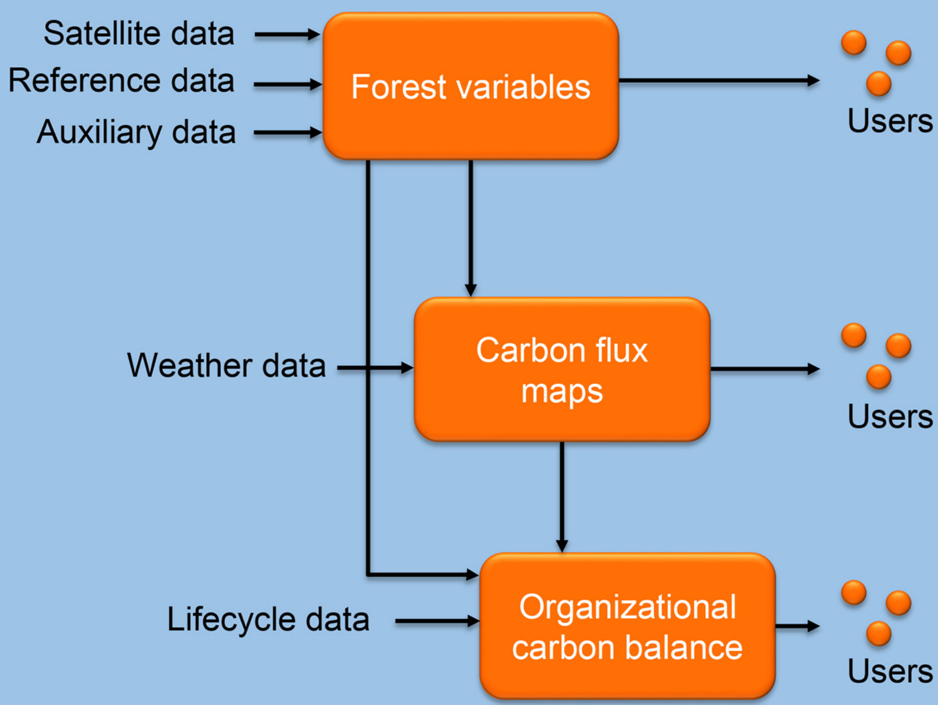

VTT
beyond the obvious

Forest Flux

Final Report

Tuomas Häme | Laura Sirro | Lauri Seitsonen | Yrjö Rauste | Matti Mõttus | Jukka Miettinen | Matthias Dees | Lincoln Davis | Fernando Rossi | Juho Penttilä | Markus Auvinen | Jussi Rasinmäki | Annikki Mäkelä | Francesco Minunno | Xianglin Tian | Gheorghe Marin | Marius Dumitru | Margarida Tomé | Susana Barreiro

VTT TECHNOLOGY 403

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Abstract

The overall objective of the Forest Flux (forestflux.eu) project was to foster the development of the Copernicus Earth Observation (EO) market and improve the profitability of forest management by implementing a world-first service of high-resolution maps of forest carbon fluxes, storage, and their development over time, using satellite imagery and associated data. The services were offered from the same process of data refinement. In this process, the outputs of the previous phase were inputs to the next phase. The earlier phase outputs were also products that were delivered to the users.

Forest Flux services were implemented on the scalable Forestry TEP cloud platform that enables integration of the Forest Flux products with the business processes of end users. The services are available via an Internet connection.

Computed products were mostly digital maps with supporting quantitative figures, such as statistical data on uncertainty. They were provided for nine user organizations and sites in Europe, South America, and Africa. In total, approximately 1,200 map products were delivered.

Forest Flux project received funding from the European Union's Horizon 2020 Research and Innovation program under grant agreement No 821860.

Executive summary

Sustainable forest management requires up-to-date and reliable information, not only on forest structure, but also on its primary productivity and carbon stocks, and on changes. Information is increasingly demanded for forest management purposes, to prove responsible asset management to the shareholders, and to follow the European policies and treaties.

The overall objective of the Forest Flux (forestflux.eu) project was to foster the development of the Copernicus Earth Observation (EO) market and improve the profitability of forest management by *implementing a world-first service of high-resolution maps of forest carbon fluxes, storage, and their development over time, using satellite imagery and associated data*. The services were offered from the same process of data refinement. In this process, the outputs of the previous phase were inputs to the next phase. The earlier phase outputs were also products that were delivered to the users.

We consider the project objectives achieved and the target technology readiness level 8-9 reached. The services developed in the Forest Flux project fulfill requirements for the monitoring of forest resources and carbon. They improve the profitability of forestry through provision of information on the value of forest asset while promoting its ecological sustainability.

Forest Flux services were implemented on the scalable Forestry TEP cloud platform that enables integration of the Forest Flux products with the business processes of end users. The services are available via an Internet connection.

The forest variables that are computed with the developed Forest Flux system include traditional structural variables, such as biomass-related variables, annual increment, and major tree species. They also include carbon flux variables, which are annual Gross Primary Production (GPP), Net Primary Production (NPP), and Net Ecosystem Exchange (NEE). Earlier carbon flux models were extended in the project to temperate and sub-tropical vegetation zones and verified with flux tower data.

Computed products were mostly digital maps with supporting quantitative figures, such as statistical data on uncertainty. They were provided for nine user organizations and sites in Europe, South America, and Africa. In total, approximately 1,200 map products were delivered.

Quality assurance procedures were defined for all elements of Forest Flux services. Specific software was developed for the quality assurance of the forest structural variable estimation and category classifications.

A commercial service entity for forest structural and carbon flux variables is available from Forest Flux. This enables frequent monitoring of forest resources and carbon for forest owners, timberland management companies, investors, the insurance sector, as well as governmental and intergovernmental bodies.

The Forest Flux services will improve success and growth of European value adding service provision industry, thus providing jobs and prosperity for society. The

services also help society adapt to climate change and manage forest resources in a sustainable manner.

Forest Flux project received funding from the European Union’s Horizon 2020 Research and Innovation program under grant agreement No 821860.

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List of acronyms

ALS	Airborne laser scanner
AOI	Area of Interest
API	Application Programming Interface
CROBAS	Tree growth and CROwn BASe from carbon balance
EO	Earth Observation
fAPAR	fraction of Absorbed Photosynthetically Active Radiation
FSC	Forest Stewardship Council
GIS	Geographic Information System
GPP	Gross Primary Production
ICOS	Integrated Carbon Observation System
LUE	Light-Use-Efficiency
NEE	Net Ecosystem Exchange
NEP	Net Ecosystem Production
NPP	Net Primary Production
PREBAS	PRELES+CROBAS
PRELES	PREdict Light-use efficiency, Evapotranspiration and Soil water
REST	Representational State Transfer
RMSE	Root Mean Square Error
TEP	Thematic Exploitation Platform
VHR	Very High resolution
YASSO	Yet Another Simulator of Soil Organic matter

1. Main results

1.1 Project context and objectives

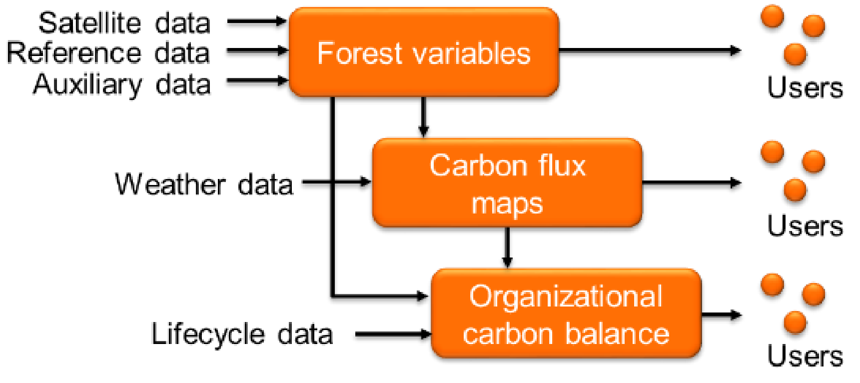


Figure 1. Forest Flux overall concept.

Sustainable forest management requires up-to-date and reliable information, not only on forest structure, but also on its primary productivity and carbon stocks, and on changes. This information improves the profitability of forestry through provision of information on the value of forest asset, while promoting its ecological sustainability. Information is increasingly demanded also to prove responsible asset management to the shareholders and investors, and to follow the European policies and treaties.

Hence, the market drivers for Forest Flux were the needs for

- A complete and up-to-date description of existing forest resources at an affordable price, and
- Inclusion of carbon as one of the decision criteria for forest management, beyond the currently dominating timber volume and direct economic value.

The business value of up-to-date forest resource data is the same as in any business process: in knowing the existing inventory of the production resources as the basis for production planning. The role of carbon is driven by climate change and the attempts to mitigate it.

The overall objective of the Forest Flux project was to foster the development of the Copernicus Earth Observation (EO) market and improve the profitability of forest management by *implementing a world-first service of high-resolution maps of forest carbon fluxes, storage, and their development over time, using satellite imagery and associated data*. The services were offered from the same processing chain where the outputs of the previous phase are inputs to the next phase. The earlier phase outputs were also used to serve the customers (Figure 1).

To achieve the overall objective, the following specific objectives were defined:

1. Assure the scientific coherence and accuracy of the Forest Flux products at large geographic scales;
2. Implement a scalable modular computation system for predicting forest structural variables, carbon stocks and fluxes, and the total carbon footprint on a commercially available computing platform;
3. Openly demonstrate the value of the services to the wider user community;
4. Perform a complete system integration with the existing business processes of the user;
5. Remove technical and communication barriers from European companies and institutions for using carbon flux and storage information in their operational decision making.

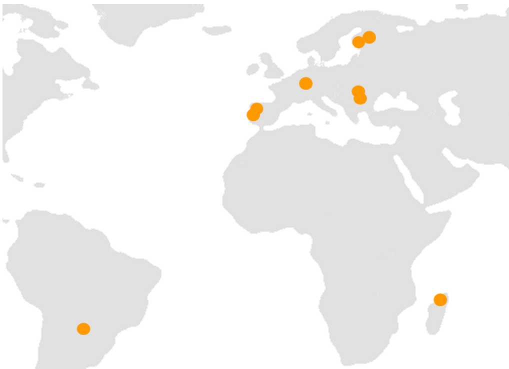
Forest Flux was conducted for nine user organizations and sites in Europe, South America, and Africa by six project partners (Figure 2, Figure 3). The sites represented managed boreal and temperate natural forest, eucalyptus plantations, and a reforestation site.

