Assesscarbon

Final Report (FR)

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1.0	8.2.2021	Final	To be submitted to ESA

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1. Introduction

1.1 Purpose of the document

The Assesscarbon project developed and demonstrated at a pre-operational level an approach for large area forest biomass and carbon modelling in Forestry TEP. The first half of the project concentrated on creation of the models and datasets to be used in the demonstration, while the second half of the project focused on implementation of the service into Forestry TEP and running the demonstration. This document describes goals, phases of implementation and the main achievements of the project.

1.2 Document Structure

This document is organized as in the following:

- Section 1 is this introduction, providing the purpose of the document
- Section 2 presents the main goals and structure of the project
- Section 3 presents the achievements of the project
- Section 4 provides conclusion and ideas of future development

1.3 Highlights of the project

1. A novel Sentinel-2 image mosaicking approach was used to create cloud free image mosaic (using 2019 and 2020 imagery) over the target area covering Finland and the Russian boreal forests until the Ural Mountains.

2. Forest structural variable estimation models were developed for large area estimation using a new approach, which allowed inclusion of several Sentinel-2 tiles as input in the model creation.

3. Data assimilation approach, which uses multi-temporal observations, was developed for the estimation of primary production. This approach allows continuous improvement of estimates as the number of multi-temporal observations increase.

4. A processing pipeline was developed and implemented on Forestry TEP. It allows semi-automated production of forest structural variable and primary production estimates for large areas. When the required models for the target area have been developed, the bulk processing of the desired output variables can be run in an automated fashion through a REST API interface.

5. The feasibility of the system was demonstrated by producing Growing Stock Volume (GSV), Gross Primary Production (GPP), Net Primary Production (NPP) and Stem Volume Increment (SVI) maps in 10 m spatial resolution for the entire target area including 214 Sentinel-2 tiles.

2. Project overview

2.1 Objective

The overall objective of the Assesscarbon project was to develop and demonstrate at a pre-operational level an approach for large area forest biomass and carbon modelling in Forestry TEP. The demonstrated service combined ground reference data, Sentinel-2 imagery and primary production modelling. This main objective was reached through three specific scientific and technical objectives of model development, Forestry TEP integration and demonstration (Table 1).

Table 1. Scientific/technical objectives of Assesscarbon project.

Objective title	Objective description
1. Forest Structural Variable and Primary Production modelling	Development of models for forest structural variable estimation and a framework for the assimilation of satellite data into a primary production and forest growth models.
2. Forestry TEP integration	Integration of forest variable and primary production estimation procedures into Forestry TEP.
3. Demonstration	Demonstration of service capability via compilation of results for a selected area of interest and target date

The *first* specific objective (Forest Structural Variable and Primary Production modelling) covered the model development for forest variable estimation and development of a modelling framework. It enabled assimilation of satellite measurements in the primary production estimations making mapping of biomass and carbon possible in spatially explicit manner in 10 m spatial resolution. The *second* objective was to integrate the above-mentioned framework into the Forestry TEP platform to produce primary productivity estimates in a scalable fashion. The *third* objective was to demonstrate the service capability for a selected area of interest and target date. Together the three objectives created a foundation for a novel approach to derive large extent biomass and carbon pool and flux estimates and forecasting in a scalable fashion on an online platform.

The first half of the project concentrated on creation of the models and datasets to be used in the demonstration, while the second half of the project focused on implementation of the services into Forestry TEP and running the demonstration.

2.2 Consortium

The Assesscarbon project consortium consisted of four different companies, each with a unique expertise that is needed to meet the goals for the project (Table 2). Together these companies could accomplish the goals of the project in a way that none of the consortium members could have achieved alone. VTT had the overall responsibility and coordination tasks of the project. VTT was also responsible for the development and implementation of the Forest Structural Variable models. Terramonitor (Satellio Oy) provided cloud free Sentinel-2 mosaics used in the project. Simosol Oy implemented the service demonstration and the University of Helsinki was responsible for the Primary Production model development.

Table 2. Assesscarbon project consortium.

Company	Main tasks in the project
VTT Technical Research Centre of Finland Ltd.	• Overall coordination of the project • Management and reporting • Development, implementation and demonstration of structural forest variable modelling in Forestry TEP environment
Terramonitor (Satellio Oy)	• Sentinel-2 image mosaic creation
Simosol Oy	• Implementation and demonstration of primary production modelling in Forestry TEP environment
University of Helsinki	• Primary Production model development • Journal manuscript lead

2.3 Workflow and schedule

The workflow of the project can be coarsely divided into two phases: 1) Training/development phase and 2) Implementation phase (Figure 1). In the first phase, the mosaicking methods and estimation models were developed and tested, while in the second phase, the services were implemented in Forestry TEP and the demonstration was conducted.

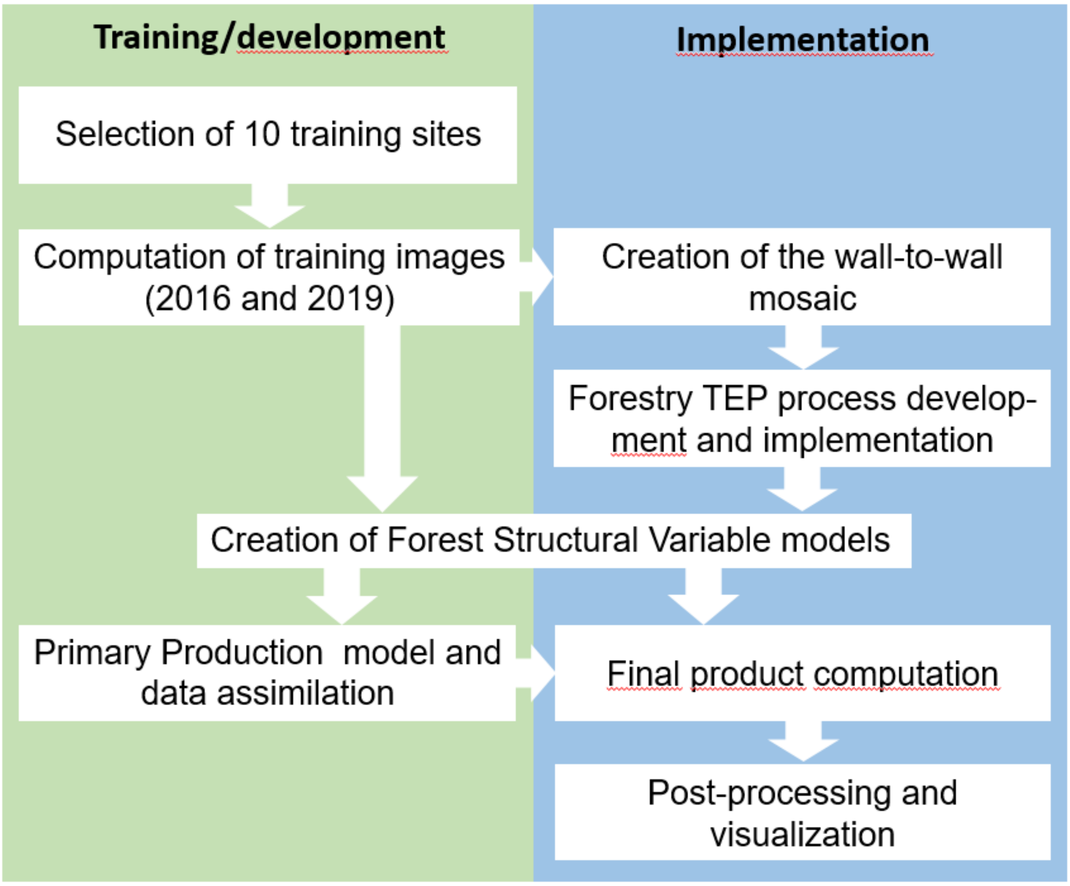

Figure 1. Project workflow.

There was some overlap between the two phases, but in broad terms the first phase included Work Packages 1 and 2 (WP1 and WP2), while the second phase was implemented in Work Package 3. In addition, there was a Management and Reporting Work Package (WP4), which ran throughout the project. The overall duration of the project was 12 months, of which around half was spent for the training and development activities, while the other half was reserved for service implementation, demonstration and reporting (Figure 2).

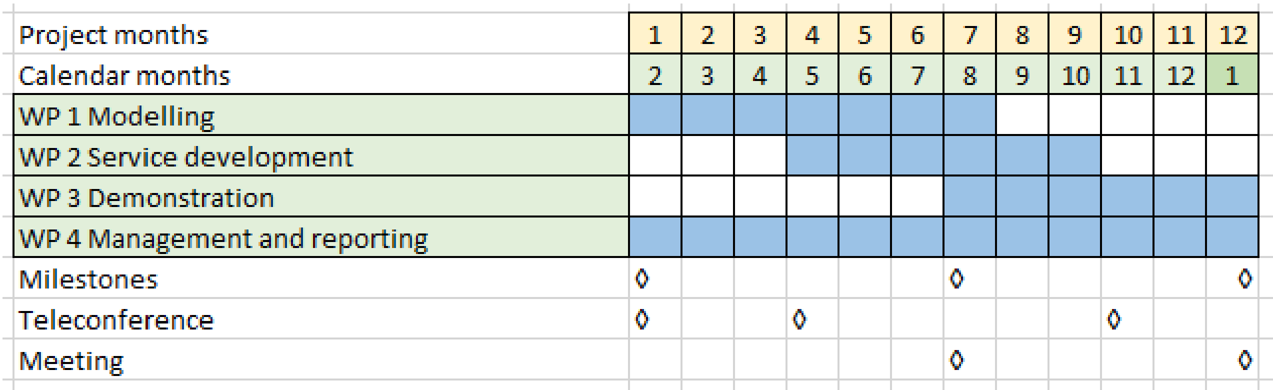

Figure 2. Gantt chart of Assesscarbon.

