PEOPLE

Ecosystem Restoration

D6: NORTHERN BRITISH COLUMBIA DEMONSTRATION VALIDATION REPORT

January 2024

Prepared for:

Society for Ecosystem Restoration In Northern British Columbia (SERNBC)

Hatfield Consultants LLP

#200 - 850 Harbourside Drive
North Vancouver, British Columbia, Canada V7P 0A3
Tel: 1.604.926.3261 • Fax: 1.604.926.5389
www.hatfieldgroup.com

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

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Prepared by:

HATFIELD CONSULTANTS LLP
#200 - 850 HARBOURSIDE DRIVE
NORTH VANCOUVER, BC
CANADA V7P 0A3
TEL: 1.604.926.3261 • WWW.HATFIELDGROUP.COM

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AMENDMENT RECORD

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1.0 INTRODUCTION

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 forestry from Romania. INCDS is in charge for the forest resources assessment and monitoring

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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

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. **Vegetation Spectral Recovery** – The PEOPLE-ER Vegetation Spectral Recovery tool provides a flexible, powerful set of EO data analytics solutions to support forest landscape ER assessment. The tool provides a method for high-resolution satellite EO data time series analysis to enable monitoring of vegetation recovery in forested ecosystems from boreal to tropical biomes.
2. **K Nearest Neighbour Tool** – The PEOPLE-ER k-NN tool enables wall-to-wall prediction of target variables of interest using field reference data and selected EO datasets.
3. **Wetland Function Trends** – The PEOPLE-ER Wetland Function Trends tool provides a flexible, powerful set of EO data analytics tools to support wetland ER assessment. The tool provides methods for high-resolution satellite EO data time series analysis to enable monitoring of inundation dynamics and trends in natural to heavily modified wetland ecosystems.

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 defined in the Algorithm Theoretical Baseline Documents (D7).

1.1 SCOPE OF DELIVERABLE D6 VERSION 2

Deliverable 6 (D6) version 1 defined the validation methodology for the PEOPLE-ER methods and algorithms to be developed and the specific demonstrations with Early Adopters. This updated version of D6 is the Validation Final report, presenting the tools/algorithm applied in each demonstration and the full set of results and associated accuracy assessment.

2.0 TOOL VALIDATION AND AGILE DEVELOPMENT

The PEOPLE-ER project solutions development followed an Agile methodology within which verification and validation are critical to ensure the project addresses the Early Adopters' needs.

2.1 TOOL VALIDATION METHODOLOGY

Validation focuses on the information product(s) of the tools and whether these products meet Early Adopter requirements. This includes accepted statistical methods of accuracy assessment based on independent reference data. The approach to validate a tool's product is dependent on the tool and the specific Use Case. Please see Section 3 to 7 below for more details regarding each Use Case's validation methodology.

Verification ensures the quality of the product and algorithm and was achieved by activities like code reviews, and unit tests. The verification of PEOPLE-ER tools and algorithms was driven by the solutions addressing the user stories defined as part of the Agile method. Additionally, as the tools and algorithms are developed under the FAIR principles for scientific data management, the development history, code base, and all other relevant information are publicly available through each tool's GitHub repository and documentation site, as well as the distribution of some tools on the Python Package Index (PyPI).

User acceptance testing relates to both the verification and validation to ensure that the solution and products can meet the intended use, goals, and objectives in the intended environment. In the Agile method, validation and verification is continuous, including design, build, integration, and delivery to the user. This was defined in the **Deliverable D4 Agile Development Plan**. At the end of the Agile development phase, the Early Adopters are required to objectively evaluate the products and solution through an evaluation process resulting in a value statement, which is included in **Deliverable D9 Early Adopters Assessment Report**.

2.2 TOOL VERIFICATION RESULTS

The Spectral Recovery tool development followed an Agile approach. As such the tool went through multiple development sprints. Throughout these sprints, code reviews were carried out to catch any errors in the code, as well as verify the logic behind it. Weekly "stand-up" meetings were conducted among the development team to discuss progress, next steps, and any issues that had been encountered.

Automated unit tests were written to help verify the functionality and correctness of the Spectral Recovery tool. At a high level, a unit test asserts that an individual unit of code returns the expected output when given a specific input. The expected output is determined independently from the code. If the unit test "passes" then the code returned the expected output for the given input. If it "fails", it did not. Although unit tests alone do not verify correctness, selecting a representative set of examples to test means that unit tests can help catch errors and ensure expected behaviour throughout the Agile development cycle.