The project was coordinated by VTT Technical Research Centre of Finland Ltd., which was responsible for the method development for the structural forest variables, services for two users, dissemination, and contributed in the service chain development, as well as in the business plan. Unique Land Use GmbH coordinated user interaction activities and preparation of the business plan and contributed in the services. Simosol Oy implemented the image processing chain with a support by VTT and participated in the business plan. The University of Helsinki supported by the University of Lisbon developed carbon biomass, growth, and carbon assimilation models. INCDS was a close link to the users as an actor in forestry itself.

The project was carried out in two phases. Both phases included user interaction, service development, service piloting, and analysis of the results. Based on the experiences and feedback from the first project phase, all elements of Forest Flux services were further developed in the second phase.

Most products were digital maps with supporting quantitative figures, such as statistical data on uncertainty. The products of the organizational carbon balance module were numerical information only.

A service platform that produces and integrates these products with the business processes of end users was set up.



Pilot user	Pilot location
Tornator Oy	Finland
Forstwirtschaftliche Vereinigung Schwarzwald eG	Germany
Paraguay Agricultural Corporation S.A.	Paraguay
ALTRI Florestal S.A.	Portugal
União da Floresta Mediterrânica	Portugal
INCDS – Forest District Renasterea Padurii	Romania
INCDS – Forest District Sfanta Maria	Romania
ICOS Finland	Finland
Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH	Madagascar

Figure 2. Project sites.

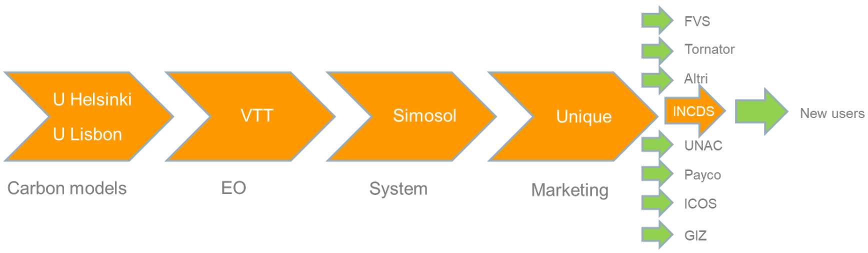


Figure 3. Our team and user organizations.

1.2 Service development

1.2.1 Service specification

Three service types were developed: forest structural variable services, carbon storage and flux services, and organizational carbon balance services (Figure 1). Several products were specified for each service type, reflecting the requirements for forest management planning and carbon inventory Table 1.

Table 1. Forest Flux product portfolio.

Structural forest variables	Biomass and carbon flux	Organizational carbon balance
Forest inventory	Biomass and carbon stock	Storage and fluxes in standing stock and soil
Forest cover	Above-ground tree biomass	Harvest and manufacturing emissions
Stem basal area	Below-ground tree biomass	Emissions from silviculture
Tree mean height	Carbon stock in trees	Transport emissions
Tree mean diameter	Soil carbon	
Stem volume	Annual primary production	
Stem number/density	Gross primary production	
Broadleaved proportion	Net primary production	
Conifer proportion	Evapotranspiration	
Tree species proportion	Annual stem volume increment	
Site fertility type	Net ecosystem exchange	
Stem volume by assortment	Forecast	
Diversity within an area unit	Above-ground tree biomass change/forecast	
Wooded area percentage	Gross primary production change/forecast	
Wooded area patch number	Net primary production change/forecast	
Wooded area perforation density	Evapotranspiration change/forecast	
Tree species variability	Annual stem volume increment change/forecast	
Forest height variability	Net ecosystem exchange change/forecast	
Change	Carbon stock in trees change/forecast	
Cover change	Carbon stock in soil change/forecast	
Harvests		
Damage		

1.2.2 Forest structural variables

The forest *structural variable services group* provides information on forest area, forest status, and their changes. The inventory-type services concern a selected year, whereas the information of the change services tell of the development between two or several time periods. The ecology or diversity services describe variability of a selected inventory product within an optional area unit. The output is, for instance, a number of tree species within one square kilometer grid cells. Successive diversity products for different years can be subtracted to indicate diversity dynamics. The main method to compute the structural variable products was the Probability algorithm (Häme et al., 2013, 2001; Miettinen et al., 2021). This method can compute all the variables of interest in the same run. The variables are output as continuous values. In the case of categorical variables, the outputs show the membership probabilities of a pixel to all the classes in question. The final classification is derived by selecting the class with the highest probability. A key benefit of the Probability is that the model can be manually adjusted. This makes it possible to achieve reasonable results also with limited ground reference data.

The uncertainty of the estimation was assessed by computing the root mean square errors from the estimated values and independent sample of ground reference data. In addition, the bias, with respect to the average of the test reference data of field measurements, was computed.

The Autochange method was used to make a map of changes between the acquisition dates of two satellite images. Autochange outputs the magnitude of the change, indication of change type, and approximate land cover class without applying ground reference data. The final change classification is compiled from these three outputs (Häme et al., 2020). In addition, change maps were made in some cases from separate estimates of forest variables from different points of time. A forest damage map was computed on one site by applying a time series of vegetation indices to very high resolution satellite data; on another site, a neural network classification was used to map the success of forest regeneration.

1.2.3 Carbon flux and biomass

The computed forest structural variables were used as inputs for the primary production models that output Gross Primary Production (GPP), Net Primary Production (NPP), and Net Ecosystem Exchange (NEE) or Net Ecosystem Production (NEP), which is the same as NEE but with an opposite sign (Figure 1, Figure 5).

The GPP was computed using a semi-empirical Light Use Efficiency (LUE) model PreLES (Predicting Light Use Efficiency) that also outputs evapotranspiration (Mäkelä et al., 2008; Peltoniemi et al., 2015). The CROBAS process-based growth model provided information about the fraction of Absorbed Photosynthetic Active Radiation (*f*APAR) for PreLES (Mäkelä et al., 2008; Valentine and Mäkelä, 2005). The *f*APAR depends on the state of the canopy, species, and site fertility type. Other inputs for PreLES were daily temperature, vapor pressure deficit, precipitation, and parameters related to soil water holding capacity. PreLES computed the daily GPP that was further accumulated to an annual GPP, describing carbon assimilation through photosynthesis. The *f*APAR from CROBAS is updated when the forest state changes due to forest increment or management, for instance (Figure 5).

The PREBAS model (Minunno et al., 2019; Peltoniemi et al., 2015; Valentine and Mäkelä, 2005) combines PRELES that calculates (GPP) and CROBAS that allocates GPP to plant respiration and plant component growth. This outputs the NPP. One PREBAS component of the NPP is a tree-growing stock volume increment that is a key variable in forestry. This alternative way to the traditional allometric equations was used to estimate the growing stock increment in Forest Flux.

The CROBAS model outputs tree litter fall as one of its components (Minunno et al., 2019). The litter that will be decomposed by microbes is one of the inputs of the YASSO model that estimates carbon loss by soil respiration (Liski et al., 2005). NEP is obtained by subtracting the soil carbon loss from the NPP that was calculated using PREBAS. The Net Ecosystem Exchange is the same as NEP but with an opposite sign.

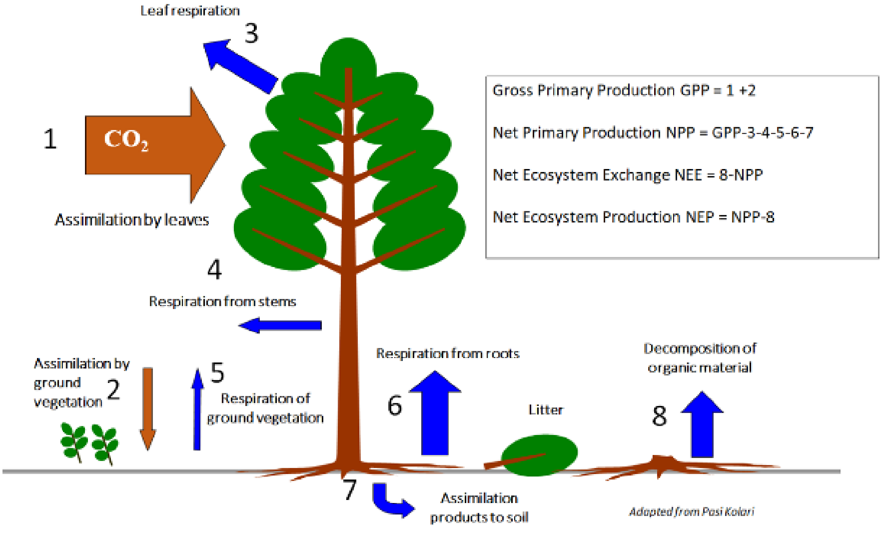


Figure 4. Primary production variables. The numbers in the figure refer to the box in the upper right corner.

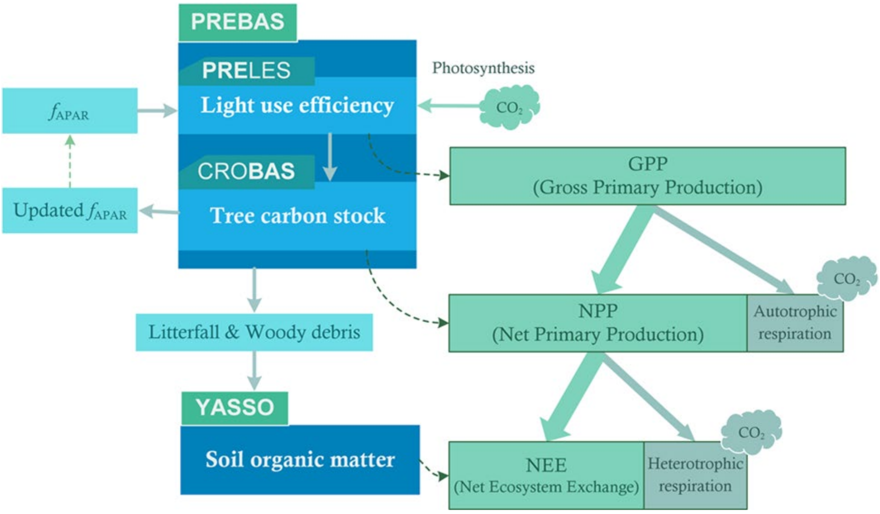


Figure 5. The three models used for the computation of primary production.