2.4 Management activities

The management activities included general project activity planning and coordination, project (both official and internal) meeting arrangements, reporting and payment arrangements. In addition, the main contract between ESA and VTT, as well as the subcontracts between VTT and the subcontractors were signed in the early phases of the project.

Altogether five official project meetings were held during the project, the last of which is the Final Review meeting, still ahead at the time of writing of this report. Note that all of the project meetings were held as teleconference due to the COVID pandemic that raged in Europe during the entire duration of the project and prevented any international travel.

1. The kick-off meeting was held as teleconference on the 7th of February 2020
2. The first Progress Meeting was held as teleconference on the 5th of May 2020
3. The Mid-term Review Meeting was held as teleconference on the 1st of September 2020.
4. The third Progress Meeting was originally planned to be held on the 5th November, but was twice postponed due to medical reasons, and was finally held as teleconference on the 23rd November 2020.
5. The Final Review meeting is scheduled to be held as teleconference on the 10th February 2021.

Table 3 lists the reports delivered to ESA. The list includes documentation related to the meetings, regular Monthly Progress Reports, Quarterly Progress Reports and all the official document deliverables (**in bold**).

Table 3. Documents delivered to ESA during the Assesscarbon project.

N.	Document reference	Type of document	Date of issue
1	Kick-off meeting agenda	Meeting Agenda	10.2.2020
2	Kick-off meeting presentation	Presentation slides	10.2.2020
3	Kick-off meeting MoM	Minutes of Meeting	10.2.2020
4	MPR1_Feb2020	Monthly Progress Report	9.3.2020
5	MPR2_Mar2020	Monthly Progress Report	1.4.2020
6	Progress meeting 1 agenda	Meeting Agenda	4.5.2020
7	QPR1	Quarterly Progress Report	4.5.2020
8	Progress meeting 1 presentation	Presentation slides	6.5.2020
9	Progress meeting 1 MoM	Minutes of Meeting	6.5.2020
10	MPR4_May2020	Monthly Progress Report	1.6.2020
11	MPR5_June2020	Monthly Progress Report	1.7.2020
12	**D1-MTR**	**Mid-Term-Review Report**	**12.8.2020**
13	Mid-Term-Review agenda	Meeting Agenda	18.8.2020
14	Mid-Term-Review presentation	Presentation slides	1.9.2020
15	Mid-Term-Review MoM	Minutes of Meeting	2.9.2020
16	MPR7_Aug2020	Monthly Progress Report	1.9.2020
17	**D2-TN1**	**Forest Structural Variable and Primary Production models**	**4.9.2020**
18	MPR8_Sep2020	Monthly Progress Report	1.10.2020
19	Progress meeting 3 agenda	Meeting Agenda	2.11.2020
20	QPR3	Quarterly Progress Report	2.11.2020
21	Progress meeting 3 presentation	Presentation slides	24.11.2020
22	Progress meeting 3 MoM	Minutes of Meeting	24.11.2020
23	**D4-TN2**	**Service routines**	**6.11.2020**
24	MPR10_Nov2020	Monthly Progress Report	1.12.2020
25	MPR11_Dec2020	Monthly Progress Report	4.1.2021
26	Final-Review agenda	Meeting Agenda	28.1.2021
27	**D8-FR**	**Final Report**	**8.2.2021**
28	**D9-FP**	**Final Presentation**	**10.2.2021**
29	**D6-Man 1**	**Journal Manuscript**	**9.2.2021**
30	**D10-CCD**	**Contract closure documentation**	**After FR meeting**

The full list of deliverables including also other than document deliverables is provided in Table 4. Note that the minimum requirement of **D7-Web 1 Project bog posts** (two blog posts) was reached already on the 9th September 2020, as marked in Table 4.Altogether three blogs were posted during the project on the Forestry TEP website, and a final fourth one is planned after the finalization of the project:

1. Assesscarbon laying the foundation for scalable large area carbon pool and flux modelling in Forestry TEP (20 Apr 2020)

2. Assesscarbon project ready to start implementing biomass and carbon modelling pipeline into Forestry TEP (9 Sep 2020)

3. First large scale forest variable maps processed in Forestry TEP for the Assesscarbon project (24 Nov 2020)

4. *Final blog post to highlight the main results of the project* (after the finalization of the project)

Table 4. List of Assesscarbon deliverables.

ID	Title	Deadline	Status	Description
D1-MTR	Mid-term Review Report	During August 2020	**Delivered 12.8.2020**	Summary of main activities, progress and issues outstanding
D2-TN1	Forest Structural Variable and Primary Production models	End of WP1: 7th September 2020	**Delivered 4.9.2020**	Description of Forest Structural Variable and Primary Production models developed in WP1
D3-Geotiff1	Sentinel-2 mosaic image for the target area	End of WP1: 7th September 2020	**Delivered 4.9.2020**	Cloud free Sentinel-2 mosaic of the target area in GeoTiff format
D4-TN2	Service routines	End of WP2: 7th November 2020	**Delivered 5.11.2020**	Description of the service routines implemented in F-TEP
D5-Dem 1	Demonstration of the service	End of project: 7th February 2021	**Delivered 1.2.2021**	Maps of tree volume, GPP, NPP and volume growth for the target area.
D6-Man 1	Journal manuscript	End of project: 7th February 2021	**Delivered 9.2.2021**	A scientific journal article manuscript
D7-Web 1	Project bog posts	End of project: 7th February 2021	**Delivered 9.9.2020**	Min. 2 Project blog posts on F-TEP website.
D8-FR	Final Report	End of project: 7th February 2021	**Delivered 8.2.2021**	Summary of main activities
D9-FP	Final Presentation	End of project: 7th February 2021	**Delivered 10.2.2021**	Summary of main activities
D10-CCD	Contract Closure Documentation	Contract Closure	**To be delivered after Final Review**	

3. Description of project activities

3.1 Planning phase

During the planning phase (the first month), a detailed plan for the project execution was defined. This plan concentrated on developing scalable services that will be flexible to use with large datasets covering large areas. *The underlying approach selected to reach this goal was to utilize Sentinel-2 tiles as the building blocks in all phases of the process. All models and services used for this purpose were developed, redefined or modified to enable processing of multiple Sentinel-2 tiles in a coordinated manner.*

The technical set-up of the development was based on the following data (divided into training and final production datasets):

- For training/development:
  - 10 x Sentinel-2 tiles (five from Finland, five from Russia), for 2016 and 2019; with imagery acquired between June and September
  - Finnish Forest Centre (Metsäkeskus) field plots 2016 and 2019.
  - Finnish Meteorological Institute weather data
- For final products:
  - Sentinel-2 mosaic for 2019/2020 (15th June – 31st August 2019 and 15th June – 31st July 2020); 214 Sentinel-2 tiles, covering Finland and western part of Russian taiga until the Ural Mountains
  - Weather data (datasets generated by the Finnish Meteorological Institute)
  - Flux tower measurements (Hyytiälä, Sodankylä and Fyodorovskoye eddy-covariance sites).

Detailed activity plan designed at the beginning of the project outlined the sequence of activities to be conducted as follows:

1. Selection of training sites (i.e. 10 Sentinel-2 tiles), based on field data locations, and other influencing factors, optimizing the representativeness of the sample
2. Creation of training images
3. Development of *Probability* software to handle large datasets in a scalable fashion, and implementation of the improved software to Forestry-TEP
4. Creation of Forest Structural Variable models with the training dataset, followed by an accuracy assessment
5. Development of a data assimilation framework for Primary Production models (utilizing the bi-temporal test areas)
6. Creation of the final mosaic
7. Forestry TEP service pipeline development and implementation
8. Demonstration of the production of volume, GPP, NPP and volume growth in for the target area
9. Post-processing and visualization
10. Preparation of journal manuscript

3.2 Selection of training sites

The training sites were used to: 1) test the mosaicking algorithm to be used in creation of the final wall-to-wall mosaic and 2) provide training data for development of the data assimilation framework for primary production estimation (Section 3.5). For the development of the data assimilation framework, it was essential to collect observations from two points of time, separated preferably by minimum of three years. Years 2016 and 2019 were used. The training sites were selected to include a representative sample from the project interest area (i.e. Boreal zone from Finland until the Ural Mountains), taking into account 1) availability of field data and 2) the availability of early (2016) Sentinel-2 data. The final selection of training sites included ten Sentinel-2 tiles, five in Finland and five in Russia (Figure 3).

