FORESTRY FUTURES TRUST ONTARIO

Knowledge Transfer and Tool Development (KTTD)
Final Report

SECTION A: PROJECT INFORMATION		
Project Title: Developing an inventory of eastern hemlock for Ontario		Project Number: 8A-2021
Interim Report accompanies each invoice. Period Cover by Report: April 2021 – March 2024	Interim Report:	Final Report: X
Project Lead (Name, Title, and Organization) Dr. Ben DeVries Assistant Professor Department of Geography, Environment and Geomatics University of Guelph		
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SECTION B: SUMMARY OF WORK COMPLETED

1. Summary of project progress: April 2021 – March 2024

Summary of project accomplishments

(1) Collection of ground inventory data over 81 randomly sampled forest plots across the province, including species identification.

(2) Positive identification of the invasive Hemlock Woolly Adelgid near Grafton, Ontario, the northernmost sighting of the insect in the province to date.

(3) Collection and harmonization of additional tree species and hemlock occurrence data from municipalities, conservation authorities, and land managers with forest resources inventory (FRI) data to generate a robust training dataset.

(4) Development of a Sentinel-2 satellite image processing workflow and a phenology-based tree species classification model geared towards Eastern Hemlock and co-dominant species.

(5) Generation of an Eastern Hemlock inventory for Ontario, encompassing the known range of hemlock across the province and differentiating between dominant hemlock, co-dominant hemlock-mixwood, and co-dominant hemlock-evergreen forest stands.

(6) Dissemination of results at the Canadian Symposium on Remote Sensing in Yellowknife, NWT in July 2023 and at an FFT-KTTD webinar in November 2023.

Year 1 2021- 2022

Note: All activities conducted between April 2021 and March 2022 inclusive were funded as in-kind contributions through Dr. DeVries and Dr. MacQuarrie.

1.1. Recruitment of M.Sc. student and completion of coursework (May 2021 – April 2022)

Amy (Zhaoshu) Shi was recruited in the summer of 2021 to the Masters of Science program at the Department of Geography, Environment and Geomatics (GEG), University of Guelph. Amy started her MSc studies in September 2021 and has completed the required coursework for her program as of April 2022. As co-investigator on this project, Dr. Christian MacQuarrie applied to be an adjunct graduate faculty member at the University of Guelph. His application was recently approved, and he now serves on Amy's advisory committee. Another faculty member at GEG, Dr. Faisal Moola, joined Amy's supervisory committee. Dr. Moola brings with him his expertise in field ecology, including some past work on Eastern Hemlock ecology. A portion of Amy's coursework included a preliminary assessment of Sentinel-2 image time series for forest species classification in southern Ontario. This work is described in Section 1.2 below. Amy recently submitted her final research proposal, which describes the development of an Eastern Hemlock classifier based on Sentinel-2 image time series.

1.2. Development of a Sentinel-2 image pre-processing workflow (May 2021 – December 2021)

We began developing a satellite image pre-processing workflow in the summer of 2021, in preparation for the development of the Hemlock classifier. A series of python-based tools, including (1) automated download scripts from the Copernicus Sci-Hub portal; (2) pre-processing of top-of-atmosphere reflectance to surface reflectance imagery using the *sen2cor* software package; and (3) generation of spectral indices from surface reflectance images.

1.3 Investigation of multi-temporal data for species classification (September 2021 – December 2021)

As part of her coursework requirements, Amy Shi undertook a study on the separability of forest stands based on dominant canopy species using Sentinel-2 image time series. In this study, a range of spectral indices computed from the imagery pre-processed as described above were tested over several forest prism plots in Halton County. The novel red-edge spectral bands included in Sentinel-2 were found to be particularly important in discriminating between canopy species classes. Additionally, there was a distinct difference in phonologic signatures between certain canopy classes. These results will support the development of the Eastern Hemlock classifier by guiding the selection of spectral and temporal metrics to be computed form the Sentinel-2 imagery.