1.2.4 Organizational carbon balance

The organizational carbon balance builds on the previous service layers: forest structural variable estimation and carbon storage and fluxes, while adding one additional layer: the wood harvested from the forest and manufactured into wood-based products. Part of these additional fluxes are carbon emissions from execution of wood harvesting, transport, and manufacturing processes, including recycling. Another aspect taken into consideration with the wood-based carbon product storage is substitution of non-renewable materials with the renewable ones.

1.3 Technical development of the services

1.3.1 Processing workflow

Forest Flux processing workflow consists of seven subsystems each of which contains a set of processing steps and dedicated tools. The subsystems of the workflow are EO data procurement and pre-processing, computation of forest structural variable estimates, change detection, computation of forest ecology indicators, carbon flux computation, organizational carbon balance computation, and compilation of end products.

The core of the workflow, *i.e., the* subsystems and the tools that are needed for map production, are listed in Table 2. The subsystems were implemented in Forestry TEP. The exceptions were organizational carbon balance, insect damage mapping in Germany, tree seedling detection with VHR images in Madagascar, and some interactive processing for the images. They were implemented outside the Forestry TEP.

Forestry TEP software tools for the sub-systems were developed to a level that would enable automated service production. This would include updating existing Forestry TEP services, implementing already-existing software, or implementing completely new software modules on the platform.

The main input data for Forest Flux services are satellite images, field measurements, weather data, and user-specific wood lifecycle data. The Forest Flux production chain is able to take several remote sensing data sources. In the project, the main source for earth observation data was Sentinel-2 imagery. Software for processing of point clouds from airborne laser scanner and computation of spectral features from VHR satellite images were implemented on Forestry TEP in addition to software for Sentinel-2, Landsat and similar data.

1.3.2 Quality control and uncertainty assessment

Quality assurance concerned input data, production chain modules, as well as intermediate and final products (Table 2). The main sources for uncertainty were reference data for forest structural variables, insufficient correlation between forest variables and satellite data, geometric and radiometric errors in the satellite images, errors in other input data sets, and the uncertainty of the carbon flux models. The quality of the forest structural variables affects the accuracy of the ecology, biomass and carbon flux, and organizational carbon balance products.

Specific software was developed for the quality assurance of the forest structural variable estimates and category classifications. The tools divide reference data set randomly to training and test sets and compute uncertainty metrics using the test data set. Uncertainty is visualized on scatterplots. The test result can be downloaded from the Forestry TEP for further investigation.

Direct accuracy assessment of products requires an independent test set of reference data about target variables. In most cases, this kind of data is not available for biomass and carbon flux products. However, considerations on the reliability of the products can be made on the basis of the accuracies of the input data sets and the results of previous uncertainty analyses of PRELES, PREBAS (=PRELES+CROBAS) and YASSO models. The situation is otherwise similar for the organizational carbon balance products, but the results also depend on the reliability of silviculture, harvests, and transport input data.

Table 2. Steps of the principal Forest Flux processing chain. Steps that were implemented outside Forestry TEP are marked in *italics*.

Subsystem	Step	Tool	Input	Output	QA	Automation
EO data procurement and pre-processing	Acquisition and pre-processing of Sentinel-2 images	Search Fmask40 Envimon	AOI polygon	Pre-processed satellite images and cloud masks	Visual analysis of pre-processed images	High
	Mosaic compilation and AOI extraction	MosaicImages CropAndMaskImage-ByShape	Pre-processed images AOI polygon	Satellite image mosaic for the AOI	Visual analysis of the mosaic	High
	Compilation of true and false color images from Sentinel-2 data	*Interactive definition of look-up tables using ER Mapper software*	*Pre-processed satellite images*	*True and false color image maps*	*Visual analysis of the image maps*	Medium
	Compilation of true and false color VHR satellite images	*Pan-sharpening and interactive definition of look-up tables using ER Mapper software*	*VHR satellite images*	*Pan-sharpened true and false color VHR images*	*Visual analysis of the images*	*Medium*
	Visual interpretation of sample plots using true and false color VHR images	*GIS software*	*Pan-sharpened true and false color VHR images*	*Sample plot data set with land cover class proportions for the plots* *or delineation of areas subject to changes*	*Check of the output by another person*	*Low*
Computation of forest structural variable estimates	Selection and pre-processing of reference data	PlotGeoPackage2Shape TrainTestSplitGIS software	Reference data from the user or public sources	Reference data divided in training and test sets	Analysis of forest variable value distributions and their correlation with reflectance values	Low or medium depending on the reference data
	Forest variable estimation, forest mask computation	ProbaCluster ProbaModel	Pre-processed satellite images	Continuous forest variable estimates	Uncertainty assessment using uncertainty assessment set	Medium

Subsystem	Step	Tool	Input	Output	QA	Automation
		ProbaEstimates	Reference data for model training Reference data for uncertainty assessment Optional forest mask			
	Optional way for forest mask production from the result of ProbaCluster	*Rule-based classification, e.g., in ERMapper*	*Classification result from ProbaCluster* *Field reference data, visual image maps from Sentinel-2, VHR, GoogleEarth, or other available data*	*Forest mask*	*Uncertainty assessment using reference data collected from VHR satellite images*	Medium
From user	Computation of forest ecology indicators	WoodedAreaAndVariableDev WoodedAreaPatches TreeSpeciesDiversity	Forest cover maps Continuous forest variable estimates	Forest ecology indicator raster layers	Visual analysis and comparison of output and input layers	High
	Computation of the forest ecology change indicators	SubtractImages	Forest ecology indicator raster layers	Forest ecology indicator raster change layers	Visual analysis and comparison of output and input layers	High
Change detection	Computation of change features	AutoChange	Pre-processed satellite images Forest mask when available	Change features	Comparison of output to source and optionally to VHR images	High
	Forest cover change classification	AutoChangeHarvest GIS software	Change features	Change classification	Comparison of output to source and optionally to VHR images	Medium
	Cartographic generalization of forest change classification	SmallAreaFilter	Change classification	Change classification with cartographic generalization	Comparison of output to source and optionally to VHR images	High

Subsystem	Step	Tool	Input	Output	QA	Automation
Carbon flux computation	Computation of biomass, carbon storage and fluxes	PrimaryProduction	Daily temperature and precipitation, structural forest variable estimates	Biomass and carbon flux raster maps	Comparison of output to flux tower data when available	Medium
Organizational carbon balance computation	*Compilation of additional input variables*	*IPTIM Carbon*	*Additional input data from user (silviculture, harvest, transport etc.)*	*Additional input data in standardized format*		Low
	Organizational carbon balance computation	*IPTIM Carbon*	*Computed carbon and carbon flux maps, user-provided additional input data*	*Tabular data*	*Missing values in user-provided data introduce considerable uncertainty in results.*	High
Computation of end products	Computation of forest inventory raster maps	AddSumLayers CategoryProbabilities2Category ProductPostProcessing	Continuous forest variable estimates Cloud mask Forest mask	Forest inventory maps with numerical and color coding	Visual analysis	High
	Computation of forest inventory vector maps	ImageToGridShape ImageToStandShape	AOI polygon Stand vector data set Masked continuous forest variable estimates	Forest inventory vector maps	Visual analysis and comparison of output and input layers	High
	Computation of forest ecology indicator raster maps	ProductPostProcessing	Forest ecology indicator raster layers	Forest ecology indicator raster maps with numerical and color coding	Visual analysis	High
	Computation forest change raster maps	ProductPostProcessing	Change classification with cartographic gen. Cloud mask	Forest change raster maps	Visual analysis	High
	Computation of forest change vector maps	ImageToGridShape PolygonizeImage	AOI polygon	Forest change vector maps	Visual analysis and comparison of output and input layers	High

Subsystem	Step	Tool	Input	Output	QA	Automation
			Change classification with cartographic gen.			
	Computation of bio-mass and carbon flux inventory, monitoring and forecast raster maps	ProductPostProcessing	Biomass and carbon flux raster maps Cloud masks Forest mask	Biomass and carbon flux inventory, change and forecast raster maps	Visual analysis	High
	Computation of bio-mass and carbon flux inventory, change and forecast vector maps	ImageToGridShape ImageToStandShape	AOI polygon Stand vector data set Biomass and carbon flux maps	Biomass and carbon flux inventory, change and forecast vector maps	Visual analysis and comparison of output and input layers	High

1.4 Implementation of the production chain on Forestry Thematic Exploitation Platform

The tools implemented in Forestry TEP were integrated in one processing chain, using JupyterLab notebook and the Representational State Transfer (REST) Application Programming Interface (API) provided by Forestry TEP. The subsystems and the related tools were harmonized, *i.e.,* the inputs and outputs were defined so that the high level of automation in production was possible. New Forestry TEP software components were implemented if missing elements in the processing chain were identified. The remaining analyst-driven steps were mainly related to quality assurance.

The production system included the following components:

- Analyst web interface for map production using the REST API of Forestry TEP and JupyterLab Notebook workflow (https://jupyterlab.readthedocs.io/en/stable/).
- Workflow server – the JupyterLab backend counterpart for the analyst web interface, providing the actual code execution
- EO data processing and carbon flux computation components implemented on the Forestry TEP platform (http://f-tep.com)
- Organizational carbon balance computation service, which is produced with the IPTIM Carbon product of Simosol, was integrated to the carbon flux computation.

Forest Flux users could download the maps directly from Forestry TEP using web links. Written reports of the services were delivered via emails.