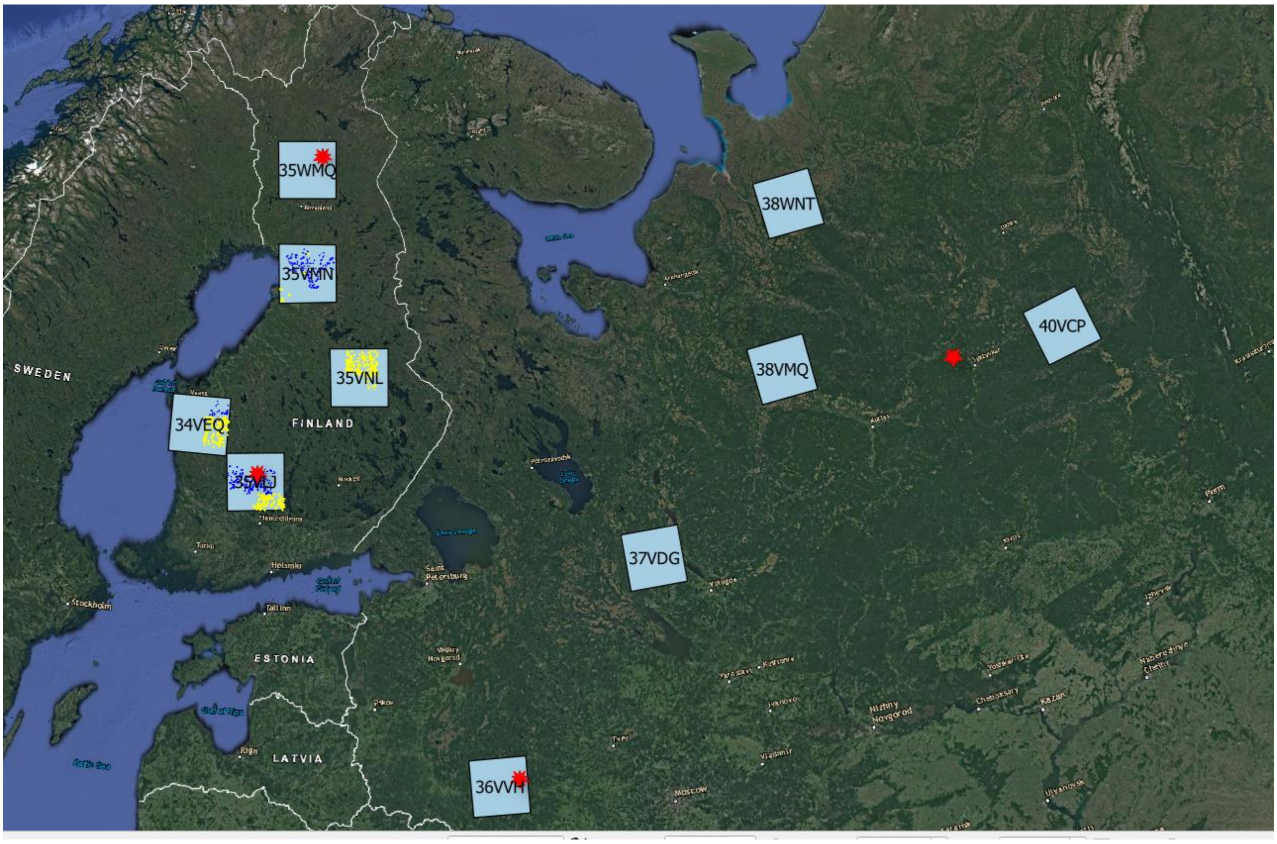

Figure 3. Training site locations (Sentinel-2 tiles). Red stars indicate locations of flux towers. Field sample plots are shown in yellow (2019) and blue (2016) dots.

3.3 Training image computation

Cloud-free composite images for 2016 and 2019 were created for each training tile. The images were created with Sentinel-2 Level 2A data acquired between June and mid-September. The training images were created by Terramonitor (Satellio Oy). The process can be roughly divided into three steps: data selection, merging algorithm and quality control. The objective of the merging algorithm is to create a cloud-free image out of many observations, which are imperfect (e.g. that include clouds, haze or smoke). To do this, each pixel is evaluated according to four criteria: cloudiness, haze, shadows and the resemblance to usual pixels observed in the location (based on a reference mosaic). A weight is then given for each pixel according to the criteria above. A cloudy pixel will have a very low weight, whereas an optimal forest pixel will have a much higher one. These weights are then used to average the observations given as input and produce the final image.

The algorithm works particularly well when many observations are available from the same location. In the Assesscarbon training sites, images from June to mid-September were selected. For several image tiles in 2019, more than twenty observations could be used for generating the output image, which produced good quality results (Figure 4). In some tiles in Russia, however, less than 10 cloud free observations were available, resulting in lower quality of the mosaic images.

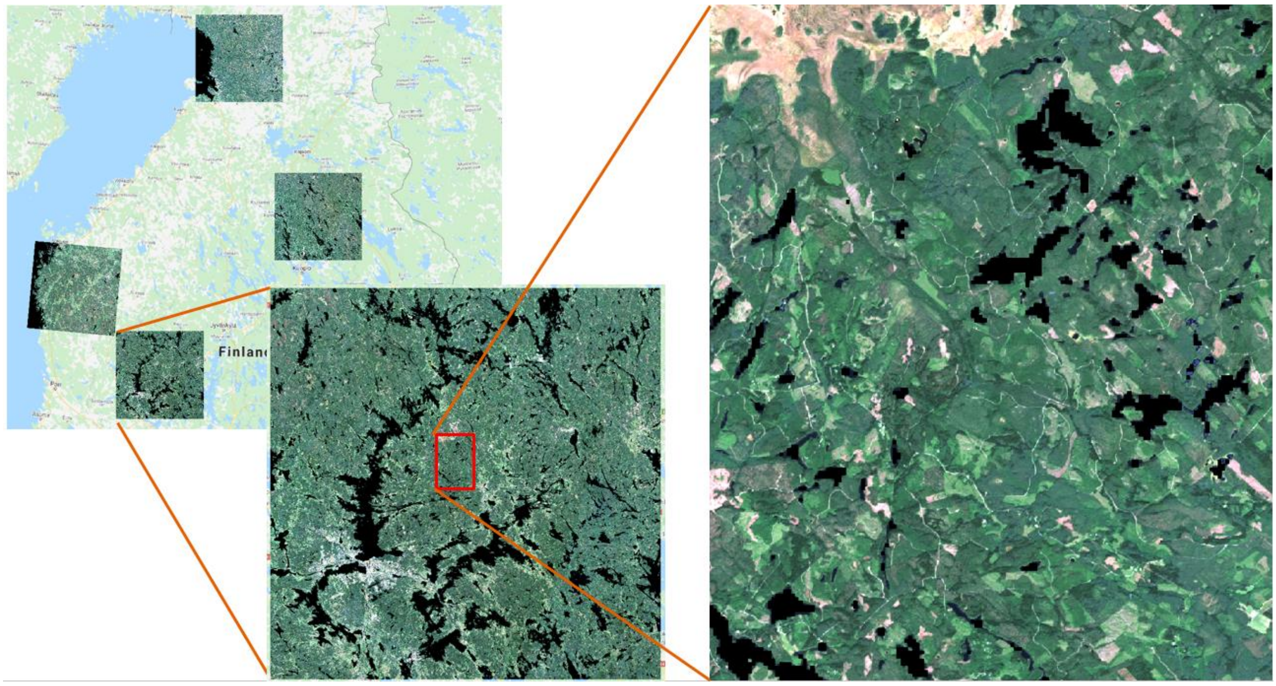

Figure 4. Sample of 2019 training images in Finland (35VLJ).

The situation for 2016 was different because of inferior image availability. On average, only around ten observations were available from the same location. This was mainly due to the lower observation frequency in 2016 with only one Sentinel-2 satellite in orbit. This lowered clearly the quality of the 2016 mosaics. The mosaics from the area of Finland were generally of adequate quality. This is important, since these are the sites with field data, and therefore the most important sites for development of the dynamic forest variable models as well.

Although the tests on the training sites confirmed that the approach is suitable for the final mosaic creation and forest structural variable estimation, it also highlighted the necessity for a quantitative quality parameter, in addition to visual evaluation. This led to development of three quality parameters that were calculated for the final mosaic tiles (see Section 3.6), and later utilized for masking purposes in the creation of the final output layers of the project.

3.4 Forest Structural Variable model creation for the training tiles

The Structural Variable Models were created using *Probability* software chain with the Finnish Sentinel-2 mosaic tiles and field sample plot measurements. The *Probability* forest classification and estimation process (Häme et al. 2001) contains three different components, which together form a comprehensive package of forest classification/estimation tools combining field data with satellite imagery. The three parts are 1) Proba Cluster, 2) Proba Model and 3) Proba Estimates. These tools were used in the development and testing of the Forest Structural Variables models. All of the processing was run in the Forestry TEP online environment. The process was described in full in deliverable D1-TN1, *Technical Note 1: Forest Structural Variable and Primary Production models*. The approach is summarized below.

The creation of the training images has been described above. The Finnish Forest Centre 9 m radius circular field sample plots were used (https://www.metsakeskus.fi/node/321) as reference data. The 2019 field sample plots spread out to four of the training tiles. Altogether 2546 sample plots were available after the visual screening where invalid points were removed. These plots were split into a training set which included 1697 plots and an accuracy assessment set which included 849 plots. For the 2016 mosaics, a combination of field data from 2015 and 2016 was used. The plots spread out to three training tiles. The 2015 plots were screened and all plots in areas that had experienced significant changes (like clearcuts) before the 2016 image observation were removed. Altogether, this 2015-2016 field dataset included 2508 plots, 1672 for training and 836 for accuracy assessment.

Models were computed for eight structural forest variables. Seven of these were needed as input for the Primary Production model. Stem volume was additionally estimated because it was one of the final project outputs. Median value was used in the model creation phase for each cluster for Basal area (G), Diameter (D) and Height (H) and Volume (V), while average value of the sample plots was used for Pine proportion (P%), Spruce proportion (Sp%), Broadleaf proportion (Bl%) and site type. The median approach is less affected by potential outlier plots, but the average approach produces more reasonable estimates for the proportional variables (i.e. their sum equals closer to 100).

The final models for the 2016 and 2019 training imagery were computed using 60 clusters created with maximum likelihood clustering. The models used six bands (green, red, red edge 1, NIR, SWIR 1.6 µm and SWIR 2.1 µm)

The accuracy metrics of the 2016 and 2019 model for all of the continuous variables are provided in Table 5 and Table 6. For the 2019 model, accuracies are on the same level that has been achieved in previous projects using the *Probability* estimation process (Astola et al. 2019). This can be considered as a good result and an indication of consistent quality of the 2019 composite images. The 2016 accuracies were clearly lower, due to lower quality of the 2016 images. For the site type categorical variable, both of the models produced around the same level of overall accuracy (51% for 2016 and 52% for 2019). These can be considered rather low, but the majority of erroneous classification were only off by one class, having minor effect on the Primary Production models where they are used as input.