For example, if given a recovery target of 100 and a pixel with value 70 in year 0 and 80 in year 1, the expected Years-to-Recovery (Y2R) (White et al. 2022) of the pixel is 1 because 80% of the recovery target is 80 and the pixel equals 80 in year 1. To check for correctness in the tool, a unit test asserts the Spectral Recovery tool's Y2R function returns 1 when given the recovery target and pixel values discussed above.

Each metric, index, and core function of the Spectral Recovery tool are unit tested. The current set of 126 unit tests cover 85% of the source code, with 100% of tests passing as of the 0.2.1b2 version of the tool released on December 21st, 2023. The unit tests can be viewed on the GitHub repository and can be independently executed by anyone who downloads the source code.

In addition to unit tests, integration tests were written to further verify results. Integration tests assert individual components of the tool, like reading geoTIF file format, computing indices, and computing recovery metrics, work together to produce expected results. Integration tests can also be viewed and executed by downloading the Spectral Recovery tool's source code from GitHub.

This information is summarized in the Agile development reports and the overall version control history available via GitHub. The development process resulted in over 400 commits and closed 26 PRs.

2.3 TOOL TESTING RESULTS

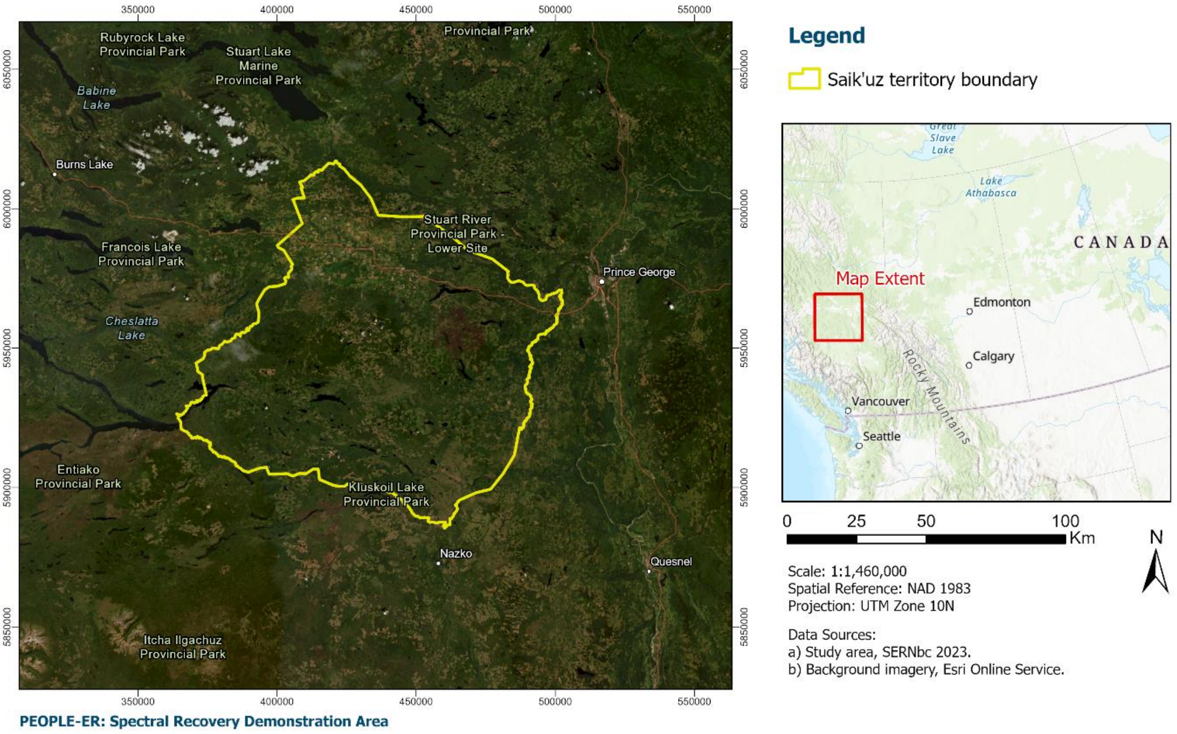
All tools were shared with the Early Adopters throughout different stages of development to ensure that their needs were being met. At the end of the Agile development phase (Task B) Early Adopters will be requested to contribute objectively to **Deliverable D9 Early Adopters Assessment Report**.