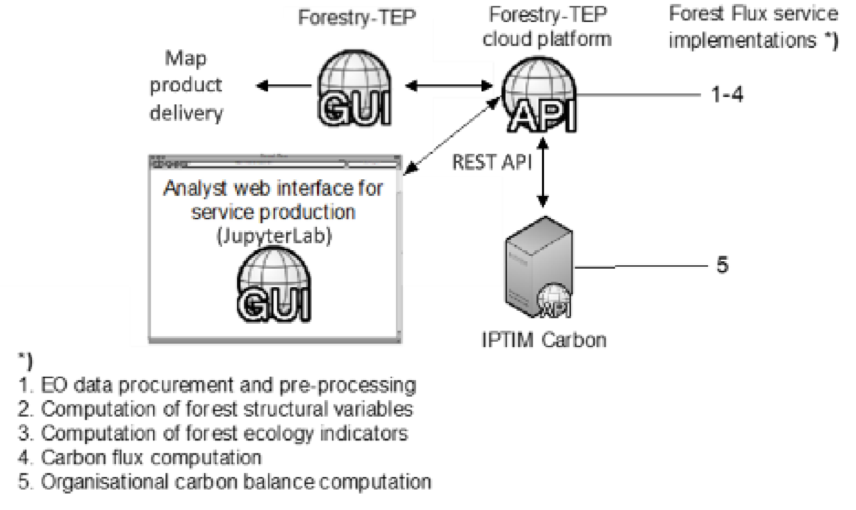


Figure 6. Forest Flux production system setup.

1.5 Demonstration

1.5.1 Service examples

Forest Flux pilot services were provided in two phases to nine core users in six countries. The contents of the pilot services were agreed on with the users in signed Service Agreements. In total, approximately 1,200 raster or vector maps were delivered.

Most users were interested in receiving maps of forest structural variables. Maps of the stem diameter, basal area, tree height, tree species proportions, and site fertility type were computed for all study sites except for the forest regeneration site, because they were also required for the computation of biomass, carbon flux, and organizational carbon balance. Forest variable values varied a lot between the pilot sites. Examples of the tree height and stem basal area maps in the Romanian, Finnish, and German pilot areas, shown in Figure 7 and Figure 8, illustrate the differences. The number of tree species also varied remarkably. In the Eucalyptus plantations, only one species was included in the estimation; in the Finnish area, three species groups were separated (Figure 9); but in the German site, the number of species in the reference data was seven.

The uncertainty of the forest variable estimates also varied depending on the area, EO data source, and on the availability and quality of the reference data. The relative root mean square errors (RMSE) were 29–55% for stem volume, 20–41% for stem basal area, 11–35% for tree mean height, and 11–41% for stem mean diameter when Sentinel-2 images and up-to-date sample plot data were used. The relative RMSE was computed by comparing the absolute RMSE to the mean of the variables in the test set. On the Finnish site, the RMSE for stem volume was 44%, using Sentinel-2 data only, and 31% after introducing additional airborne laser scanner data (Figure 10).

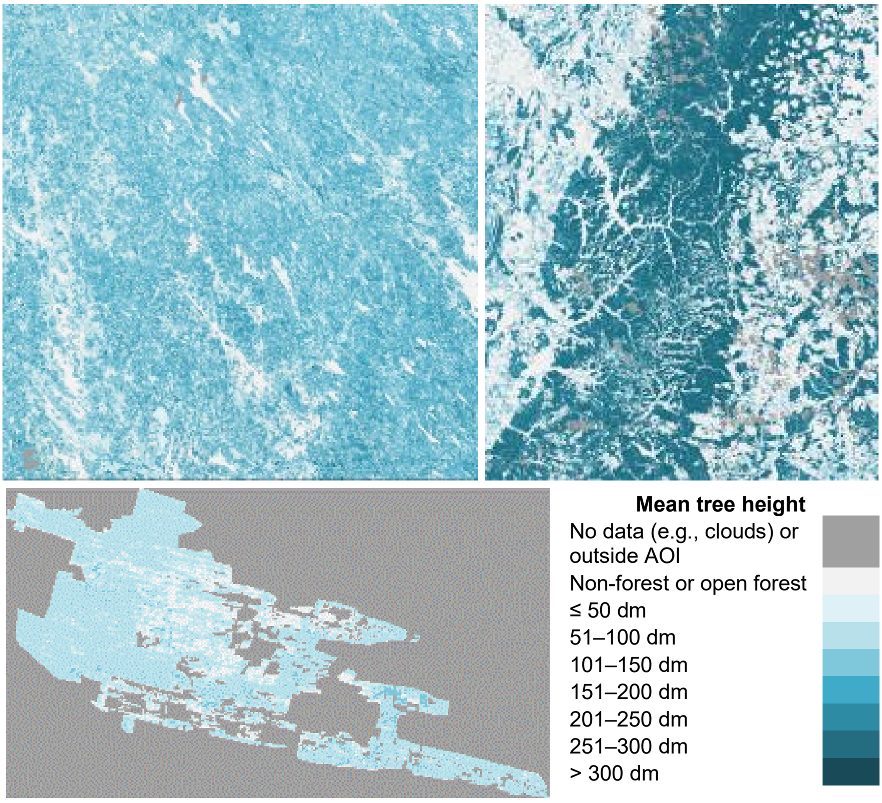


Figure 7. Map of estimated mean tree height in the in Finnish pilot area (on the upper left), German pilot area (on the upper right), and in the Romanian pilot area (on the lower left), using Sentinel-2 images. German site, area 90 km x 100 km. The Finnish site, area size 100 km x 100 km. For the Romanian site, area size 19 km x 10 km.

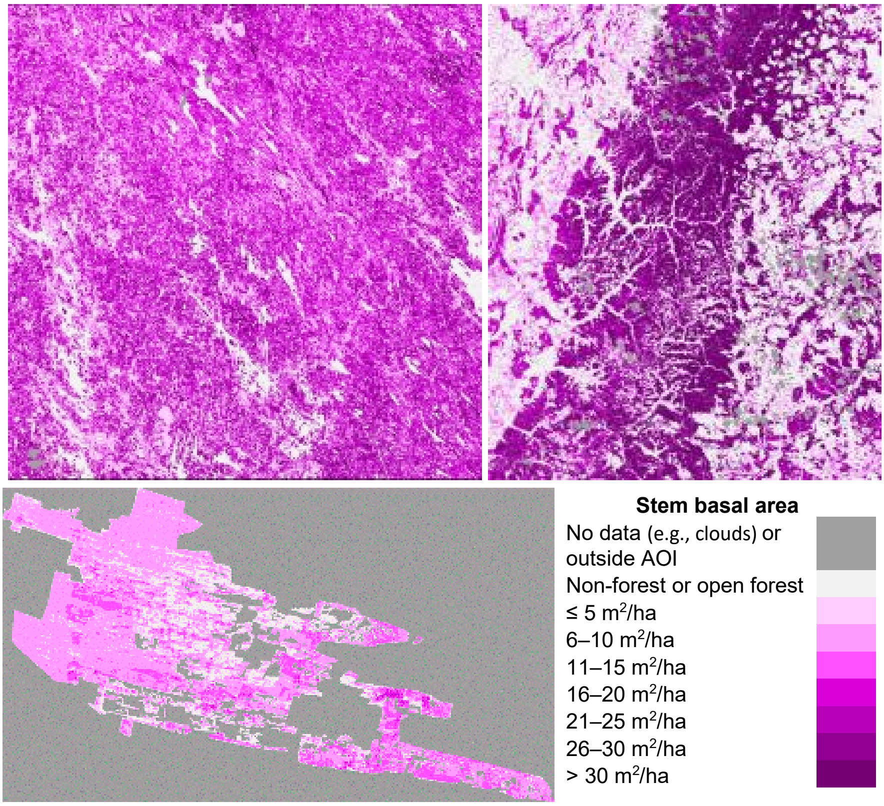


Figure 8. Map of estimated stem basal area in the in Finnish pilot area (on the upper left), German pilot area (on the upper right), and in the Romanian pilot area (on the lower left) using Sentinel-2 images. Area size 90 km x 100 km for the German site, 100 km x 100 km for the Finnish site and 19 km x 10 km for the Romanian site.

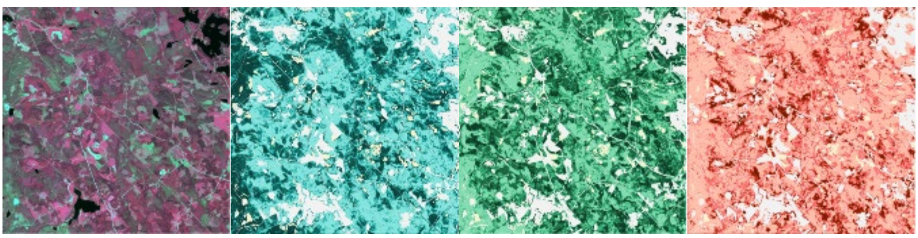


Figure 9. False color composite (on the left) of Sentinel-2 image from June 2019 in the pilot area in Finland and estimates of proportion of pine, spruce, and broad-leaved trees (from left to right). The darker color indicates higher proportion. Area size is 7.5 km x 7.5 km.

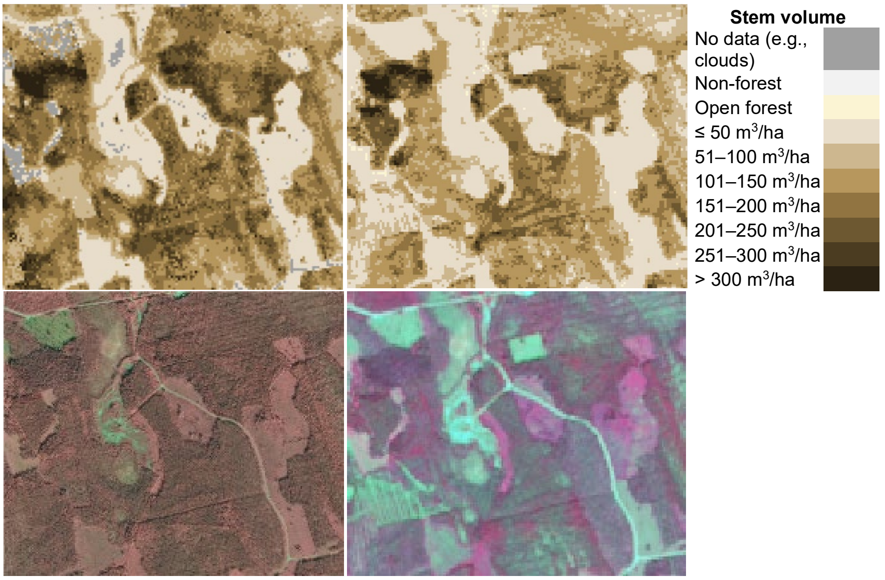


Figure 10. 1.4 km x 1.2 km are of stem volume estimates, produced using S2+ALS (up left) and S2 (up right) and corresponding area in 2019 Deimos VHR image and 2020 Sentinel-2 image.