Table 5. Accuracy metrics for continuous variables in the final 2016 model.

	G	V	D	H	PINE %	SPRUCE %	BL %
RMSE	7,79	91,28	6,08	50,77	36,2	26,8	24,8
RMSE %	43,7	63,7	36,9	36,6	72,3	94,0	127,4
Bias	-0,54	-10,20	-0,30	-0,11	-1,5	0,3	0,7
Bias %	-3,0	-7,1	-1,8	-0,1	-3,0	0,9	3,6

Table 6. Accuracy metrics for continuous variables in the final 2019 model.

	G	V	D	H	PINE %	SPRUCE %	BL %
RMSE	6,96	84,78	6,10	47,64	27,3	26,3	22,1
RMSE %	37,4	55,1	37,1	33,2	61,8	86,4	95,3
Bias	-1,19	-13,95	-0,73	-5,54	1,0	-0,2	-0,5
Bias %	-6,4	-9,1	-4,4	-3,9	2,2	-0,5	-2,3

Regardless of the lower accuracy of the 2016 model, the structural forest variable estimates were produced as planned for all the training sites for 2016 and 2019, to be used as input in the data assimilation framework development described in Section 3.5. Figure 5 illustrates the volume estimates produced with the 2019 data.

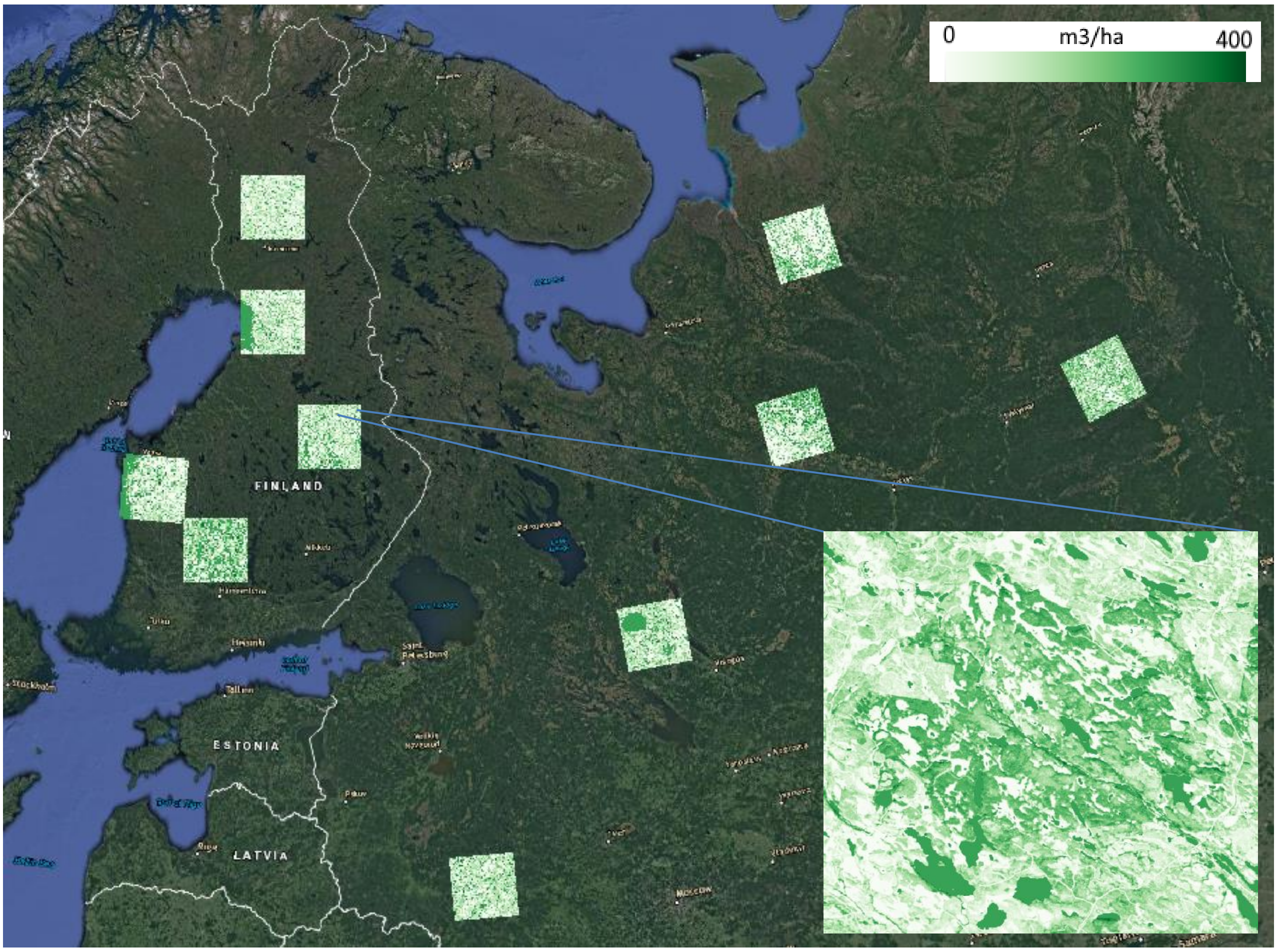

Figure 5. Volume estimated by the final 2019 model for all of the 2019 training images, with around 10x10 km sample from the Finnish tile 35VNL showing the Hiidenportti National Park.

3.5 Data assimilation into the Primary Production model

In Assesscarbon, we developed two data assimilation frameworks that, through the implementation of a few steps, allows to combine repeated measurements of Sentinel-2 data and forest model predictions. A framework was used to update the forest structural variables (state variables: G, D, H, P%, Sp% and Bl%) that dynamically change over time (ForVarDA, Figure 6); while a framework was used to improve the estimates of site type, the site related parameter that stays relatively stable over time (STDA, Figure 7).

The Primary Production model is PREBAS, a process based model that is a combination of a light use efficiency model (PRELES) and a forest growth model based on the pipe model theory (CROBAS). The process was described in full in the deliverable D1-TN1, *Technical Note 1: Forest Structural Variable and Primary Production models*. Here, we provide a summary of the description. Due to the problems of the 2016 training image quality, only four training tiles in Finland and a subset of one mosaic tile in Russia could be finally utilized in the primary production modelling development.

A Bayesian approach was used for data assimilation. The Bayesian method relies on probability theory and allows accounting the uncertainty in measurements and model structure. The uncertainty of satellite-based estimates was calculated using the accuracy assessment set of the field sample plots of 2016 and 2019. A multivariate normal distribution was fitted for the error quantification of the structural variables G, D, H, P%, Sp% and Bl%; while a probit model was used for the site type uncertainty. With the probit model we assigned to each site type (varying from 1 to 5) the probability of being the correct one. For the parametric uncertainty of the forest model we considered the posterior distribution of model parameters estimated in a previous calibration (Minunno et al., 2019). PREBAS was Bayesian calibrated for scots pine, Norway spruce and silver birch in Finland using permanent national forest inventory data and permanent growth experiments.

Since the uncertainty quantification is numerically expensive, the use of surrogate models was needed to reduce the computational load of the analyses. A surrogate model is a cheap and fast model that mimics the outcome of a more complex model. In our case, we used regression models (surMod) to reproduce PREBAS outputs. The independent variables of surMod are the structural forest variables (V, G, D, H, P%, Sp% and Bl%) at initialization (t1), while the dependent variables are the same variables predicted by PREBAS at the time of the second satellite measurement (t2).

The data assimilation framework for the structural forest variables consists of 5 steps that were implemented at pixel level:

1. Fitting of surrogate models to simulate PREBAS outputs, in this step we considered also model parametric uncertainty;

2. Monte Carlo simulations (MC) for uncertainty quantification of the initial state variables at t1;

3. Computing the forest structural variables at t2 using the surrogate model;

4. Combine model simulations with satellite based estimates at t2 using the Bayesian theorem.

5. The maximum a posteriori (MAP) estimates of forest structural variables are used to initialize and run PREBAS, producing new maps of carbon balance and forest growth and their relative uncertainty.