1.4. Data collection, sample and target design.

We secured data from a number of field plots across Ontario through the SilvEcon Hemlock database. These spatial data have been sourced from municipalities and conservation authorities from across the province, with whom data sharing agreements were signed. Among other stand attributes, this dataset indicates the estimated density of Hemlock per stand. Using the Hemlock dataset, we constructed a stratified random sampling scheme, where primary sampling units (PSU) are randomly selected from "high-density" and "low-density" hemlock stands. Each randomly sampled PSU covers a 60-m by 60-m square plot, designed to encompass nine 20-m Sentinel-2 pixels. Within each PSU, five 20-m by 20-m secondary sampling units (SSU) were delineated, including four in each corner of the PSU and one in the centre of the PSU.

Year 2 2022-2023

Note: Activities conducted between April 2022 and March 2023 inclusive were funded both by the Forestry Futures Trust and in-kind contributions through the University of Guelph.

1.5 Field plot assessments

A team led by the GLFC visited 81 SSU's during the summer of 2022 and measured species composition and DBH and height of all conifer trees found within the plots. In addition to these plots, Dr. Faisal Moola (UG) contributed data from 31 field plots with designed as described above and sampled across southern Ontario, bringing the total number of ground plots used in this study to 112. MSc student Amy Shi (UG) processed all field data and classified individual field plots based on dominant and co-dominant tree species for use in a Hemlock classifier. A notable outcome of our field assessments was the identification of Hemlock Woolly Adelgid at a location near Grafton, Ontario in July 2022. The field team reported the sighting to the Canadian Food Inspection

Agency, who later confirmed the presence of the insect (https://www.canada.ca/en/food-inspection-agency/news/2022/08/hemlock-woolly-adelgid-confirmed-in-grafton-on.html).

1.6 Development of a novel phenology-based classification method

From September 2022 to March 2023, we developed a method for identifying leading species at the stand level using dense time series of 20-m resolution Sentinel-2 data. This method is based on the Bayesian phenological model-fitting algorithm described in Babcock et al. (2021). We analyzed modelled phenological patterns derived from Sentinel-2 time series data retrieved over all SSU's for which field data had been collected (Section 1.4). Several key results have emerged from this research:

1. Spectral indices derived from Sentinel-2's novel red-edge bands out-perform more conventional indices like the normalized difference vegetation index (NDVI) when modelling phenology in coniferous and mixed forest stands in Ontario.

2. Remotely sensed phenology is highly effective at separating forest stands into broad classes (hardwood, softwood, mixwood) and allows to a lesser extent the separation of stands into Hemlock density classes. The phenological parameters representing the seasonal minimum greenness, green-up rate, and green-up timing are most important for separating forest types by broad classes as well as varying degrees of Hemlock density. This result indicates that remotely sensed phenologic metrics derived from Sentinel-2 time series data combined with ancillary environmental data holds promise for developing an Eastern Hemlock classifier.

MSc Student Amy Shi presented the results of this model to the FFT-KTTD webinar series in November, 2023.

Year 3 2023 – 2024

1.7 Refinement of the Hemlock classifier

Further validation and quality assurance of the phenology-based hemlock classifier results revealed serious artifacts in the resulting maps resulting from differing satellite observation densities in regions where satellite orbital tracks overlap. It was determined that the model used to derive phenological features to be used in the classifier was very sensitive to these differing data densities, generating biases in the classification model results. To address this source of bias, a revised data pre-processing and classification scheme was developed in January and February 2024. The revised workflow consists of the following steps described in Section 3.

2. Milestones

Given the structure of the graduate program at the University of Guelph, the first year of our project was planned around coursework and initial training of the MSc student. As such, most milestones and deliverables are being addressed in the second year of the project (2022-2023). Progress on and plans for the milestones described in the original proposal are describe below:

2.1 Identification of sample sites and site access permissions secured

Sample sites have been identified using a stratified random sampling approach based on a Hemlock database and other existing geospatial data for the Province of Ontario. Access to most of these sites has already been secured. We are working to secure access to all remaining sample sites.