Very High Resolution (VHR) satellite images were applied in three pilot areas in addition to the Sentinel-2 data. VHR images proved to be useful in the crown cover estimation in a Portuguese site (Figure 11) and locating tree seedlings in Madagascar (Figure 12).

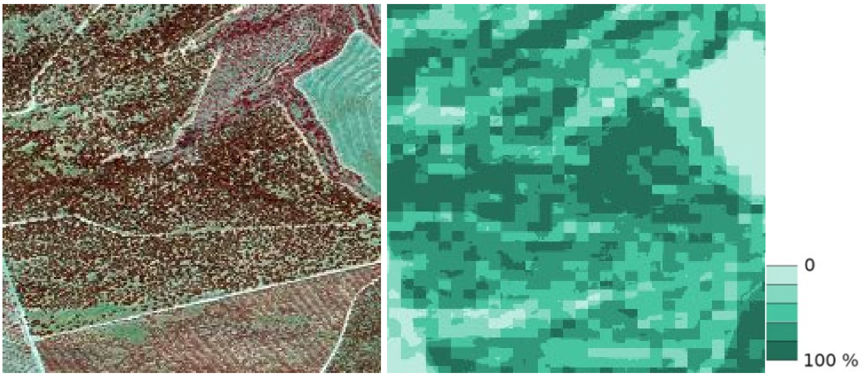


Figure 11. Extract of the crown cover map computed using very high resolution satellite imagery in the pilot area in Portugal. On the left, false color composite of GeoEye-1 image, acquired 30.6.2020; and on the right, the crown cover estimate computed using the image. The size of the area is approximately 800 m x 850 m.

Figure 12. Example of tree map from the pilot area in Madagascar. Pan-sharpened color infrared images from Worldview-2 (left) and the resulting remotely sensed tree cover map (right). Blue lines show the stand boundaries.

Forest change maps on forest harvests and forest cover change were computed from most of the pilot areas. The main source data set was Sentinel-2 (Figure 13 and Figure 14). In the German pilot area, VHR satellite images were used for detection of insect damage (Figure 15).

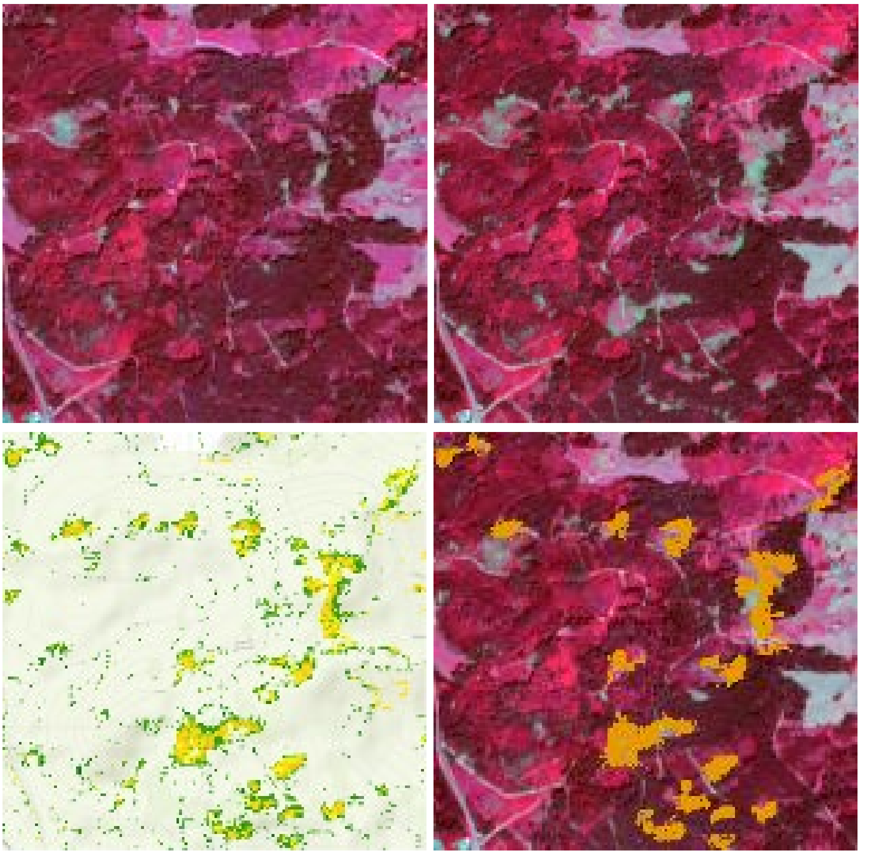


Figure 13. Images on the upper row show false color composites of Sentinel-2 satellite images from Southern Germany, acquired 18.8.2019 and 7.8.2020. The lower left image shows the intermediate product of change analysis applied to the images: change magnitude for the areas where change type indicates biomass decrease. Green color means low change magnitude, yellow color is intermediate, and red color is high change magnitude. In the image on the lower right, the detected changes, whose area exceeds 0.5 ha, have been marked with orange color.

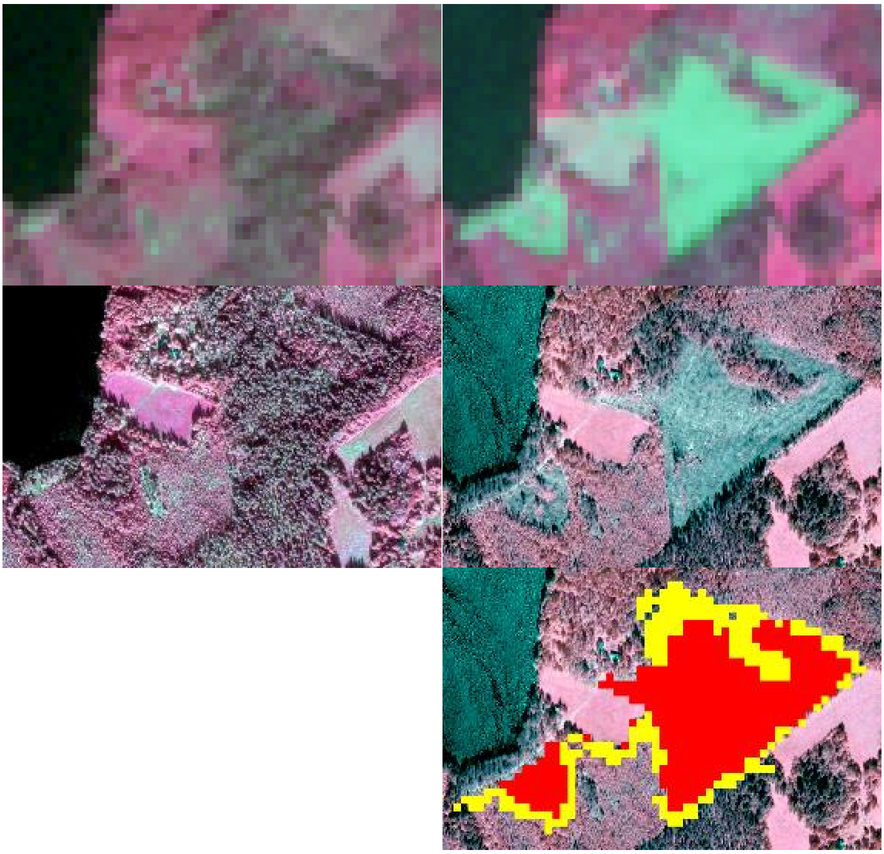
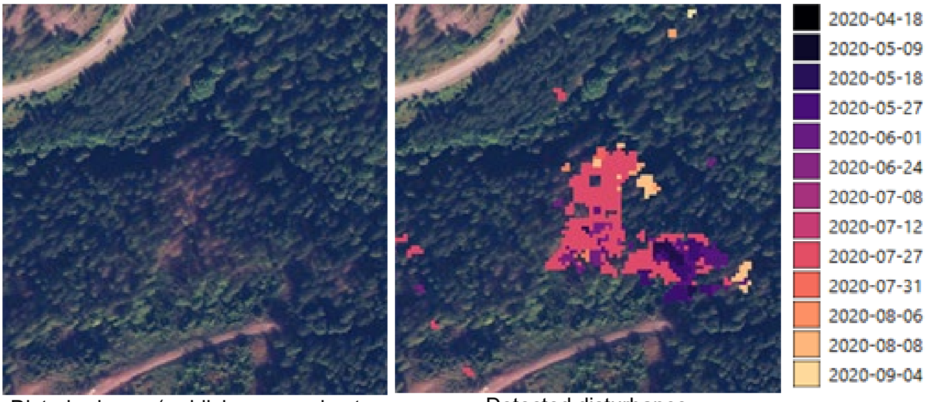


Figure 14. On the upper row, false color composites of Sentinel-2 images from 2019 and 2020 in the pilot area in Finland. In the middle row, Pleiades false color composites, from 26.8.2019 and 25.6.2020. On the bottom row, changes detected from Sentinel-2 overlaid on the Pleaides image from 2020. Red color indicates clear cut and yellow color thinning or other changes with smaller magnitude. The size of the area is 370 m x 570 m.



Disturbed area (reddish crowns due to bark beetle infestation)

Detected disturbance

Figure 15. Example of the disturbance detection using VHR satellite images in the German pilot area in 2020. Disturbance layer overlaid on WorldView-3 VHR data, from September 9, 2020. The colors in the legend indicate the date of the change.

Forest ecology products were computed using the forest structural variable maps. These products were provided from two pilot areas in Portugal and in Finland (Figure 16).