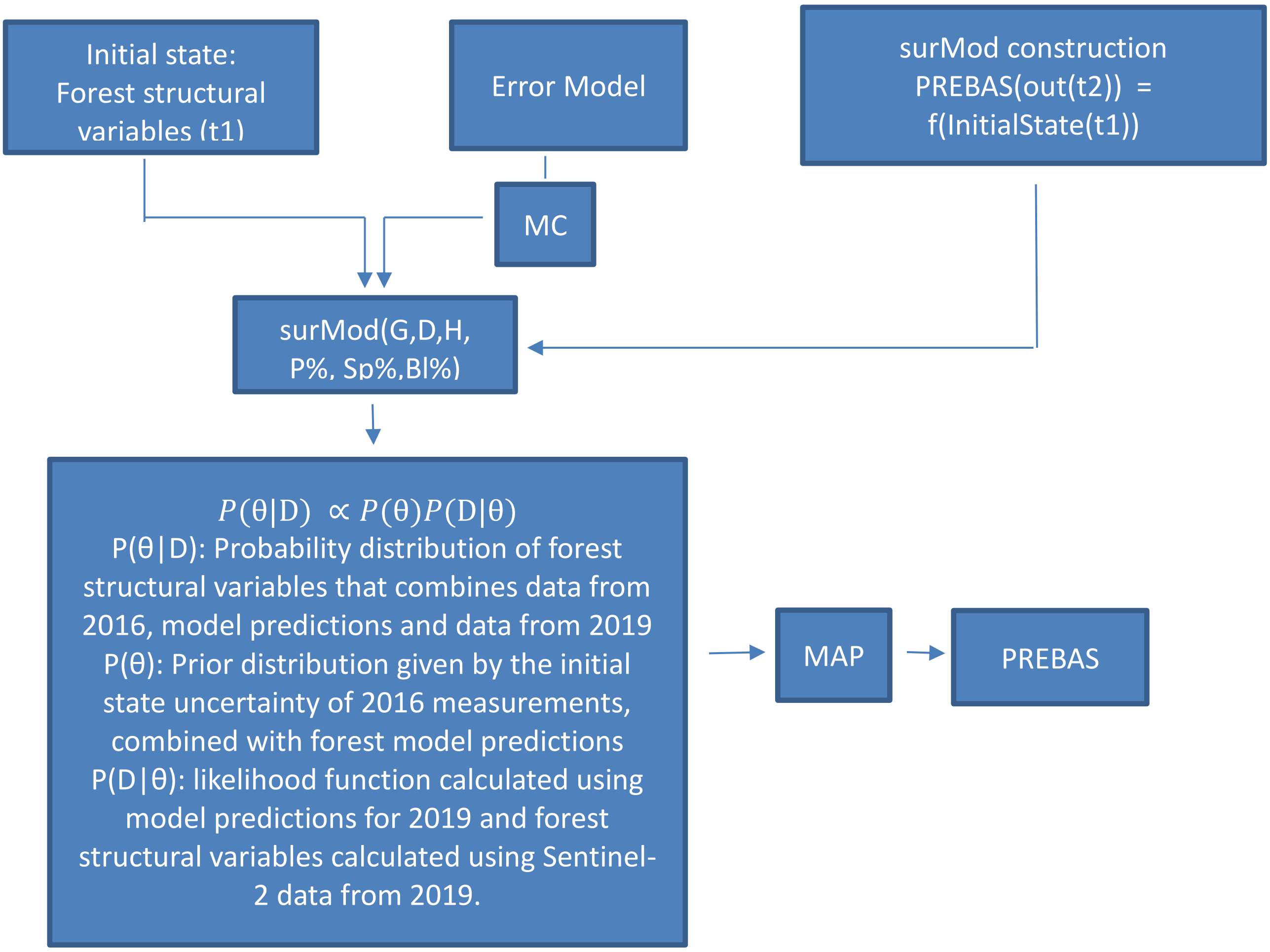

Figure 6. Flowchart of data assimilation of forest structural variables.

The data assimilation framework for site type estimates consists of seven steps that were implemented at pixel level:

1. Fitting of surrogate models to simulate PREBAS stand volume predictions. PREBAS parametric uncertainty accounted for in this step.

2. Uncertainty quantification of the initial state variables at t1.

3. Computation of stand volume at t2, inputting the surrogate model with the 5 different site types. In this way we created 5 models differing only for site type.

4. Combine model simulations with satellite based estimates at t2 using the Bayesian theorem.

5. Calculating the integrated likelihood for each site type/model and performing a Bayesian model comparison (BMC). BMC allows to compare different models and provides the probability of each model of being the correct one. In our case, we were quantifying the probability of each site type of giving the correct stand volume estimate.

6. Combine BMC results with the probit models of satellite based estimates for t1 and t2.

7. Produce new maps of site type and their relative uncertainty.

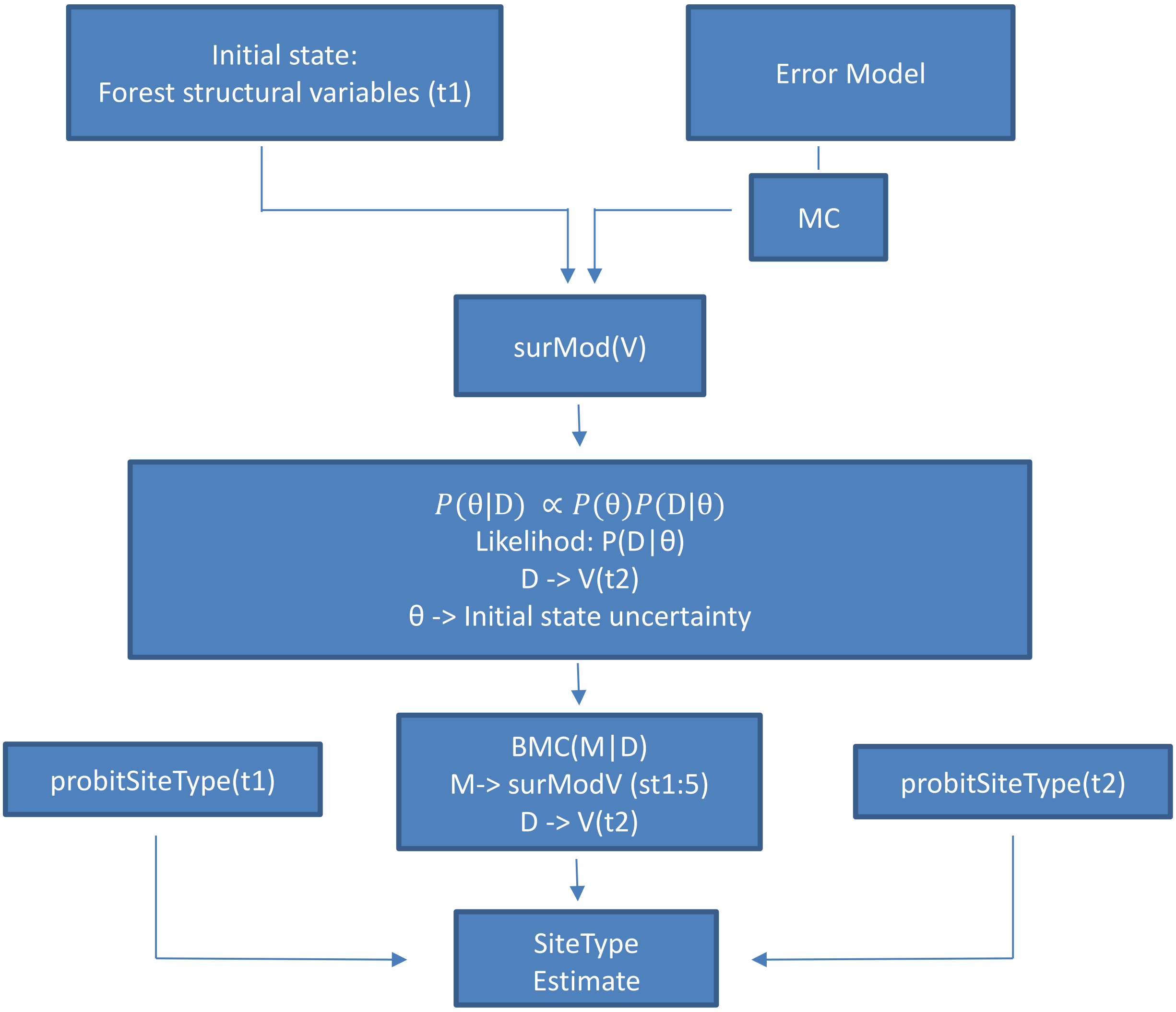

Figure 7. Flowchart of data assimilation of site type.

The accuracy of the PREBAS estimates of Gross Primary Production (GPP) was evaluated with the eddy-covariance estimates from the Sodankylä, Hyytiälä and and Fyodorovskoye flux towers. At all sites model predictions were lower than the measurements (Figure 8). Model predictions were expected to be lower than the flux measurements because understory vegetation was not included in the modelling analysis, while understory contributes to the carbon and water balance measured by the towers.

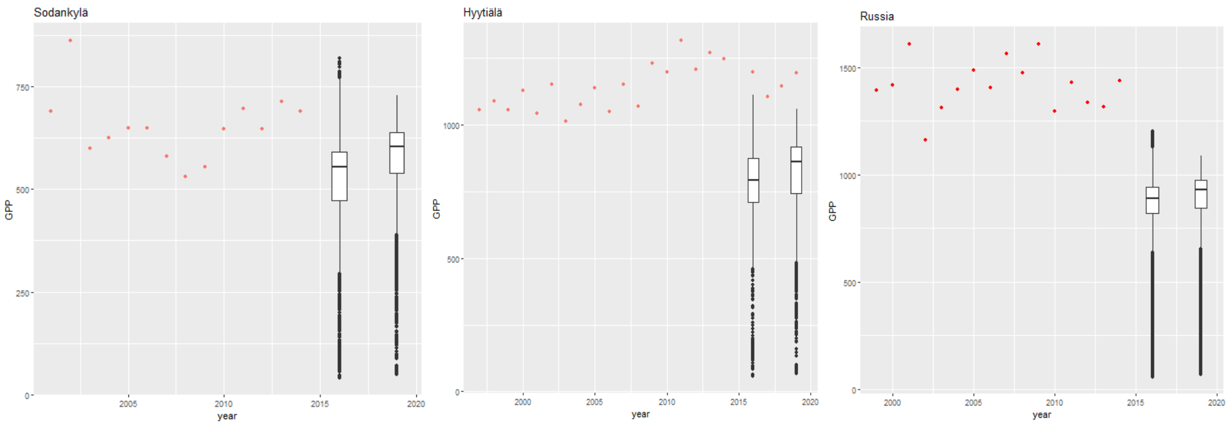

Figure 8. GPP at Sodankylä, Hyytiälä and Fyodorovskoye. Eddy covariance measurements (dots); PREBAS estimates for 2016 and 2019 (boxplots).

In Hyytiälä and Sodankylä understory contributed between 10 and 15% of the foliage biomass, while data were not available for Fyodorovskoye. Modelled GPP was 30% lower at Hyytiälä and 40% lower at Fyodorovskoye. In addition to the understory modelling other factors can cause a bias in GPP. Possible sources of error could lay in the initial state variables estimates and in the model structure. These aspects will be further investigated.