2.2 *Completion of plot assessments*

81 plots (defined as Secondary Sampling Units; SSU's) were completed by the project team by August of 2022. An additional 31 20-m circular plots measured in southwestern Ontario were acquired from the laboratory of Dr. Faisal Moola (UG), bringing the total number of field plots used in this project to 112.

2.3 Completion of Sentinel-2 image composites and covariates

Spectral, temporal and spatial metrics have been developed through Amy Shi's coursework. Time series stacks of corresponding imagery have been produced for several test sites across the province. Novel phenological metrics were designed and tested over field plot sites for their ability to separate forest stands based on: (1) broad forest types; (2) varying hemlock density; and (3) dominant and co-dominant tree species. Figure 1 shows an example of such a separability analysis, where the minimum seasonal greenness phenological feature (α_1) was shown to provide a high degree of separability between low-density, medium-density, and high-density hemlock stands, using four spectral indices as inputs.

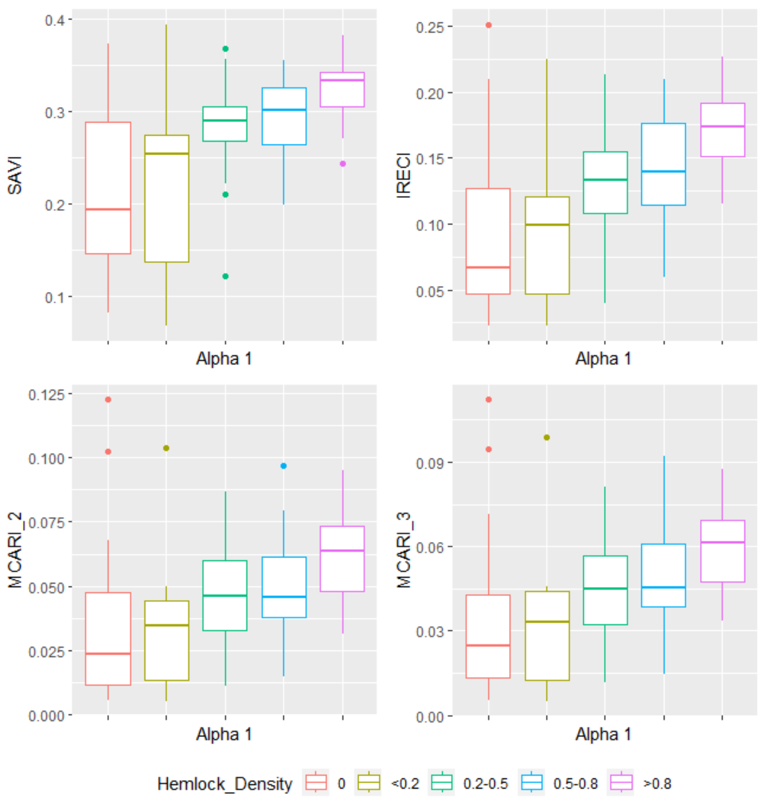

Figure 1. Separability of the seasonal minimum (α_1 phenological feature) derived from four different Sentinel-2 based spectral indices between field plots with different densities of Eastern Hemlock. α_1 derived from all four tested indices was able to distinguish between low density (0% to 20%), medium (20% - 80%) and full density (80% - 100%) hemlock stands.

Figure 2 shows the results of a complete separability analysis between eight species composition classes (hemlock and non-hemlock), seven phenological features, and four spectral indices. These results show that of the phenological features, minimum seasonal greenness (α_1) can provide a high degree of separability between several commonly found tree species in Ontario. This result is intuitive when comparing deciduous and evergreen stands, as evergreen stands would be expected to exhibit higher greenness during winter months. Interestingly, several combinations of evergreen species exhibited a high degree of separation with each other, indicating that remotely sensed phenological features (or multi-temporal imagery, more generally) are important classifying evergreen tree species. Green-up rate (α_3), day-of-year of green-up inflection (α_4), and green-down rate (α_6) were also shown to aid in the separation between certain evergreen classes.