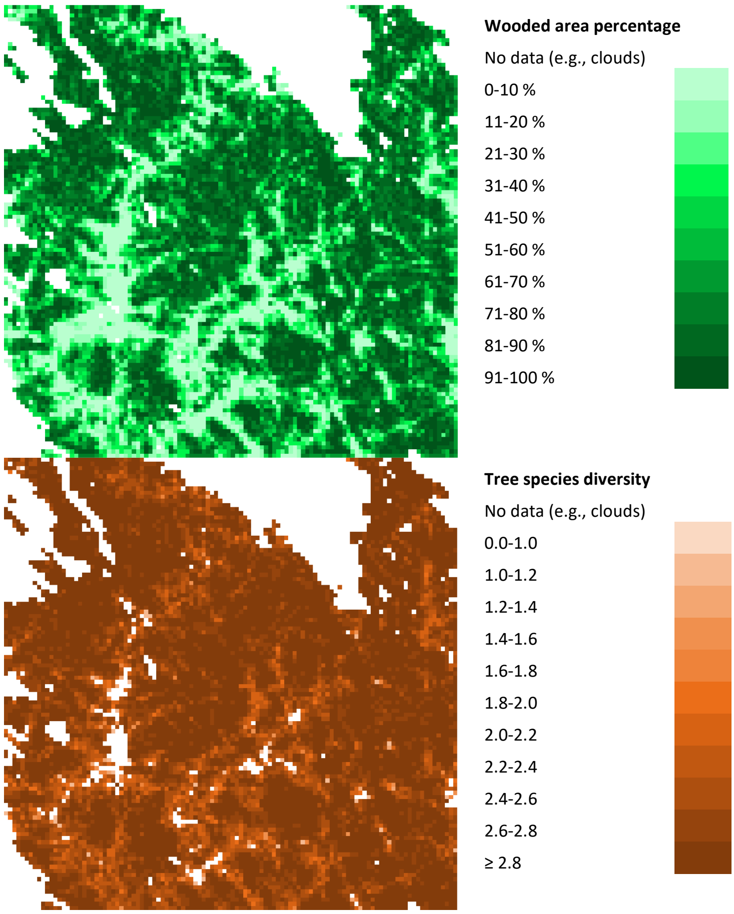


Figure 16. Examples of forest ecology inventory maps: wooded area percentage within 1 km^2 cell and tree species diversity map showing the average number of tree species in the cell. Finnish site, 100 km x 100 km.

Biomass and carbon flux maps were provided from most of the pilot areas. The maps included estimates of biomass, carbon storage, or carbon flux for a certain target year (Figure 17, Figure 18, Figure 19, Figure 20). Flux change maps provided the change of the estimates between years, and forecast products showed predictions for the future development of the carbon fluxes. The accuracy of the carbon flux products could not be tested directly for the pilot areas, because reference data was not available. However, information was available on the performances of flux models from an earlier comparison of the model outputs with flux tower data.

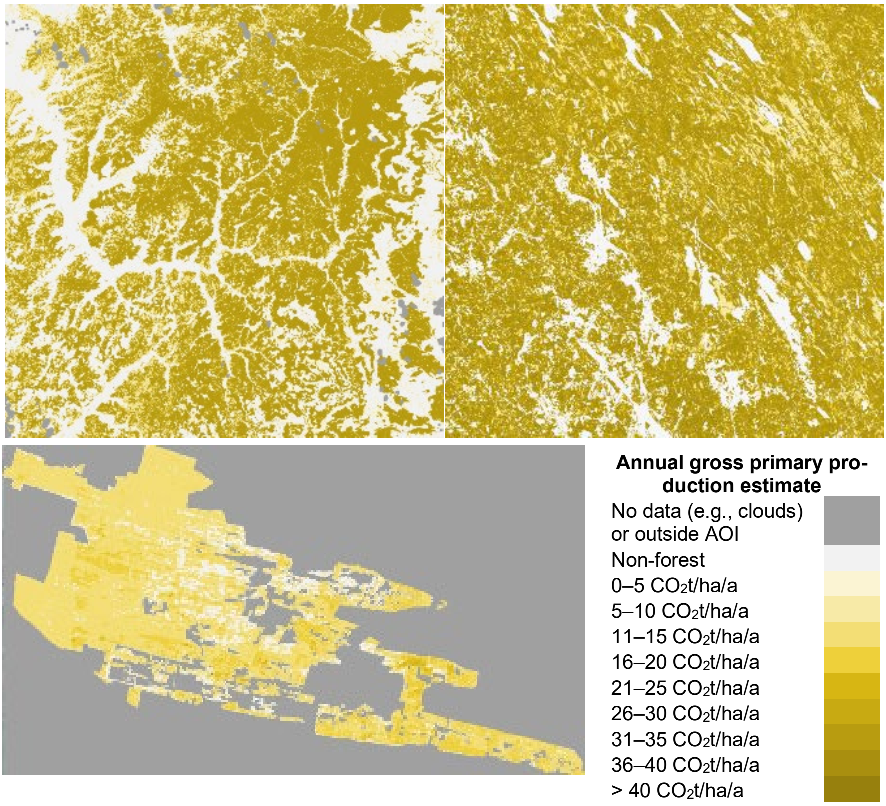


Figure 17. Examples of gross primary production (GPP, carbon assimilated by green plants per unit time and unit area, expressed in CO_2 equivalents) estimates in the German (upper left), Finnish (upper right), and Romanian (lower left) pilot areas. Area size 40 km x 40 km for Germany, 50 km x 50 km for Finland and 19 km x 10 km for the Romanian site.

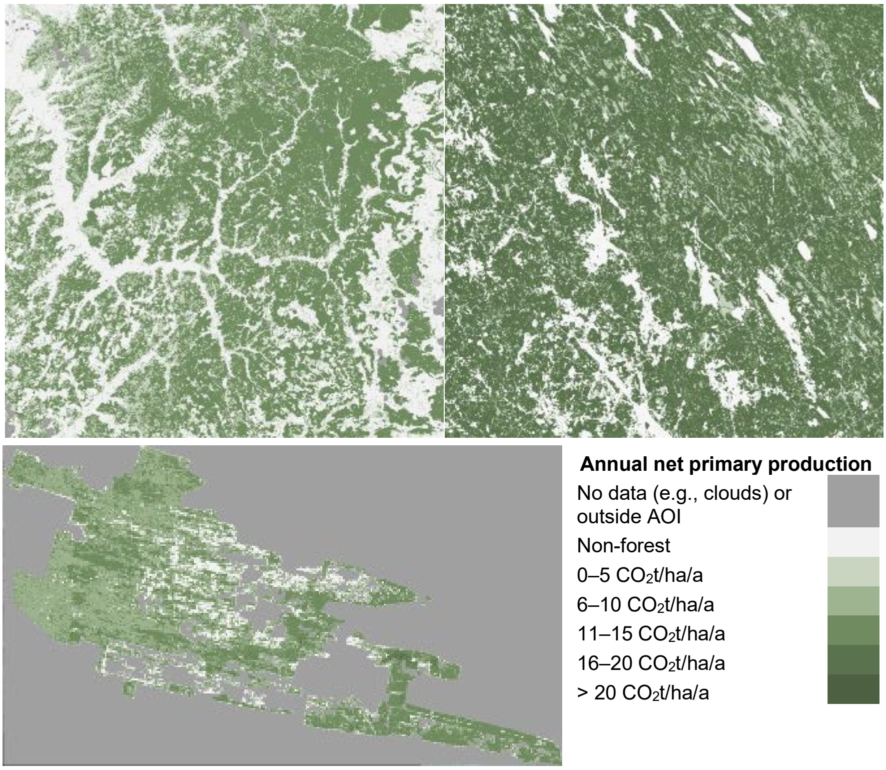


Figure 18. Examples of net primary production (NPP, Carbon used in new plant biomass production per unit time and unit area, expressed in CO_2 equivalents) estimates in the German (upper left), Finnish (upper right), and Romanian (lower left) pilot areas. Area size 40 km x 40 km for Germany, 50 km x 50 km for Finland, and 19 km x 10 km for the Romanian site.

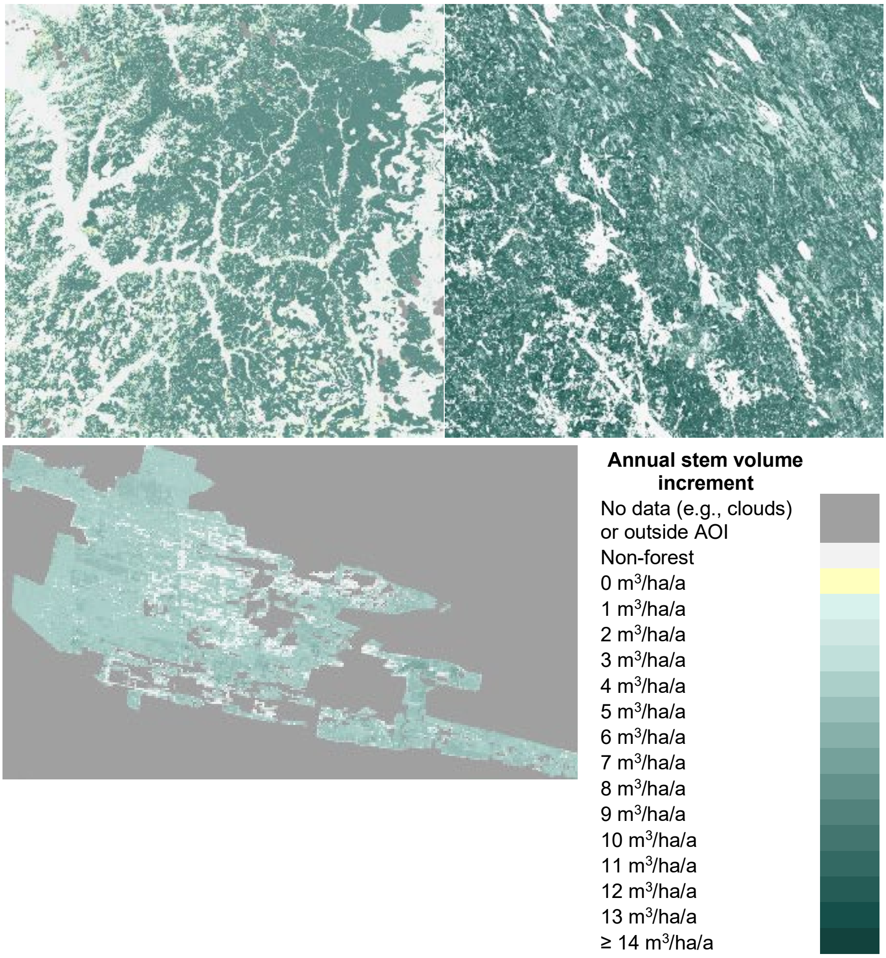


Figure 19. Examples of estimates of annual stem volume increment (net primary production allocated to tree stem growth and measured in change of stem volume in the German (upper left), Finnish (upper right), and Romanian (lower left) pilot areas. Area size 40 km x 40 km for Germany, 50 km x 50 km for Finland, and 19 km x 10 km for the Romanian site.