3.0 SERN BC – CANADA FOREST LANDSCAPE DISTURBANCE RECOVERY

3.1 DEMONSTRATION STUDY AREA AND OBJECTIVE

The demonstration area with SERNbc is the traditional territory of the Saik'uz First Nations, located in Northern British Columbia, Canada. The traditional territory has a very large spatial extent (totaling 1,016,920 ha) and consists of multiple land uses, including urban, agricultural, and forested areas. The territory's forests have seen decades of disturbances, including but not limited to wildfires, harvest, and pest outbreaks. Critical to the successful management of such a large landscape is the effective collection of information related to ecological disturbances as well as adequate monitoring of ecosystem restoration efforts and their subsequent progress.

Figure 1 Spectral Recovery tool Demonstration Area.



SERNbc are collaborating with Saik'uz First Nation to support in planning ecological restoration efforts occurring within the traditional territory. Of particular interest to SERNbc is monitoring the relative success of variable restoration treatments or interventions for forest restoration. Monitoring the success of restoration efforts typically involves intensive field work, yet as the territory is such a large area, monitoring individual disturbances and subsequent restorations processes is challenging and unfeasible. The objective of the PEOPLE-ER demonstration is to use satellite-derived spectral data to assess ecosystem recovery of forests following ecological disturbances. By showing that spectral data can reveal information concerning forest health and structure recovery, the demonstration supports the use of remote sensing tools for effective monitoring of recovery processes occurring across a landscape.

3.2 DATA AND METHODS

3.2.1 EO Data

For the initial tool analysis, a time series derived from Landsat Collection 2-Level 2 Tier 1 satellite imagery was used, however since the initial analysis, the tool's features have been expanded to provide support for the use of Sentinel-2 imagery. The Landsat composites used in the time series analysis were generated using a Google Earth Engine tool published by Francini et al. (2023), which uses the annual best available pixel compositing method (Hermosilla et al. 2016). The time series covered the years from 2000 to 2023, with 24 annual composites. Six spectral bands were required for the analysis: blue, green, red, near infrared, and shortwave infrareds 1 and 2. Limiting the tool's development to these bands represented a compromise in terms of maximizing the tool's cross-compatibility across different sensors and platforms, whilst still providing adequate spectral information to calculate a variety of spectral indices.

While this demonstration used Landsat composites due to the time period over which the disturbances occurred, Sentinel-2 composites can be utilized from 2016 onwards. Sample Sentinel-2 composites for the tool were created using the “Sentinel-2 MSI Level-2A" image collection in Google Earth Engine, which contains Bottom-of-Atmosphere, sen2cor-processed, products downloaded from ESA's scihub. Clouds were masked out of the images using the QA60 cloud mask band and then for each year the median pixel value was selected, resulting in a timeseries of annual median composite. The composites contained blue, green, red, near infrared, and shortwave infrareds 1 and 2, spectral bands to match with the Landsat composites.

3.2.2 Reference Data

For the evaluation of the spectral recovery tool, shapefiles providing information on the location and timing of wildfire forest disturbances were used. The shapefiles are openly available through the British Columbia (BC) Data Catalogue and are maintained by the BC Wildfire Service. For the initial testing of the tool, the analysis was restricted to wildfires that occurred between the years 2005 and 2018. These years were chosen to ensure compatibility with the time series composites, whilst also allowing for a five-year recovery monitoring window that enabled the calculation of recovery metrics. The severity of fire impacts varies within and between disturbance polygons, which is not taken into account in this demonstration analysis.

Other reference data required for the validation of the spectral recovery tool was LiDAR data, publicly available through the LidarBC initiative. The LiDAR data, provided by GeoBC, was collected between July 21, 2019 and October 11, 2019 (GeoBC 2020). This data only covers a small spatial extent of the Saik’uz traditional territory, restricting the validation process to 17 wildfire polygons that occurred within that area, in the time period of interest. LiDAR data are acquired between 1 to 15 years after the wildfires occurred.