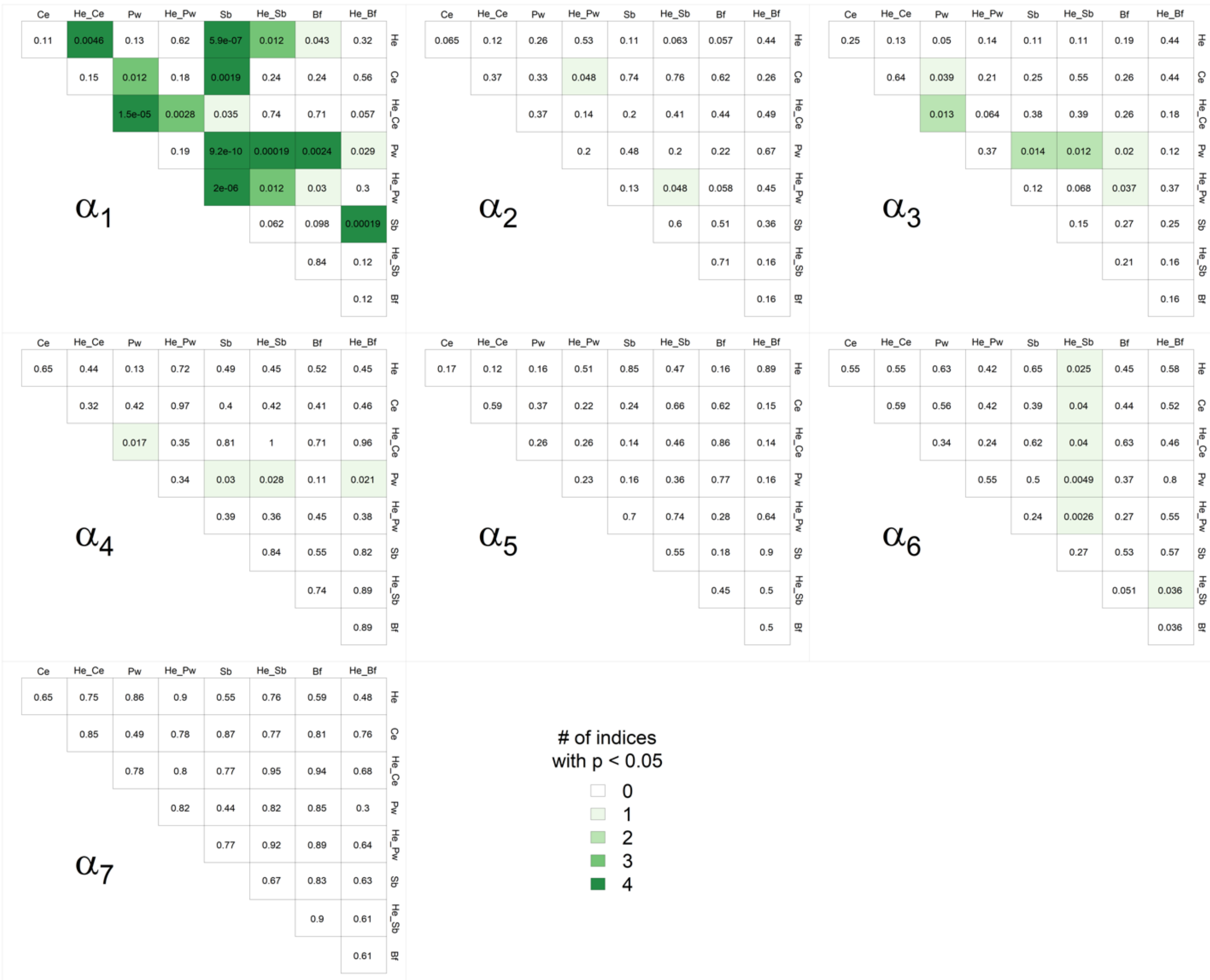

Figure 2. Contingency matrices between dominant and co-dominant evergreen stands by phenological feature (α). The values in the cells are the lowest p-value obtained from a post-hoc Dunn test (where a low p-value indicates high separability between the two classes when using a particular phenological feature). The shades of green indicate for how many spectral indices a p-value less than 0.05 was obtained. Phenological features represent specific phenological stages or properties and are defined following Babcock et al. (2021): α_1: minimum greenness; α_2: greenness range; α_3: spring green-up rate; α_4: day-of-year of spring green-up inflection point; α_5: peak greenness trend; α_6: autumn green-down rate; α_7: autumn green-down inflection point. Species included in the comparison were: Cedar (Ce), Hemlock (He), White Pine (Pw), Black Spruce (Sb), and Balsam Fir (Bf), either dominant or co-dominant with another species.

2.4 Completion of classifier training

Two versions of the hemlock classifier were developed in this project. The first version was completed in September 2023 and presented as a FFT KTTD webinar by MSc student Amy Shi. Subsequent validation and quality assurance revealed serious artifacts in the classified maps resulting from variable Sentinel-2 observation densities in regions where the satellite's orbital paths overlap. To mitigate this problem, a new workflow was developed in January and February 2023. This workflow entailed the following steps: (1) Compute 10-day composite images of the spectral indices described in Section 1.1 on the Google Earth Engine, resulting in 36 multi-temporal features representing average phenological conditions over a four-year period; (2) Extract 10-day composite time series over all training data locations; and (3) Train a Random Forests model relating multi-temporal vegetation index profiles to detailed dominant and co-dominant tree species classes (39 in total).

2.5 Full assembly of data products