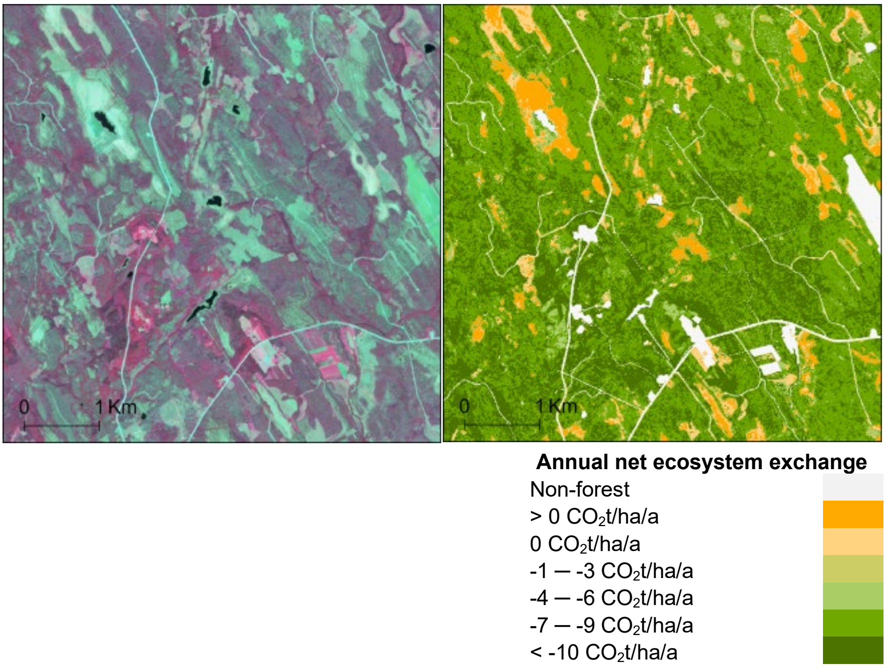


Figure 20. False color composite of Sentinel-2 images (on the left) and Net Ecosystem Exchange (NEE, Net amount of carbon released from an ecosystem into the atmosphere per unit time and unit area, expressed in CO_2 equivalents) in 2020 (on the right) in the pilot area in Northern Karelia. Area size is about 5 km x 5 km.

1.5.2 User feedback

1.5.2.1 Private forest owners

Private-forest-owning companies and forest industry found that Forest Flux products could complement their existing businesses by, for example, providing a useful check of existing operations. However, the Forest Flux products in their current stage of development did not replace their present information sources for forest management. The Forest Flux services need ground reference data for the analysis of satellite or airborne data. A complete replacement of ground reference data is consequently not realistic. The users were strongly interested in high-quality products, in particular forest change information, as this may lead to cost savings and improved timeliness for forest management and planning. Information on carbon was, in principle, of great interest. Carbon mapping was considered to have the largest commercial potential among the users of the project.

Currently, the *private forest owner users* did not consider direct use of the Forest Flux products very likely. However, checking the accuracy of forest inventory and monitoring of forest cover changes was seen as useful. The users stated a strong interest in carbon information, but did not have the means of monetizing it, because forest carbon certification is still an ongoing political discussion in Europe. The reputational benefit of carbon information was not seen to be at the same level as with some of the other users. This benefit is already partially captured via certification (for example, FSC certification) and the marginal gains from Forest Flux could be relatively small.

Public forest users of the Forest Flux project had access to free forest inventory data provided by the state. This reduced their interest in commercial services, although they gave a positive assessment. They expressed interest in the carbon information but did not have any plan in its monetization.

The *science user* ICOS had very different uses for Forest Flux services compared to the other users. Forest inventory and monitoring information was not considered directly relevant, whereas their interest was in the carbon flux products. ICOS and similar organizations could be significant users of Forest Flux services, but it would require a public financing body.

A *developing aid organization* could see a strong potential for the Forest Flux inventory products and forest change products. For instance, in challenging conditions of forest regeneration sites, the Forest Flux approach can offer a cost-effective approach for the monitoring of the success of plantation.

1.5.3 Cost benefit summary

Many users saw potential in the Forest Flux services. However, several users would also require improved accuracy for forest inventory products, but some reported accuracy improvement compared to the present information. The present inventory methods were often based on field inventories and provided consequently accurate data. This means that the satellite-image-based information should be offered at a very low cost. Airborne Lidar data was used together with Sentinel-2 data on one site, which improved accuracy in forest inventory products. Such data is not, unfortunately, available from most global locations. Another means for accuracy improvement is using very high resolution commercial data, as on some sites of Forest Flux. Their main benefit may be in tree species and crown cover estimation and improvement of spatial details.

Most users reported that their costs for integrating Forest Flux information into their forest management systems were relatively low. Provision of reference data for the project did not require any significant effort for the user, either.

Carbon information was universally regarded as beneficial. However, none of the pilot users could specify how they will realize a profit from this information, and no users have an established method for converting carbon flux information into sellable carbon credits. In summary, carbon is of interest, but the market is still missing.

Several pilot users requested that future services should increase focus on updating forest inventory regularly and including pests and other unforeseen damage.

Based on the user feedback, the current marketable options for Forest Flux products are as follows:

- Forest inventory and change products aimed at private-sector forest owners and development agencies – in particular, for countries and regions where forest inventory information is less developed.
- Pest and disease mapping would have a wider interest for several user groups.
- Demand for forest carbon product will certainly increase as the regulations around forest carbon certification become more established. Carbon flux products should be tailored to fit the requirement of carbon certification.
- Provision of information on biomass and carbon flux for scientific users through institutional support and public funding.

2. Exploitation and outreach

2.1 Market development

The overall motivation of the Forest Flux project was to utilize Copernicus Earth Observation information to develop commercial products and services that enable customers to improve the profitability of forest management and to provide cost-efficient information services. Forest flux is a first-of-its-kind service of high-resolution maps for the forest inventory, forest monitoring, and forest carbon fluxes and storage at present and over time.

A business plan was prepared as a key deliverable of Forest Flux. A summary of it is shown in Table 3.

Table 3. Business plan key elements.

Forest Flux Project Business Plan	
Identity *Forest Flux provides high-quality Earth Observation Services to improve forest management and accurately monitor forest carbon fluxes.*	**Problem** *Reduce inefficiency of traditional forest inventory, improve reliability and timeliness of EO-based forest information services.*
Our solution *Implementing a world-first service of high-resolution maps of forest carbon fluxes, storage, and their development over time.*	**Target market** *While the products are open to a wide range of customers, the target markets are private forest owners and forest investors (including impact investors).*
Competition *Public-sector research entities and private service companies, with variable technological approaches: (1) traditional forest inventory services, (2) large-scale EO technologies, and (3) cutting-edge remote sensing technologies for small- to medium-scale inventories.*	**Revenue streams** *Sales of Forest Flux products to private forest owners and forest investors or larger commercial companies looking to reduce their carbon footprint.*
Marketing activities *The dissemination and communication activities include stakeholder events, bilateral communication, meetings workshops and conferences, as well as web and social media outlets.* *Marketing will occur directly through the client networks of participating companies.*	**Expenses** • *Production, distribution, and design development* • *Business operations and marketing* • *Forestry TEP* • *Consulting* • *Product update and maintenance of products*
Team and key roles • *Commercial partners (Unique land use and AFRY/Simosol)* • *Consulting and development partners (VTT, University of Helsinki, University of Lisbon).* • *Forestry TEP platform (VTT)*	**Milestones** *Short-term objectives are establishing a client base and transition to a for-profit business.* *Medium-term objective includes a higher profitability and growth of the client base.*

2.2 Outreach

The outreach activities of Forest Flux included dissemination as a one-way delivery of information and communication as a dialogue. We did not consider these two ways of outreach completely separate or alternative activities, because, ideally, dissemination quickly turns to communication.

Ten audience groups were identified as listed below. All of them, except 'Broad public', include potential commercial users of Forest Flux services. Our core users covered the groups that are in bold on the list. The dissemination, targeting the broad public, was considered important, because it can reach members of the potential users and political decision makers who make regulations that can positively affect the service potential.

1. **Private forest owners,**
2. **Forest and wood industry,**
3. **Forest and wood industry,**
4. **Forest service enterprises,**
5. Forest investment and insurance sector,
6. Governmental bodies,
7. International regulative bodies,
8. NGO's,
9. **Scientific users,**
10. Broad public

The main interaction with the core users was bilateral communication, including meetings and workshops in which the service needs and feedback from the conducted services was discussed. The Covid-19 pandemic closed many public activities for outreach during most part of the Forest Flux project. Possibilities to physically attend professional and scientific events were consequently limited, unlike the writing of scientific papers and using social media tools (Table 4).

The scientific community is unlikely to become a major commercial customer, but it is very important in raising awareness of the Forest Flux services and achieving acceptance to their credibility.

Table 4. Dissemination and communication activities by audience category.