3.6 Creation of the final mosaic and Forest Structural Variable model

The final wall-to-wall mosaic was created with the same approach that was used in the creation of the training tiles and described in Section 3.3 'Training image creation'. The area covered the entire Finland and the Russian taiga until the Ural Mountains (Figure 9), including 214 Sentinel-2 tiles. The temporal range included 15th June - 31st August in 2019 and 15th June - 31st July in 2020. Images from two years were needed to ensure sufficient number of high quality observations and consequently high quality for the final mosaic.

Figure 9. Assesscarbon final mosaic. Altogether, the area includes 214 tiles and cover the entire Finland and the Russian taiga until the Ural Mountains.

Slightly more imagery was used from year 2020. The average proportion of 2020 observations used in the 214 tiles was 55% and median 59%.The figures were computed by dividing the number of 2020 observations by the total number of observations for each tile (giving tile-wise proportions of 2020 imagery) and subsequently computing the average and median of these values over the entire mosaic. The final mosaic included seven spectral bands and three quality layers (b02, b03, b04, b05, b08, b11, b12 + ql1, ql2, ql3). The three quality layers represent:

1. ql1 = Number of valid observations per pixel
2. ql2 = Variance of the weights used for the observations in the compositing algorithm
3. ql3 = Probability of at least one good observation

The main quality parameter is the ql3, which describes the probability of at least one good observation for each pixel. The probability of at least one good observation is calculated per pixel using the formula $P = 1 - \prod(1-p_i)$, where p_i denotes the probability that observation i is good for $i \in \{1,...,n\}$, where n denotes the number of observations for the pixel. The other two quality parameters were produced to enable detailed evaluation of the process and support further development of the compositing algorithm.

The Structural Forest Variable model for the final mosaic tiles was computed using the same parameters as the 2019 training model described in Section 3.4. Altogether 5226 field plots (3471 for training and 1755 for accuracy assessment) spread over six tiles across Finland were used to compute the final model (Figure 10).

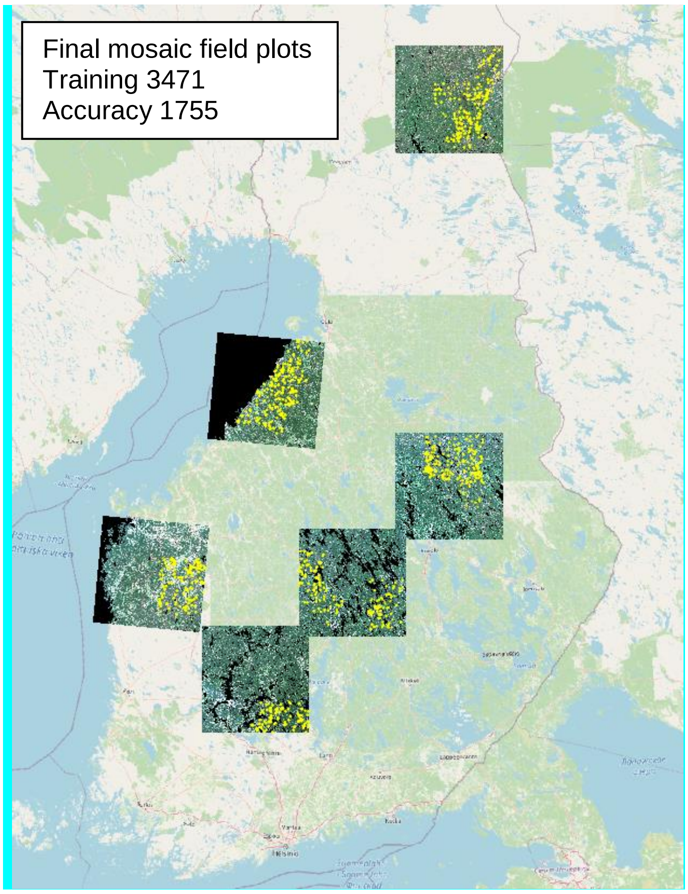

Figure 10. Final mosaic tiles used for the final Forest Structural Variable model creation. Sample plots overlaid in yellow colour.

The accuracy statistics for the continuous variables are provided in Table 7. They are generally on the same level as in the 2019 training model. As said before, this can be considered a good result while using mosaic imagery. This is particularly the case for the final model, since the final model includes field data also from Lappland, which increases the variation of forest types within the training data. We are therefore confident that the final model will provide reasonable Forest Structural Variable estimates for the target area.

Table 7. Accuracy metrics for continuous variables in the final Forest Structural Variable model

	G (m^2)	**V (m^3)**	**D (cm)**	**H (m)**	**PINE %**	**SPRUCE %**	**BL %**
RMSE	7,18	84,49	5,73	4,57	29,3	26,7	20,3
RMSE %	39,4	58,5	35,5	33,5	64,1	89,6	90,7
Bias	-0,65	-8,01	-0,15	0,00	0,7	-0,7	-0,4
Bias %	-3,6	-5,6	-0,9	0,0	1,6	-2,5	-1,8

For the site type, the final model accuracy was significantly better than in the 2016 and 2019 training models. The overall accuracy for the final model was 62%, while for the 2016 and 2019 training models overall accuracies of 51% and 52% were reached, respectively. This is believed to be at least partly due to the higher quality of the final Sentinel-2 mosaic. The final Forest Structural Variable model was used to compute the final output products.

3.7 Forestry TEP service pipeline development and implementation

The final outputs of the Assesscarbon project included estimations of 1) Volume (V), 2) Gross Primary Productivity (GPP), 3) Net Primary Productivity (NPP) and 4) Stem volume increment (SVI). In addition to these final output variables, seven intermediate variables (Table 8) needed to be computed in the processing pipeline. To enable the processing of the 214 tiles for the production of the final mosaic, a semi-automated processing pipeline was developed and implemented into Forestry TEP.

Table 8. Variables produced during the processing, including both intermediate and final output variables. *Final output layers in Italics.*

	Forest Structural Variable model		**Primary Production model**
Variables to be estimated	Basal area (G) Diameter at breast height (D) Height (H) Pine proportion (P%) Spruce proportion (Sp%) Broadleaf proportion (Bl%) Site type (Site)	INPUT →	*Gross Primary Productivity (GPP)* *Net Primary Productivity (NPP)* *Stem volume increment (SVI)*
	Volume (V)		

In total, seven individual processing services were used in the processing pipeline. The full processing pipeline is shown in Figure 11. The pipeline is divided into three sections: 1) Model creation, 2) Model verification and 3) Operational production. While the ‘Model creation’ and ‘Operational production’ parts of the processing pipeline can be run in an automated fashion, the ‘Model verification’ part involves visual analysis steps that enable fine-tuning Forest Structural Variable models to reach optimal results. A full description of the processing pipeline as well as all the services and parameters used in the creation of the final products of the Assesscarbon project was provided in deliverable D4-TN2, *Technical Note 2: Service Routines*. In the following, we provide a short description of the main points of the process.

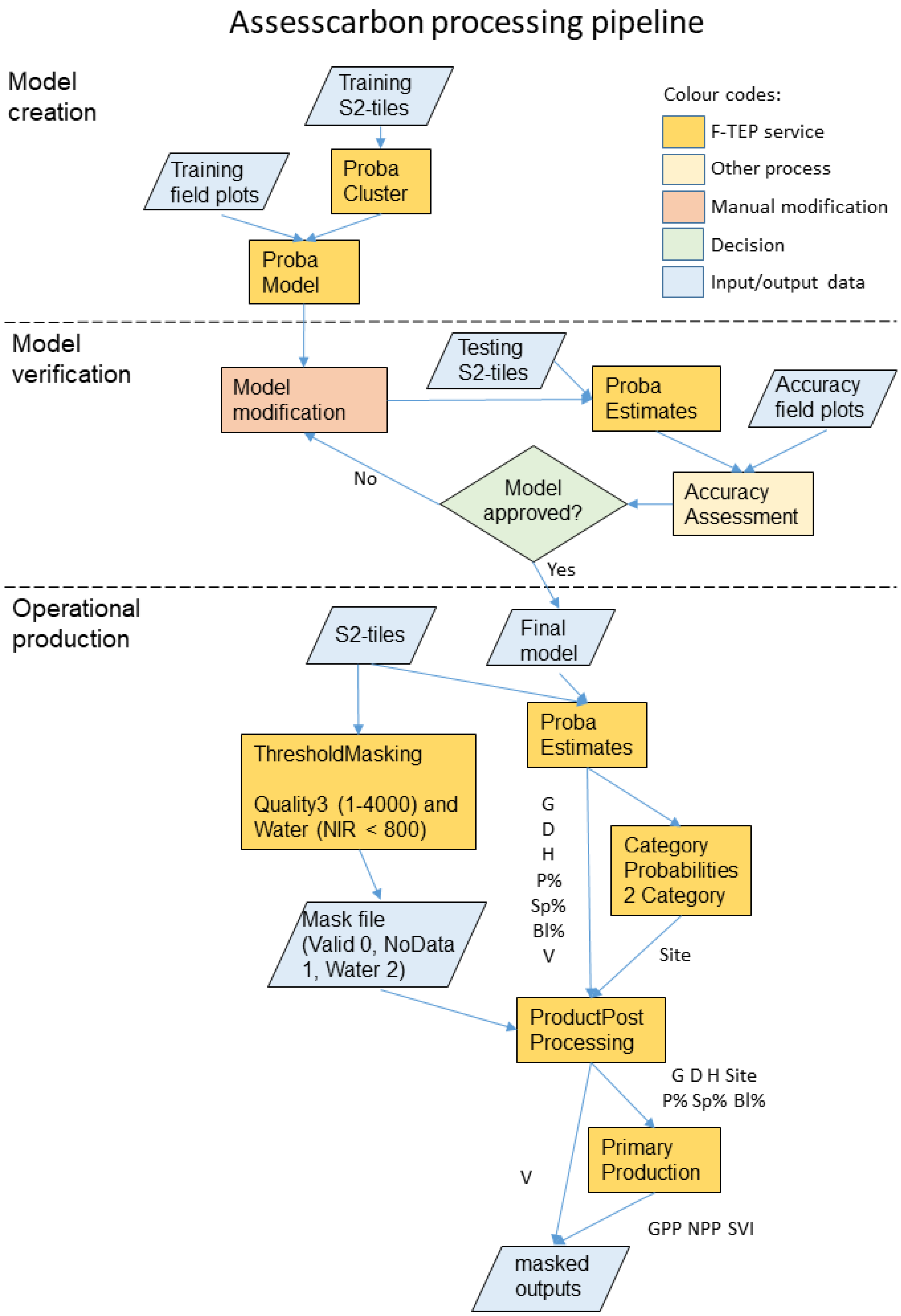

Figure 11. Processing pipeline used in the Assesscarbon project.