The model completed in 2.4 was used to generate preliminary tree species composition rasters over all Sentinel-2 tiles over southern central Ontario (approximately the known range of Eastern Hemlock across the province). The Ontario Wooded Area geospatial dataset was used to isolate only forest pixels, assigning a no-data value to all other non-forest pixels. Since the goal of this project was to identify potential hemlock stands and not to generate a comprehensive inventory of all (co-)dominant tree species across the product, only predicted classes related to hemlock were retained in the prediction rasters, and all others were assigned to a generic "non-hemlock" forest class. This was also done considering the fact that non-hemlock species were not considered in this project's validation activities, and the uncertainty of those class predictions has not been characterized. This resulted in a classified raster with the following class codes: Non-hemlock forest (0), Hemlock dominant (1), Hemlock/mixwood co-dominant (2), and Hemlock/evergreen co-dominant (3).

2.6 Generation of hemlock inventory:

A spatial inventory of Eastern Hemlock across most of its Ontario range was generated in March 2024. The inventory was generated using the detailed tree species classification described in 2.5. Since all Sentinel-2 data acquired between 2019 and 2023 was used in the random forest predictions, this inventory captures the predicted distribution of Eastern hemlock over this time period. Since Eastern hemlock is a late successional species, it is not expected that hemlock dominant or co-dominant stands will have changed substantially during that time period, with the exception of disturbances like fire or harvest. Figure XXX shows the inventory across all of southern Ontario and the southern portion of Northern Ontario, approximating the known range of Eastern hemlock across the province.

[Overall map]

Figure 3 to Figure 6 highlight several notable examples of where Eastern hemlock has been identified by the model, either as dominant stands or co-dominants with mixwood or other evergreen species. Figure 3 shows a hotspot of hemlock near Lake Opeongo, at the south side of Algonquin Provincial Park, where there is an abundance of hemlock stands. The predictions in this region are highly reliable, due to the relatively higher density of training data available over this region of the province. This is mostly due to the fact that the portion of the training data derived from the SilvEcon Hemlock Database originate from areas where hemlock densities are known to be high. Figure 4 highlights a similarly hemlock-rich region in the northern Bruce Peninsula.