Audience category	Bilateral communication	Meetings & workshops	Trade shows	Professional & scientific journals	Flyers, posters	Web & social media	Mass media
Core users	✓	✓	(✓)	(✓)	(✓)	(✓)	(✓)
Potential users	✓	✓	✓	✓	✓	✓	✓
Science users	✓	✓		✓		✓	
General public					✓	✓	✓

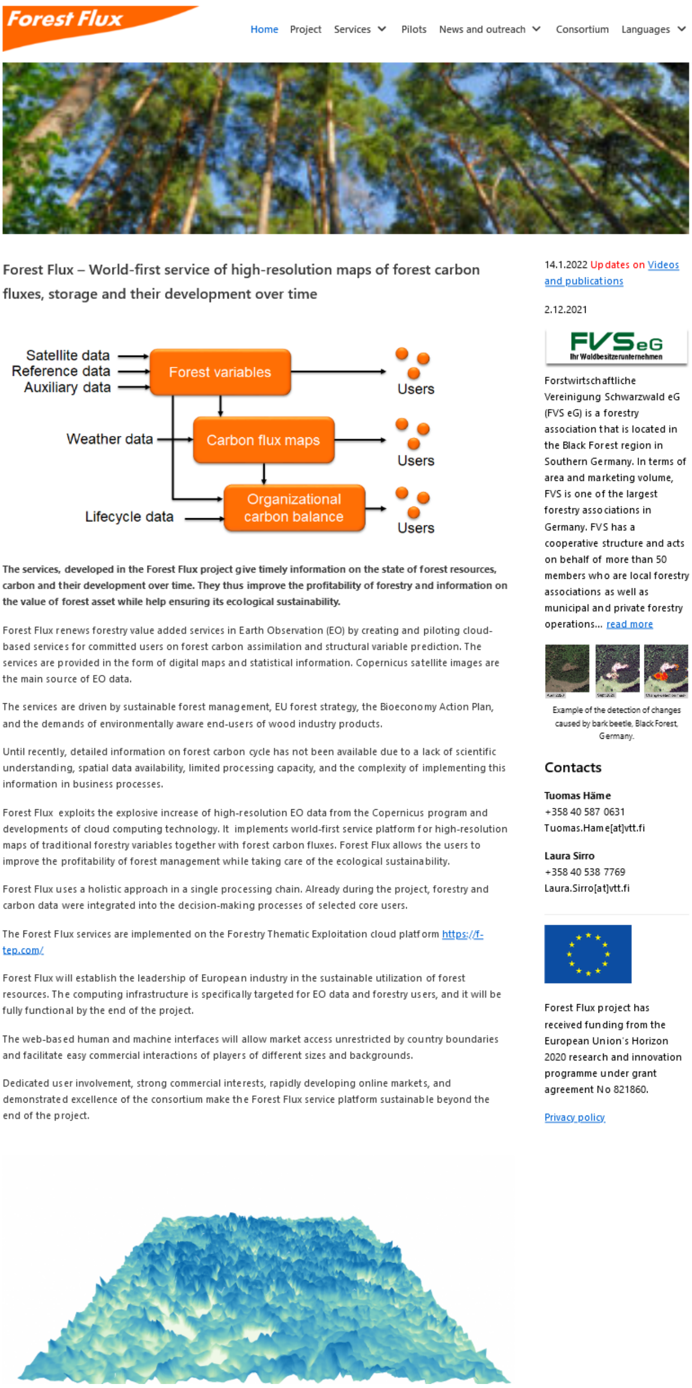


Figure 21. Front page of the Forest Flux website.

Attendance in professional and scientific events, social media, and dissemination through web pages were central activities in the early project phases, before the delivery of the first pilot services (Figure 21). Preparation of the Service Agreements with the core users required intensive communication with them. User feedback from the pilot services was a major information source to further develop the ways to handle the outreach.

A project partner that had a close relationship with a particular user was named as being responsible for the communication with this user. The partner was in charge of direct contact with the user, analyzing user requirements, presenting the service offering, support for identifying the required services, concluding the service agreement, and collecting feedback.

The outreach activities ranged from a shallow linkage with a broad community (press releases) to more detailed discussions with key users (workshops), to directly working with the users to build a service (the pilot projects) (Figure 22). This approach ensured involvement of a large audience for the dissemination.

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Meetings and workshops serve actors that are already true or prospective users of the services. The meetings varied from events for forestry professionals to research symposia. Particular attention was paid to forestry communities that are not part of the remote sensing community. All the core users represented the non-EO community.

Five scientific papers were published during the project: (Häme et al., 2021, 2020; Mäkelä et al., 2020; Tian et al., 2021, 2020).

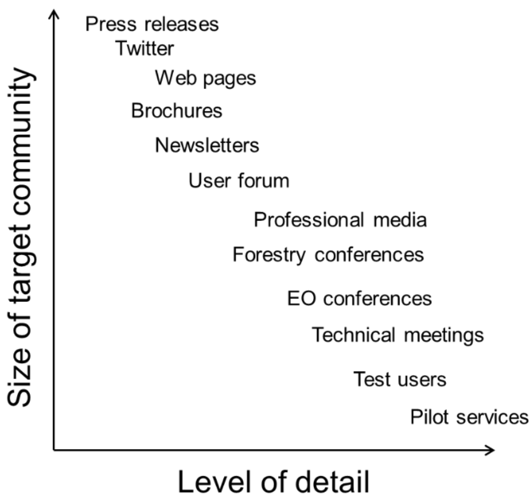

Figure 22. Means of outreach with respect to target community size and detail of information delivered.

3. Socio-economic impact

The socio-economic impact of Forest Flux was analyzed from the viewpoints of business opportunities, economy and employment, ecology, and ecosystem sustainability (Table 5).

Overall, the services developed in Forest Flux support better forest management by providing up-to-date information on forest resources, carbon, and their dynamics. Such information has a positive socio-economic importance for all stakeholders. Improved timeliness of forest resources information reduces risks and costs in forest management and investments increasing profitability. Versatile variables that include information on forest diversity at high spatial detail help to balance the conflicting requirements for forestry. When the information and the processes to produce it are made transparent, it can help the whole society to adapt to climate change, while understanding the business viewpoint.

Remote-sensing-based services for forest resources and carbon are foreseen to generate more jobs and new businesses for Europe. It is possible to build a complete service ecosystem around the Forest Flux theme.

The potential negative socio-economic effects are considered few. The field staff may be reduced along improving the remote-sensing monitoring technique. Some forest owners or countries could find the possibility to monitor their forest resources and carbon by third parties in a negative light. For instance, the pressure for increased forest conservation based on the remote survey results could be considered unfair.

Table 5. Overview of the socio-economic impact of Forest Flux.

User type	Socio-economic impact		
	Business	**Economy and employment**	**Ecology and ecosystem sustainability**
Private forest owners	- Up-to-date and versatile information improves business alternatives and predictability. - Forest management planning becomes more effective. - Increased pressure for conservation could restrict business.	- Better-known asset value improves economic stability, better-informed decisions. - Transfer of staff from field to office in the longer run - For large forest owners, improved shareholders trust and willingness to invest	- Versatile information with high spatial detail supports better consideration of ecological values and adaptation to increasing regulations. - Supports strive for carbon-neutral economy.
Forest and wood industry	- Improved information on available raw wood decreases wood supply costs. - For the forest-owning industry, the same as with private forest owners	As with private forest owners	As with private forest owners
Public forest enterprises	As with private forest owners	- Better information improves economic stability. - Other impacts as with private forest owners	As with private forest owners, but the regulations likely affect more than on the private sector.
Forest service enterprises	- Improved focusing of marketing - More effective field work	- Improved profitability of the company - More jobs	Ecological values can be considered better in fieldwork due to spatially detailed information.
EO service enterprises	- Market expansion to carbon resources - Forest Flux service entity improves offering	- -Improved profitability of the company - More jobs	Offering can be extended to ecological values due to spatially detailed information.
Forest investment and insurance sector	- Information on forest asset value reduces investment risks and thus improves profitability - Support for forest management	Up-to-date information on asset value, a prerequisite for investments and for reporting to shareholders	Ecological information fulfills shareholder requirements.
Governmental bodies	Forest Flux tools can support regional and national forest surveys.	Support to national reporting on forest resources and greenhouse gases	- Easier to fulfill international regulations - Support to regulation formulation through ecological information
International regulative bodies	Not relevant	Versatile information on forests supports consideration of economic effects of planned regulations	Information on ecological state of forest at national to continental levels
NGOs	Transparent versatile information on forests helps operation of the NGOs.	- More jobs	Fact-based information on forest ecological state

User type	Socio-economic impact		
	Business	**Economy and employment**	**Ecology and ecosystem sustainability**
		- Political influencing can be fact-based.	
Scientific users	Not relevant	- EO science: projects and funding for further method development - Forest and environmental science: spatially explicit and detailed information source	Improved information helps to take ecological values better into consideration while practicing forestry.
Broad public	Not relevant	- Transparent information on forest resources and ecology can support public opinion to better understand forestry thus influencing political decisions	See beside

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Series title and number

VTT Technology 403

Title	**Forest Flux** Final Report
Author(s)	Tuomas Häme, Laura Sirro, Lauri Seitsonen, Yrjö Rauste, Matti Mõttus, Jukka Miettinen, Matthias Dees, Lincoln Davis, Fernando Rossi, Juho Penttilä, Markus Auvinen, Jussi Rasinmäki, Annikki Mäkelä, Francesco Minunno, Xianglin Tian, Gheorghe Marin, Marius Dumitru, Margarida Tomé & Susana Barreiro
Abstract	The overall objective of the Forest Flux (forestflux.eu) project was to foster the development of the Copernicus Earth Observation (EO) market and improve the profitability of forest management by implementing a world-first service of high-resolution maps of forest carbon fluxes, storage, and their development over time, using satellite imagery and associated data. The services were offered from the same process of data refinement. In this process, the outputs of the previous phase were inputs to the next phase. The earlier phase outputs were also products that were delivered to the users. Forest Flux services were implemented on the scalable Forestry TEP cloud platform that enables integration of the Forest Flux products with the business processes of end users. The services are available via an Internet connection. Computed products were mostly digital maps with supporting quantitative figures, such as statistical data on uncertainty. They were provided for nine user organizations and sites in Europe, South America, and Africa. In total, approximately 1,200 map products were delivered. Forest Flux project received funding from the European Union's Horizon 2020 Research and Innovation program under grant agreement No 821860.
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Commissioned by	VTT and EU
Keywords	
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Forest Flux
Final Report

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