3.2.3 Forest Recovery Analysis

Preliminary tool analysis focused on the Normalized Difference Vegetation Index (NDVI) and Normalized Burn Ratio (NBR) spectral indices, as both of these indices have been used in past spectral recovery research (Vogelmann et al. 2012; Zeng et al. 2022). Previous studies have found NDVI to correspond to initial vegetation recovery, whilst NBR has been found to correspond with longer term recovery processes, such as the establishment of woody vegetation (Pickell et al. 2016). Initial tool results were compiled for restoration polygons previously disturbed by wildfire. The results were compiled using both the reference target and historical target methods. The reference target was based on reference site polygons selected by SERNbc, with the average current spectral conditions from these polygons used to support the analysis. Each restoration polygon was input into the tool with its corresponding years of disturbance. The time series composite was used to calculate the spectral indices, NDVI and NBR, and recovery metrics were computed using the time series of spectral indices. Recovery metrics were calculated on a per-pixel basis, enabling variation of the recovery progress within restoration polygons to be visualized (Figure 2). A chart of the recovery trajectory for each polygon was also generated (Figure 3). The analysis involved calculating two short-term recovery metrics: R80P (ratio of 80 percent) and $\Delta Index_{regrowth}$ (i.e., $\Delta NBR_{regrowth}$), with Y2R (Years to Recovery) being calculated as a long-term recovery metric (see **Deliverable 7 Algorithm Theoretical Baseline Definition** for technical information).

Figure 2 Example tool output: Index/recovery metric combination raster.

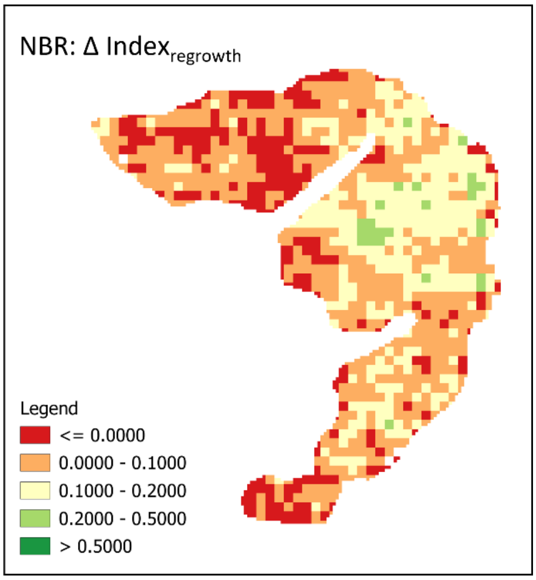
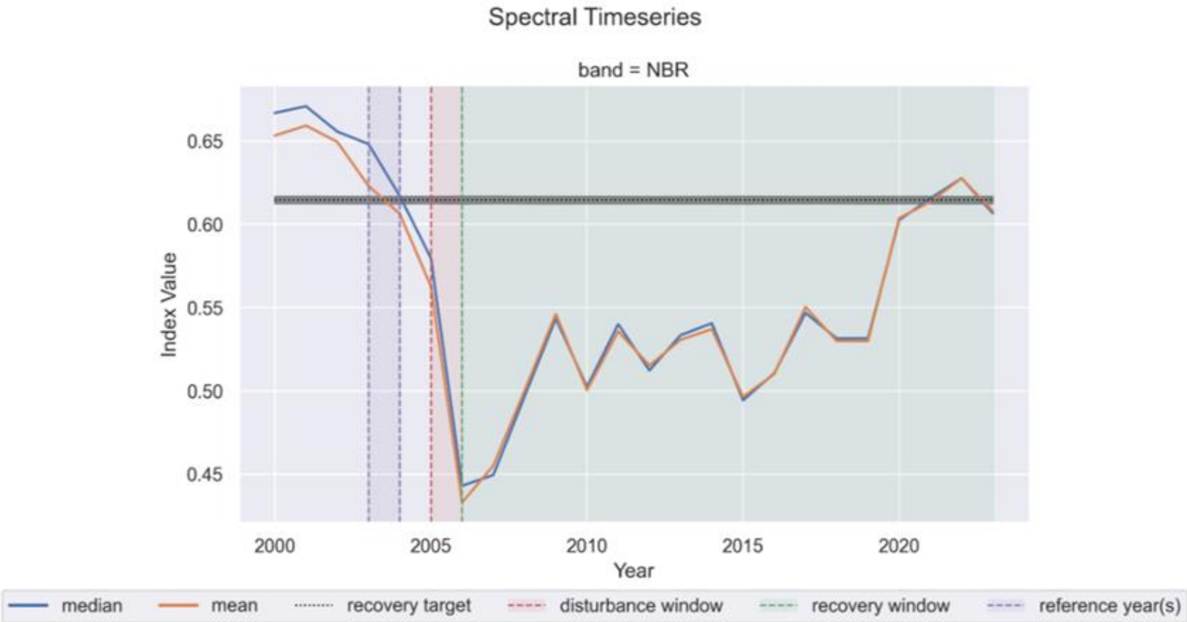


Figure 3 Example tool output: Spectral trajectory graph.