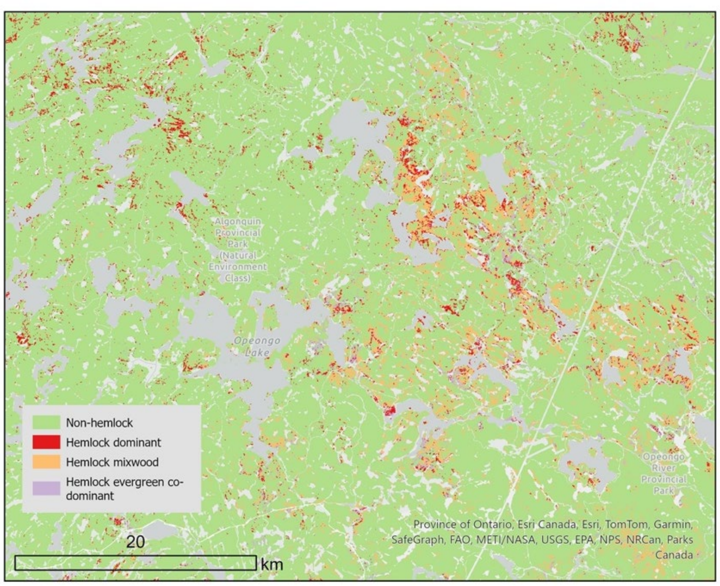

Figure 3. Identified dominant and co-dominant stands in southern Algonquin Park, Ontario.

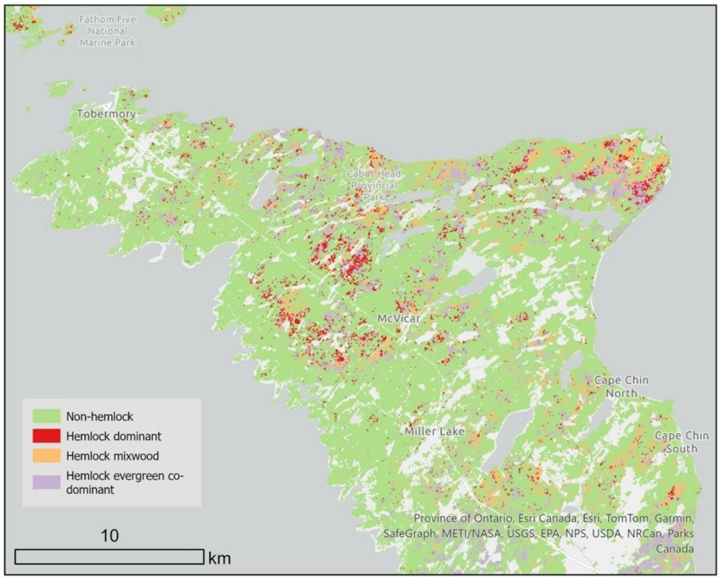

Figure 4. Identified dominant and co-dominant Eastern Hemlock stands in the northern Bruce Peninsula, Ontario.

Figure 5 demonstrates the performance of the hemlock inventory over southern Ontario, where deciduous woodlots make up the majority of the forest stands across the landscape. This occurrence is near Wainfleet, Ontario, where the invasive Hemlock Woolly Adelgid (HWA) was first identified in the province in 2020 and subsequent research on HWA treatment and detection has been ongoing. The model developed in this project was able to successfully identify hemlock-dominant stands in this region.

Figure 5. Identified Eastern Hemlock stands near Wainfleet, Ontario. The invasive Hemlock Woolly Adelgid was identified in this region in 2020, and field plots were sampled here in 2021 as part of this project.

Figure 6 demonstrates the hemlock inventory over a forested site near Grafton, Ontario, near the north shore of Lake Ontario. The project's field team visited this area and positively identified Eastern hemlock and HWA in these stands, marking the northernmost siting of the invasive in the province to date. Similarly to the Wainfleet site, the model successfully identified hemlock-dominant and hemlock/mixwood-codominant stands in this region.

