate effects of ecosystem development. In the forestry context, regulatory and voluntary reporting requirements for stakeholders are rapidly increasing due to the growing number of national and international regulations and initiatives related to forest restoration, biodiversity, and climate effects. Forestry stakeholders are required to either report, or alternatively verify reports, on the status and changes of forest characteristics. EO based monitoring approaches such as the k-NN tool support forestry stakeholders to meet their reporting and monitoring requirements.

Potential users include:

- private large scale forest owners who need to respond to reporting requirements on the status and changes of the forest, e.g. during restoration efforts following a disturbance event;
- national and international administrative organizations who need to either produce or verify reports on the development of forest ecosystems;
- NGOs interested in ecosystem restoration, biodiversity or climate;
- academics working on various aspects of ecosystem monitoring;

For the PEOPLE-ER project, the primary users of the k-NN tool were Luke in Finland and INCDS in Romania. Luke was interested in monitoring the progress of peatland restoration activities in northern Finland, while the INCDS focused on the effects of a wind storm and subsequent restoration activities on areas affected by windthrows.

6.2 CURRENT STATE AND TESTING/DEMONSTRATIONS

The k-NN tool provides a means for scalable wall-to-wall mapping of forest target variables in the interest area using field reference data and EO datasets. In the context of ecosystem recovery monitoring, it supports the Spectral Recovery Tool presented in Section 4 by providing users with the possibility to map the ecosystems' status (e.g., in the form of forest structural variable development) at any given time before the disturbance event or during restoration activities. It allows users to use any available combination of EO and auxiliary layers, together with their own or external field reference data. As described above, potential use cases of the k-NN tool go well beyond mere ecosystem restoration monitoring, including wider forest monitoring and reporting needs.

The k-NN tool has been implemented on the Forestry TEP online platform (https://f-tep.com/) to allow easy exploitation of EO datasets with GUI. The GUI at Forestry TEP facilitates the use of the tool with no or very limited EO and IT expertise. The tool is also made available as a python code on GitHub (https://github.com/PEOPLE-ER/k-NN) with supporting documentation (https://people-er.github.io/k-NN/). Both the Forestry TEP and the python version of the tool have been extensively tested and used in the demonstrations. They are considered fully operational. The Forestry TEP version of the tool has been included in the basic toolbox available for all users on the platform.

In all current implementations of the tool, the user needs to have a representative “feature bank” (i.e. a collection of spectral values and corresponding target variable values) for the area of interest. Part (e.g. 1/3) of the feature bank is typically extracted to a testing feature bank, while the remainder (e.g. 2/3) of the reference observations are used as a training feature bank for the target variable prediction. Currently this feature bank needs to be prepared outside Forestry TEP (e.g. with QGIS), but clear instructions on the format have been provided in the documentation.

In the Forestry TEP integration, users can choose between two modes of usage: simple and advanced. The simple mode requires the user to input only a few basic parameters (1. Input image, 2. Training and testing data files, 3. Number of neighbors used in the estimation and 4. Output data type). The basic mode can be run with no or very limited EO and IT experience. The advanced mode provides more experienced users a wider range of variation possibilities in the parameter combinations. For example, the users can choose target variables to be mapped or they can choose spectral bands to be included in the mapping. They can also freely associate the spectral bands with the corresponding data columns in the feature banks, allowing for greater flexibility pertaining to the band order of images and the feature bank structure. The advanced mode can be used to easily conduct a series of tests with the same datasets to choose the best parameters to be used in a given interest area.

The outputs of the current version include two maps: 1. Target variable predictions and 2. standard deviation of the predictions. In addition, accuracy metrics (Root Mean Squared Error and Bias) are calculated based on the testing and training feature banks. The RMSE and bias are provided both as absolute values and as relative values to the mean. The output maps can be downloaded or displayed and analyzed in one of the GUI applications also available in the Forestry TEP such as QGIS.

The PEOPLE-ER demonstrations in the northern Finland (Luke) and in Romania (INCDS) used the k-NN tool to produce a time series of maps on ecosystem characteristics to allow monitoring of the development of restoration areas and adjacent forests. In Finland, the main goal was to monitor the increase in vegetation volume and structure on former peat extraction areas following the end the peat extraction activities. In Romania, the main target was forest height mapping in an area that had experienced severe storm damage in 2017. In both of the areas a time series of maps was created that showed clear trends of the target variables (e.g. height and volume) in the areas of interest during the recovery period. In addition to information on changes taking place during the restoration period, the maps provided information on the ecosystem characteristics before the disturbance and allowed monitoring also the development of adjacent ecosystems as reference. INCDS has already shown high interest in applying the k-NN tool for wider area forest analysis in Romania.

6.3 CURRENT AND PLANNED USER ENGAGEMENT

User Engagement of the k-NN tool has taken place in the following forms:

- Regular online meetings with Luke and INCDS were held throughout the project to keep them updated on the activities on the testing and tool development.
- Online meetings with Luke and INCDS were held to familiarize them with the Forestry TEP platform and the k-NN tool.
- Support was provided whenever the users had questions regarding the use of the tools. This included assistance in finding the causes of errors in their specific tool executions in the Forestry TEP platform.

- A two day (3+3 hours) online workshop was organized for INCDS. This workshop included hands on training on how to prepare all necessary datasets and use the tool in Forestry TEP.

Planned user engagement includes:

- A splinter meeting tool demonstration to take place at the EGU Conference, 2024, to increase awareness of the tool and engage with potential users directly.
- Further training/support is considered for INCDS Romania, based on their potential needs.

6.4 PRIORITIES TO EVOLVE THE SOLUTION

The current version of the tool is fully functional in the sense that it can be used operationally. Further developments will be based on identified needs and/or requests arising from the user community. Continued communication and support to the current users is foreseen, while also trying to grow the number of users by promoting the tool towards a wider user community.

Potential technical developments to consider in the future include:

- Facilitation of feature bank creation within the Forestry TEP, thus removing the necessity for the user to create the feature bank offline using auxiliary software (e.g. QGIS). This would remove the need to download any image data from Forestry TEP to the user's own computer.
- Provision of pre-made feature banks for key satellite data products (e.g. Sentile-2 L2A imagery) and specific ecoregions. To create such feature banks, extensive publicly available ground reference datasets from the ecoregions of interest would need to be available.