Visual assessment of raster outputs against satellite imagery and initial band reflectance occurred to understand if initial tool results were plausible. A second visual assessment occurred using spectral trajectory graphs for each polygon, to ensure that the recovery targets were suitable for the calculation of the recovery metrics.

3.2.4 Validation Method, Results, and Discussion

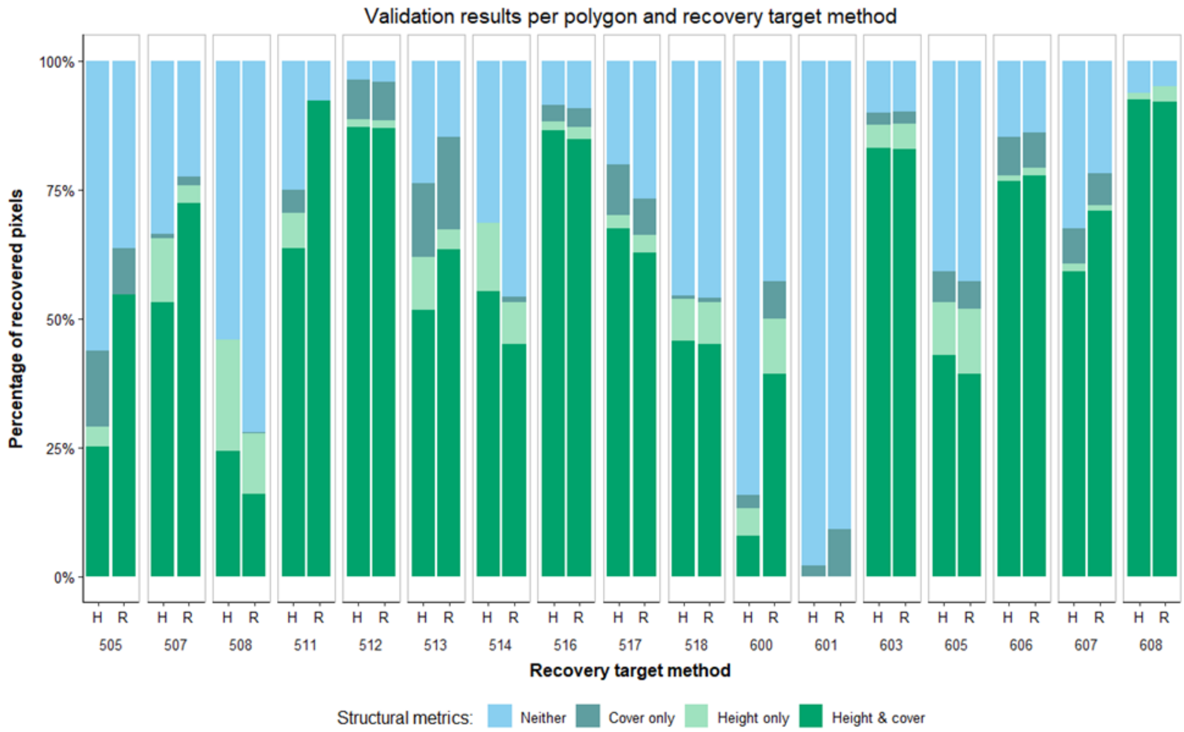
The validation process of the spectral recovery tool largely follows that of White et al. (2018; 2022), and aims to see if spectrally recovered pixels (as the tool output) also exhibited signs of structural recovery using LiDAR as a validation dataset. Due to the minimal spatial coverage of the Saik'uz First Nations traditional territory by LiDAR, the initial validation process was limited to 17 wildfire restoration areas which burned between the years of 2005 and 2018.

The LiDAR data was pre-processed and used to calculate structural height and cover metrics to match the same raster grid as the Landsat composites. Following the White et al. (2018) methods, the 99th percentile of canopy heights was used as the metric for forest height, while the percentage of first returns > 2 m was used for the metric for forest cover. White et al. (2018; 2022) define structural recovery using these metrics to coincide with the FAO benchmarks of forest recovery being canopy height greater than 5 m, and canopy cover being greater than 10%. Using LiDAR metrics, this results in structural recovery being achieved where: 99th percentile > 5 m, and percentage of first returns > 10%. Two structural binary rasters were produced for each restoration polygon, capturing pixels which met sufficient cover and height conditions, so as to be considered structurally recovered.