Figure 6. Identified dominant and co-dominant Eastern Hemlock stands near Grafton, Ontario. HWA was positively identified by the project's field team in this region in 2021 and reported to the Canadian Food Inspection Agency (CFIA). This discovery marks the northernmost observation of HWA in the province to date.

2.7 Completion of knowledge transfer products

Knowledge transfer products are currently hosted at https://bitbucket.org/bendv/fft-kttd-hemlock. The open repository contains the inventory shown above in GeoTiff format. A colour ramp is embedded in the GeoTiff file, which will automatically

3. Deviations from Proposal

Due to the COVID-19 pandemic, fieldwork was postponed to summer 2022. As such, no expenditures were made on the project during the 2021-2022 fiscal year, aside from in-kind contributions. The classifier training was originally scheduled for completion in the Fall of 2022. However, several factors contributed to delays in this activity. First, fieldwork was postponed to Summer 2022 due to some team members testing positive for COVID-19, which in turn delayed the processing of the field data. Second, a major IT incident at the University of Guelph resulted in the loss of all pre-processed Sentinel-2 imagery on our compute server (https://news.uoguelph.ca/2023/04/it-incident-update/). As a result, we re-processed all input Sentinel-2 data on the Google Earth Engine to avoid any further data losses during the course of this project. Finally, an alternative data pre-processing workflow was developed in January and February 2024 after major data artifacts were discovered during validation of the initial classification results.

4. References

Babcock, Chad, Andrew O. Finley, and Nathaniel Looker. 2021. “A Bayesian Model to Estimate Land Surface Phenology Parameters with Harmonized Landsat 8 and Sentinel-2 Images.” Remote Sensing of Environment 261 (September 2020): 112471. https://doi.org/10.1016/j.rse.2021.112471.

SECTION C: SUMMARY OF EXPENDITURES

Description of eFRI Funds Spent:

eFRI funds were spent on MSc student stipends (Amy Shi) during the Summer 2022, Fall 2022 and Winter 2023 winter semesters and travel expenses for 2022 fieldwork. Direct and indirect costs (not including in-kind contributions) are outlined in the table below:

Item	**Amount**
MSc Student	
Student stipend (2022-2023)	$ 16,270.64
Student benefits (2022-2023)	$ 81.38
Sub-total	*$ 16,352.02*
Fieldwork	
Accommodation	$ 1,424.41
Meals	$ 607.85
Ground Transportation	$ 107.04
Airfare	$ 445.68
Sub-total	*$ 2647.98*
Total Expenses	$ 19,000.00
Administrative Overhead	$ 1,900.0
Total Invoiced	**$ 20,900.00**

Table updated by SVescio June 12, 2024

Description of In-Kind Contributions:

A total of $36,725.00 CAD in Non-KTTD contributions have been spent towards the MSc student stipend between September 2021 and March 2024. These contributions are broken down as follows:

Graduate Teaching Assistantships (source: Department of Geography, Environment and Geomatics, University of Guelph):

Fall 2023	$ 6,125.00
Winter 2023	$ 6,125.00
Fall 2022	$ 6,025.00
Winter 2022	$ 6,025.00
Fall 2021	$ 5,925.00
Total	**$ 30,225.00**

The student received an additional stipend for the Winter 2024 semester totally $6500.00 from an NSERC Discovery Grant held by Ben DeVries.

SECTION D: DECLARATION

I hereby certify that the above is a true and accurate report of work completed during the reporting period noted on page one of this report.

Project Lead Authorization:

Ben DeVries (Project Lead)	University of Guelph
Name and Title (Print)	Institution
	March 28, 2024
Authorized Lead Signature	Date

Institution Authorization (university, college, company etc):

Robin Roth, Professor and Chair of Geography, Environment and Geomatics	University of Guelph
Name and Title (Print)	Institution
	March 28, 2024
Authorized Institution Signature	Date