The individual Forestry TEP services used in the processing pipeline are listed in Table 9. The components include four main processing applications (ProbaCluster, ProbaModel, ProbaEstimates and PrimaryProduction). In addition, three auxiliary programs were used for minor masking and postproduction purposes.

Table 9. Service components used in the Assesscarbon project.

N	Name	Novelty in Assesscarbon	Description
1	ProbaCluster	Verification of multiple image input functionality	Performs unsupervised image clustering
2	ProbaModel	Modified to enable multiple input files	Calculates ground-data based statistics to clusters produced by ProbaCluster.
3	ProbaEstimates	Minor technical modifications	Compute estimates of forest variables for image pixels using cluster and ground data statistics (i.e. inputs from the above services)
4	ThresholdMasking	New service	Creates masks for an input image by thresholding
5	CategoryProbabilities 2Category	Unchanged	Converts multiple category probabilities to category values
6	ProductPost Processing	Minor technical modifications	Creates masked end-products from ProbaEstimates output
7	PrimaryProduction	New in Forestry TEP	Calculates selected primary production variables

For the final model used for the Assesscarbon output production, the ‘Model creation’ part of the pipeline (Figure 11) consisted of the ProbaCluster execution with six input Sentinel-2 tiles (tiles of the final Assesscarbon mosaic), followed by the execution of the ProbaModel service with ProbaCluster output and 3471 field sample plots (as described in *Technical Note 1 (TN1), Forest Structural Variable and Primary Production models*). At the end, the ‘Model creation’ resulted in two models, one for the median variables and one for the average variables. These models were analysed and tested in the next phase of the processing pipeline.

In the ‘Model verification’ part of the pipeline (Figure 11), the models created above were visually analysed and manually modified, followed by ProbaEstimates test runs, which allowed accuracy assessment of the models using the 1755 accuracy assessment plots (as described in *Technical Note 1 (TN1), Forest Structural Variable and Primary Production models*). The ProbaEstimate service was executed using the graphical user interface (GUI) of the Forestry TEP. The rest of the activities in this processing phase were conducted outside Forestry TEP.

At this point, all the necessary datasets and components were ready for the final demonstration of the processing pipeline, i.e. the creation of the final Assescarbon output products.

3.8 Demonstration of the production of volume, GPP, NPP and volume growth for the final mosaic area

The demonstration of the production of volume, GPP, NPP and volume growth for the final mosaic area was conducted with the ‘Operational production’ part of the processing pipeline (Figure 11). All the 214 tiles of the final Sentinel-2 mosaic were processed, creating the final output layers of the Assesscarbon project. The first part of the pipeline consisted of creation of the masks and production of the forest structural variable layers. The ThresholdMasking service utilized only the Sentinel-2 tiles as input. “Clouds” were masked out based on the mosaic image quality band ql3 (band 10), using the value 4000 as the threshold (quality range 0-10000). Values lower than 4000 were masked out as clouds (mask value 1). Water areas were masked out based on the Near Infrared (NIR) band (band 5 in the mosaic tiles). Pixels with NIR value less than 800 (8% reflectance) were masked out as water (mask value 2). All other values were flagged as valid data at this point (mask value 0).

Subsequently, the ProbaEstimates service was run for the Sentinel-2 tiles, followed by the CategoryProbabilities2Category service, which creates one single site type layer from the probabilities of each site type class. At this point, the output files of both the ProbaEstimates as well as the CategoryProbabilities2Category went into the ProductPostProcessing service, which performed masking of the Forest Structural Variable outputs, separated the variables into different layers and created coloured images for easy visual evaluation of the results.

Apart from the Volume (V) layer, which itself is an output layer of the Assesscarbon project, all forest structural variable layers were used as input layers for the primary production components of the processing pipeline. The primary production layer creation started with pre-processing the input raster files. To save time and computational resources, raster files with forest structural variables were evaluated and only unique combinations of values were fed to the PREBAS model that simulates primary production. The spatial location of each combination was preserved. To execute the simulation, the ‘Rprebasso’ implementation was used which was first fetched from the internet and then used as a package in the R programming language.

Once the ‘Rprebasso’ model finished, its raw outputs were transformed into the desired variables. Then, these results were spread from a text file back to a raster format based on the mapping saved in the preprocessing steps. Only specified primary production variables were post processed and returned as outputs of the service.

The ‘Operational production’ part of the pipeline was run through the Representational State Transfer Application Programming Interface (REST API). This allowed chaining of subsequent pipeline components into an automated processing chain, making the bulk processing of the 214 Sentinel-2 mosaic tiles faster and more efficient. To enable the execution of services through the REST API, a custom Python script, “FTEP_service_call.py”, was developed. The script was configured with a configuration (.ini) file that specified the service that is to be run as well as inputs to the service. The script fetched service’s description including the defined inputs, uploaded all file inputs - if any - to Forestry TEP and executed the service (launched a job). Then, it periodically checked for the job’s status until it was done. Based on configuration settings, it then either downloaded the output files or returned reference to the outputs on Forestry TEP. If, for any reason, the execution failed, it returned a link to the logs.

For the requirements of the Asesscarbon project, a wrapper script for FTEP_service_call.py was also developed. This script, “assesscarbon_chain.py”, was given a set of tile names in its configuration file “assesscarbon_chain.ini”, as well as some other necessary settings for executing the various services in the processing chain. When executed, it repeatedly called FTEP_service_call.py (described above) which in turn executed the actual Forestry TEP service. The core functionality of “assesscarbon_chain.py” was to generate automatically appropriate configurations to each service execution and to feed outputs of one service as inputs to the next one in the chain.

Overall, the process described above allowed bulk processing of the 214 Sentinel-2 tiles, demonstrating the functionality of the forest biomass and carbon processing approach developed in this project.

3.9 Post-processing and visualization

The processing described above resulted in the output products of the Assesscarbon project including four layers: 1) Volume (V), 2) Gross Primary Productivity (GPP), 3) Net Primary Productivity (NPP) and 4) Stem volume increment (SVI). One of the output layers (Volume) was produced through the Probability chain, while the three other were outputs from the PrimaryProduction service.

The specifications of the output products are described in Table 10. All of the output products are in 214 GeoTiff format tiles, matching the size and location of the original Sentinel-2 tiles. The units used in the various products are standard units generally used with the variables. The products also include values for masked out areas (more specifically for Non-tree cover, Water and Clouds or other no data), which are consistent throughout the products.

Table 10. Final output product specifications of the Assesscarbon project.

Product	Acronym	Unit	Other values	Format
Volume (growing stock)	GSV	m^3/ha	65533: Non-tree cover 65534: Water 65535: Clouds (or other no data)	16bit GeoTiff
Gross Primary Production	GPP	CO_2t/ha/a	65533: Non-tree cover 65534: Water 65535: Clouds (or other no data)	16bit GeoTiff
Net Primary Production	NPP	CO_2t/ha/a	65533: Non-tree cover 65534: Water 65535: Clouds (or other no data)	16bit GeoTiff
Stem Volume Increment (annual)	SVI	m^3/ha/a	253: Non-tree cover 254: Water 255: Clouds (or other no data)	8bit GeoTiff

As visualization of the output products was not possible within Forestry TEP, and the project did not have resources for development of new visualization components for the platform, the visualization of the Assesscarbon output products was conducted outside Forestry TEP. First, all the output tiles were downloaded into VTT storage. Then the required layers were extracted from the output files and a mosaic image of each layer was generated for each UTM zone (zones 34-40). These mosaics were then warped to the WGS84 / Pseudo-Mercator projection (EPSG:3857) that was used in the visualization. Overview layers were added to the warped mosaics to speed up their visualization. The images were processed with GDAL tools and Python scripts. A virtual server hosting Tomcat and GeoServer was used for the visualization. The warped mosaics were added to the GeoServer instance as a layer group and a visualization web page was built using OpenLayers JavaScript library as the map rendering component.

This allowed visualization of all the output products in full 10 m spatial resolution over the internet at http://polarcode.vtt.fi/assesscarbon/. Figure 12, Figure 13, Figure 14 and Figure 15 provide overviews of the four output layers. The general visual impression of the layers is very good, providing reasonable results in both large scale and in high detail when zoomed in. The only clear artefact of the maps is the visible border in the Primary Production output layers between the two weather datasets used in the process. Further development is required to improve the use of weather datasets in the processing pipeline.