The spectral recovery approach was modified slightly from White et al.'s (2018; 2022) method as the sample size for validation was restricted by LiDAR coverage availability, and the timing of disturbances on the landscape. The tool's Y2R recovery metric (using NBR as the index) was used to determine whether spectral recovery had occurred. To accomplish this, all pixels that had met 80% of their recovery target value by the year LiDAR data was collected (provided by the Y2R metric) were deemed spectrally recovered. A binary raster was produced highlighting pixels that had reached this condition.

The three binary rasters of spectral, height, and cover recovery were then used in a classification, to determine the number of pixels deemed spectrally recovered that also displayed height recovery, cover recovery, both height and cover recovery, or neither height nor cover recovery. This resulted in a per-pixel validation of spectral recovery using structural recovery metrics, which were then assessed at the polygon level based on the percentage of recovered pixels within the polygon. This validation process was run twice, using the Y2R NBR results using a historic recovery target method and the Y2R NBR results using the reference recovery target method, to assess the relative performance of both tool methods. The historic recovery target was calculated from averaging the spectral values two years prior to disturbance of each polygon, whereas the reference target was obtained by averaging the spectral values of reference site polygons provided by SERNbc. The results of this validation using Y2R with both reference target methods are summarized for all 17 polygons in Figure 4.

Figure 4 Spectral Recovery Validation: Per-polygon and recovery target method.

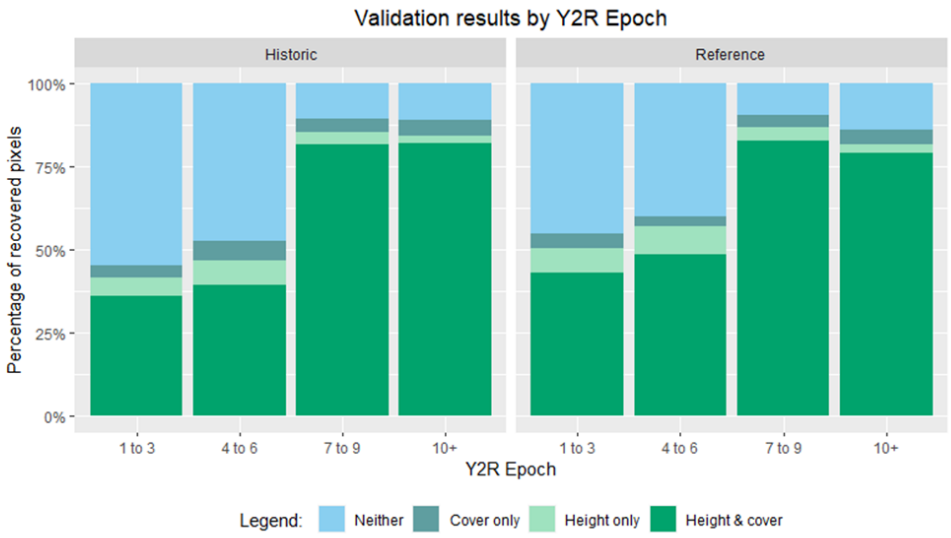


Validation results across restoration polygons were variable, with all restoration sites except for one achieving some level of both height and cover recovery. Achievement of both height and cover structural recovery was more common than achievement of height or cover alone. Upon investigation, many of the spectrally recovered pixels in polygons with a higher proportion of disagreement between spectral and structural recovery (e.g., 508, 600, 601) had disturbances ending within 3 years of the LiDAR acquisition (2019). This was further evidenced by the low number of recovered pixels in these polygons (see Table 1 and Figure 4). Conversely, the polygons with higher agreement between spectrally recovered pixels and both height and cover recovery, generally had more time between the disturbance and the lidar acquisition (exceptions are polygons 511, 513, 514, and 608). It is important to keep in mind, when interpreting these results that within certain polygons the proportion of pixels assessed as spectrally recovered is low (e.g., 508, 514, 601, 606), which may mean that the Y2R metric is accurately assessing a lack of recovery in the polygon. This aspect of performance will be further explored with SERNbc in the **Deliverable D9 Early Adopters Assessment Report**.

Table 1 Summarizes the end year of disturbance, as well as the percentage and number of spectrally recovered pixels per polygon.