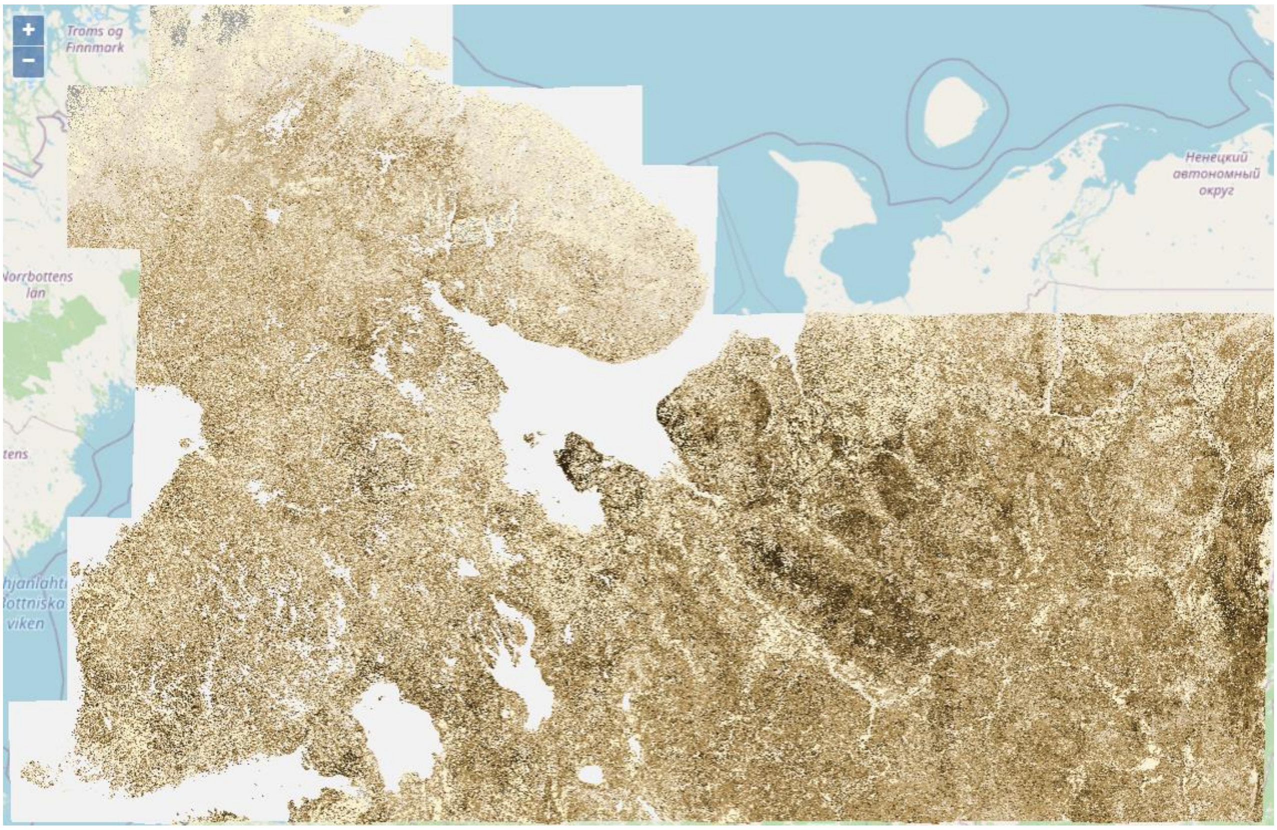

Figure 12. Growing Stock Volume (GSV) map in 10 m spatial resolution processed in Forestry TEP for Finland and the Russian boreal forest until the Ural Mountains. Colour range 0-300 m^3/ha, from light to dark.

Figure 13. Gross Primary Production (GPP) map in 10 m spatial resolution processed in Forestry TEP for Finland and the Russian boreal forest until the Ural Mountains. Colour range 0-40 CO_2t/ha/a, from light to dark.

Figure 14. Net Primary Production (NPP) map in 10 m spatial resolution processed in Forestry TEP for Finland and the Russian boreal forest until the Ural Mountains. Colour range 0-20 CO_2t/ha/a, from light to dark.

Figure 15. Stem Volume Increment (SVI) map in 10 m spatial resolution processed in Forestry TEP for Finland and the Russian boreal forest until the Ural Mountains. Colour range 0-13 m^3/ha/a, from light to dark.

3.10 Journal manuscript preparation

The key scientific result of the project will be published in a peer reviewed journal paper. The paper will focus on the presentation of the data assimilation procedures developed, highlighting the strength and weaknesses of the data assimilation frameworks. All the analyses have been completed but the manuscript is still in preparation. The aim is to submit it within February to *Environmental modelling and software* journal. A confidential first draft of the manuscript was submitted to ESA as deliverable **D6-Man 1**.

A data assimilation framework was developed to estimate forest structural variables and site fertility classes of boreal forests by sequentially combining remotely sensed observations at high resolution. Forest structural variables derived from Sentinel-2 data (10x10m resolution) collected in 2016 served as input to a process based model (PREBAS) and a model emulator. Through model predictions the state of the forests was forecasted to 2019. By means of Bayesian statistics, modelled forest structural variables were combined with new satellite based estimates for 2019. The analyses were conducted in five study sites of 100x100 km spread across Finland and Russia.

The data assimilation allowed to make use of repeated measurements of satellite data for monitoring the state of forest in boreal environment. In addition, data assimilation reduced the uncertainty associated to forest structural variables and the model emulator, used to mimic PREBAS output, reduced the computational load of the data assimilation framework making possible to ingest and process a considerable amount of data. To our knowledge, this will be the first study were a process based model and high resolution remotely sensed data were used for data assimilation in forest ecosystems. The study constitute a starting point for the development of the data assimilation framework that allows to integrate different types of satellite data and field measurements in order to achieve precise and up-to-date estimates of the forest state on large areas.

4. Conclusion and topics for further work

4.1 Overall project flow

Overall the project progressed well, largely according to plans. From management point of view the project progressed fully in schedule. Deliverables and other documentation were generally delivered in time, and other management issues (e.g. payments) were in order throughout the project. From technical point of view, there were minor surprises and complications that needed to be taken into account. These issues caused minor changes in the project execution, but did not prevent implementation of the main aspects of the project as planned. Table 11 lists the ten major points in the project implementation plan defined in the early stages of the project and comments related to the implementation of each of these points.

Table 11. Comments on the implementation of the main phases of the project.

Project phase	Comments on implementation
1. Selection of training sites based on field data, flux towers and other influencing factors.	Implemented as planned.
2. Creation of training images	Unexpected low quality of the 2016 training images (due to lack of images) and variation of levels between training tiles.
3. Development of Probability software to handle large datasets in a scalable fashion (+implementation to Forestry TEP)	Implemented as planned.
4. Creation of Forest Structural Variable models with the training dataset, followed by an accuracy assessment	For 2019 implemented as planned. For 2016, only three training tiles (instead of originally planned four tiles) were used and additional 2015 field data needed to be added. New model for the final mosaic.
5. Development of a data assimilation framework for Primary Production models	The variability of the training image quality, and thereby the structural forest variable estimates complicated the work, but did not prevent development of the framework
6. Creation of the final mosaic	Implemented technically as planned, but including data from two years to ensure high quality.
7. Forestry TEP service pipeline development and implementation	Implemented as planned.
8. Demonstration of the production of GSV, GPP, NPP and SVI for the target area	Some technical problems with Forestry TEP (see next section for details) and weather data acquisition, but at the end managed to finish processing in time.
9. Post-processing and visualization	Lack of suitable visualization features in Forestry TEP. External server was used for visualization of the output layers.
10. Preparation of journal manuscript	Implemented as planned.

A general issue that unavoidably effected the project implementation was the COVID-19 pandemic that raged in Europe during the entire duration of the project. This not only changed all project meetings into teleconferences, but also complicated all project activities throughout the project. Regardless of the pandemic, the project team found ways to process and transfer all the data and proceed with the analysis, meetings and other project activities. This was enabled largely due to the fact that the project utilized mainly online resources for data processing.

4.2 Topics for further work

Although the project went well overall, and the main goals were reached, several issues were noticed during the project that would improve the quality and/or smoothness of implementation of the forest biomass and carbon estimation products. Five areas of improvement can be identified where further development possibilities should be investigated:

1. **Mosaic quality quantification**: The project team and ESA officer discussed a lot during the project on the necessity and potential approaches to quantify the mosaic quality. The quality quantification is important for evaluation of the effects of the input data on the derived estimates. Great progress on the development of a quality parameter for the mosaics was made during the project, and the parameter was used in masking during the operational production. Possibilities to improve the quality further and the quality quantification of the mosaics should be investigated.

2. **Data Assimilation**: During this project, it was not possible to test the implementation of the data assimilation framework and its effects on accuracy in large area, since only one full coverage mosaic was produced. It will be important in the future to test the optimal practical implementation and evaluate how much better estimates the data assimilation approach provides of the state of the forests. Furthermore, the possibility of integrating multiple sources of Earth Observation and field measurements in the data assimilation process should be explored.

3. **Processing pipeline**: One of the hindrances that cased major delay during the processing was the sourcing of weather data for the primary production component of the processing pipeline. It was noticed in the middle of the processing that the database that was used for the western part of the target area, did not cover around 70 of the easternmost tiles. An alternative database was found, but it was a laborious process to acquire all the required data from the database and modify the service for the remaining 70 tiles. Optimal sourcing and ways of utilization of weather data needs to be looked into to allow smooth implementation of the services globally.

4. **Forestry TEP processing capacity**: During the project, it was noticed that the processing speed and reliability currently hinder fast execution of large processing jobs. Multiple issues affect the overall processing speed and reliability, varying from platform configuration, individual processor speeds, memory allocation and service design to other minor issues. Platform development is a continuous process. The Assesscarbon project provided valuable information and experience on the bottlenecks of the system. These issues should be tackled in upcoming system development.

5. **Output handling and visualization**: Another major issue related to Forestry TEP was the difficulty of handling and visualizing large datasets within the platform. The current output product cataloguing and storage structure is not optimal for users working with large datasets including hundreds of Sentinel-2 tiles as input files, and the corresponding output tiles. Currently Forestry TEP is first and foremost a processing platform, with somewhat insufficient capabilities to visualize and analyse large datasets including hundreds of files. These aspects should be given special attention in future development of the platform.

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