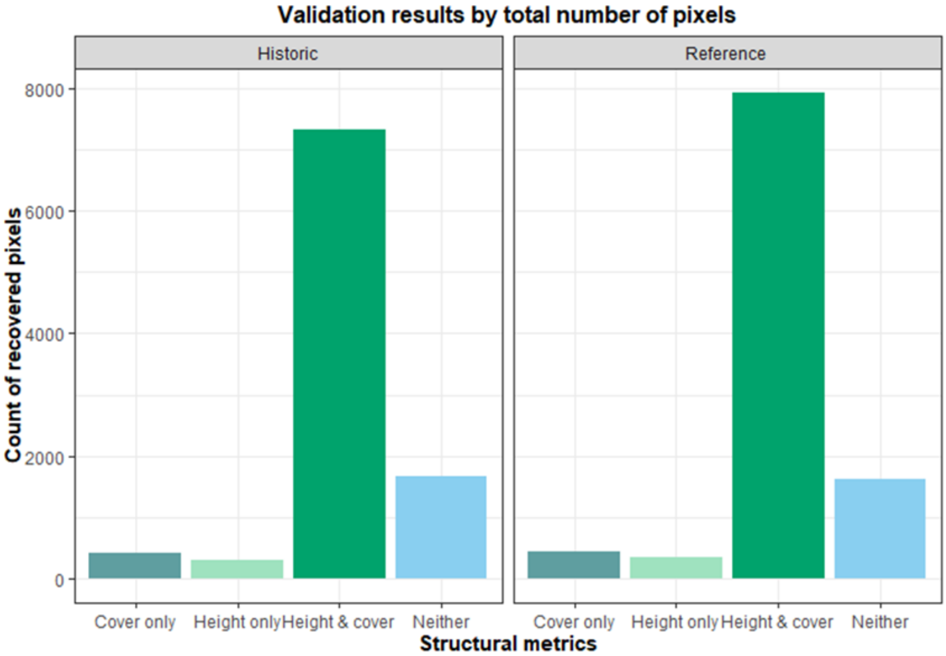
Polygon ID	Percent spectrally recovered pixels (Historic Recovery Target)	Number of recovered pixels	End year of disturbance
505	100%	160	2014
507	80%	418	2015
508	17%	52	2017
511	35%	260	2018
512	100%	416	2010
513	49%	283	2018
514	12%	37	2018
516	95%	5229	2006
517	99%	1884	2006
518	57%	204	2014
600	10%	111	2016
601	71%	66	2016
603	95%	1404	2010
605	84%	94	2014
606	100%	81	2010
607	100%	159	2010
608	100%	113	2018

Figure 5 Spectral Recovery Validation: Recovered Pixels Classified by Y2R epoch.



In Figure 5 spectrally recovered pixels are grouped into four epochs based on the number of years elapsed since the disturbance occurred, for both historic and reference target methods. This shows that spectral recovery using Y2R with the NBR index had the highest agreement with height and cover structural recovery after 7 years. For assessment of short-term recovery (<5 years post-disturbance), an alternative spectral index or recovery metric would be more informative to assess recovery progress, or assessing the recovery trajectory charts (Pickell et al. 2016).

Figure 6 Spectral Recovery Validation: Structural recovery metrics for all tested pixels.



If we group recovered pixels across all polygons and assess recovery progress (Figure 6), we see the total number of spectrally recovered pixels that achieve both height & cover recovery is far greater than those achieving either cover only or height only, and is substantially greater than the number of pixels that do not show signs of structural recovery. Figure 6 also shows that the reference recovery target method determined an overall greater number of pixels to be spectrally recovered than the historic recovery target method, but also that these pixels were correctly classified as the number of pixels meeting both height and cover requirements increased while the other categories stayed largely the same.

Figure 7 Spectral Recovery Validation: Structural metrics for historic and reference recovery target methods.

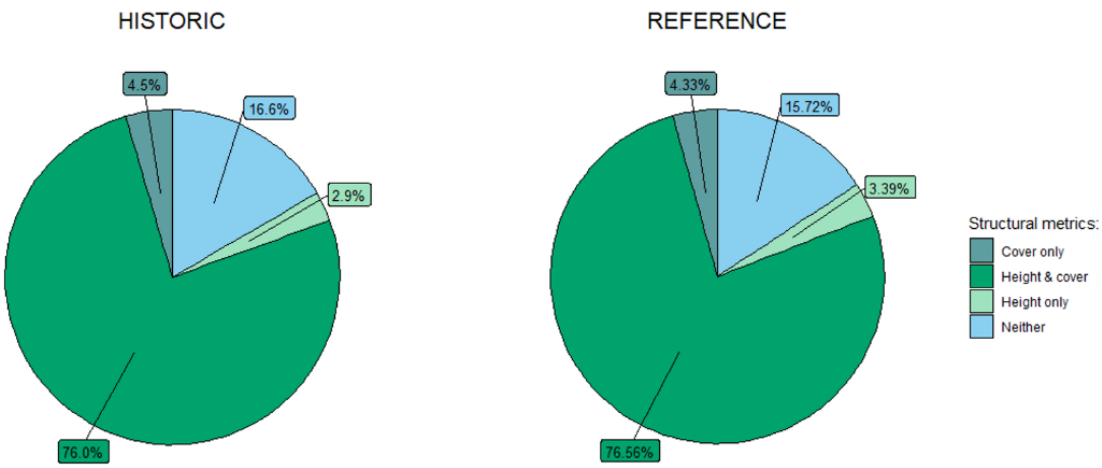


Figure 7 shows that generally, the historic and reference recovery target methods perform similarly, with only 16.6% and 15.72% of recovered pixels not reaching structural recovery benchmarks respectively. Both recovery target methods result in the designation of most spectrally recovered pixels reaching both height and cover recovery benchmarks. Overall, the historic recovery target method results in 83.4% of designated recovered pixels having reached some metric of structural recovery, while the reference recovery target method results in a slightly greater 84.3% having reached a metric of structural recovery. These results are in line with the previous findings of White et al. (2018; 2022), suggesting that the spectral recovery tool is effective at monitoring forest recovery.

3.2.5 Limitations and Future Work

It is important to note that this validation was carried out solely on pixels that had been identified as spectrally recovered according to the Y2R metric. As such this validation accounts for pixels detected as spectrally recovered by the tool, but it does not evaluate how the tool performs with respect to pixels that the spectral recovery analysis assesses as not recovered. Future versions of the tool will identify areas that Y2R does not recognize as spectrally recovered. Once this version is published, a validation will be carried out to further understand how the tool performs in correctly identifying this status compared to the LiDAR metrics.

At the time of the validation analysis, the method for calculating the historic recovery target method did not distinguish between individual pixels, instead providing a single recovery target which represents the average condition of the restoration site prior to the disturbance. Since the validation analysis, the tool's features have been expanded to include the calculation of per-pixel historic recovery targets, enabling the consideration of variable historic conditions within each restoration site. This may provide more accurate, location-specific goals for monitoring ER success, as the recovery metrics will be relative to each pixel and will not require any averaging of conditions, resulting in an entirely pixel-based analysis. Further validation will be performed to assess this new method of per-pixel historic recovery targets.

Another important limitation is that we did not assess recovery in relation to the severity of each disturbance. For wildfire or windthrow events, the severity of disturbance can greatly affect the results and will vary within the disturbance sites. In the upcoming assessment with SERNbc and for the publication of results, we aim to incorporate disturbance severity data to fully evaluate how the tool performs for varying disturbance severity.

In the demonstration, certain polygons had disturbances that ended less than 3 years prior to the acquisition of the LiDAR data. As such, it is unlikely there is sufficient time for forests to recover structurally or spectrally. This is shown by the low percentage of recovered pixels on many of these sites. This limitation was in part due to the sparse coverage of LiDAR data over the Saik'uz First Nation's traditional territory. As more LiDAR data becomes available for the territory, or validation is completed in new areas with multi-date LiDAR, the amount and variety of validation polygons will improve.

3.2.6 Main Conclusions on the Canada Demonstration Area

The main conclusions in respect to the Early Adopter needs and the demonstration objectives can be summarized as follows:

- The PEOPLE-ER spectral recovery analysis tools can effectively monitor restoration trends in disturbed sites in forested regions such as the Saik'uz First Nation's traditional territory. The

SERNbc use case demonstrated how the tool can be used to inform future restoration efforts, as well as identify sites that might need further intervention to support recovery. The key benefits are:

    - Independence of the EO data to provide an initial assessment of areas of interest for restoration practitioners to focus their efforts.
    - Synoptic nature of EO data, with the potential to complete the analysis over large areas including the entire Saik'uz First Nation traditional territory if leveraging cloud resources.
    - Flexibility built within the tool, which enables the user to adapt the tool's workflow to best suit their needs.

- The PEOPLE-ER spectral recovery tool can be used in a variety of computational platforms such as the Planetary Computer Hub, local desktop environments, or the Forestry TEP. As such, it can be used in the user's preferred environment.

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