MULTI-SENSOR MONITORING AND ASSESSMENT OF FOREST RESOURCES: SUPPORTING A FOREST OBSERVATION SYSTEM FOR SIBERIA

Christian Hüttich(1), Jonas Eberle(1), Christiane Schmullius(1), Sergey Bartalev(2), Kirill Emelyanov(3), Mikhail Korets(4), Anatoly Shvidenko(5), Dmitry Schepaschenko(5)

(1)Friedrich-Schiller-University Jena, Germany; Email: christian.huettich@uni-jena.de, jonas.eberle@uni-jena.de, c.schmullius@uni-jena.de,
(2)Space Research Institute Moscow, Russian Federation, Email: bartalev@d902.iki.rssi.ru,
(3)Joint Stock Company Moscow, Russian Federation, Email: eks@ntsomz.ru,
(4)Sukachev Institute of Forest Krasnoyarsk, Russian Federation Email: mik@ksc.krasn.ru,
(5)International Institute of Applied System Analyses, Laxenburg, Austria, Email: shvidenk@iiasa.ac.at, schepd@iiasa.ac.at

ABSTRACT

Above ground biomass - one of the considered Essential Biodiversity and Climate Variables (ECV, EBV) - is an important structural parameter describing the state and dynamics of the Boreal zone. More than 50 % of the Russian forest inventory has been updated more than 25 years ago. The consequence is that most of the existing forest inventory is obsolete. Moreover, human and environmental forest disturbances continuously affect changing forest cover and biomass levels. The magnitude and extent of ongoing environmental pressures (e.g. forest fragmentation and the impact of global climate change) and the loss rates of particular habitat types is not known so far. The ZAPÁS project and the Siberian Earth System Science Cluster (SIB-ESS-C) are aiming to provide standardized and validated forest resource geo-information products. In-situ and multi-agency satellite data are analysed in the framework of the EU-Russia Space Dialogue. At local scales biomass and forest cover change maps are generated and validated with up-to-date forest inventory data. At regional scales a synergy map of land cover and biomass information is developed to be used to improve a full terrestrial carbon accounting for Central Siberia.

1. MULTI-SCALE ASSESSMENT AND VALIDATION OF CENTRAL SIBERIAN FOREST MAPS

Looking at the large-scale distribution of the Siberian Taiga, the systematic monitoring of forest dynamics is still challenging. Satellite earth observation is the only alternative for a frequent monitoring of biomass-decreasing processes such as clear cutting, selective logging, fire, insect infestation, but also afforestation and forest succession processes [1] .

Important research needs have to be addressed for future improvements on carbon accounting by implementing timely earth observation data and improving the spatial resolution of the model input parameters, as stated by Dolman et al. [2]. The application of SAR systems in combination with the multidimensional system of forest biomass structure is a crucial tool for updating obsolete forest inventories and forest regrowth after disturbances [3]–[5]. The development of spatiotemporally more detailed and accurate biomass maps including land use and land cover change information is a pre-condition for more accurate carbon accounting and net primary production assessments. SAR data are being delivered spatially consistent at continental [6], pan-boreal [7] or global scale, as proposed by the JAXA (K&C) and ESA (GlobBiomass, [8]) space agencies for delivering future forest and biomass monitoring at global scales. Hence, is a need for inter-comparison and (cross-) validation assessments of independently derived biomass map products.

Satellite-based multi-source forest resource assessment is one of the tasks in the framework of the ZAPÁS project [9] aiming to:

- Foster integrated concepts for forest characterization based on remote sensing (Fig. 1), and to
- Assess the spatial agreement, accuracy, and transferability of forest resource maps for large area forest management purposes.

The ZAPÁS initiative particularly aims to overcome existing gaps of inadequate data integration and inter-operability as stated as one of the targeted gaps by GEO [10]. In the context of operational remote sensing, ecosystem monitoring, and forest resource assessment,

Proc. 'ESA Living Planet Symposium 2013', Edinburgh, UK
9–13 September 2013 (ESA SP-722, December 2013)

important research questions arising are: How comparable are SAR derived biomass datasets at different scales, derived with different SAR systems and modelling approaches; and thus, how operational are state-of-the-art GSV maps for large scale forest management purposes?

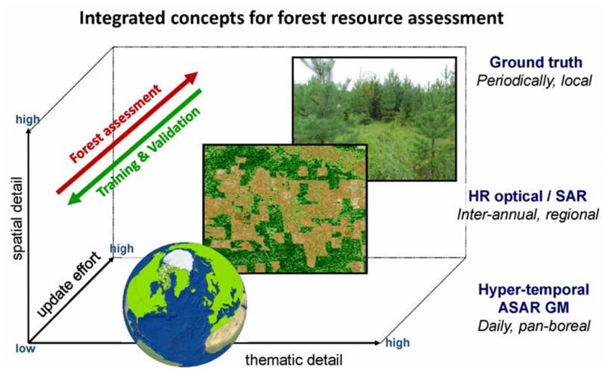


Fig 1: Integrated concept for forest resource assessment and forest geo-information cross validation to be implemented by the ZAPÁS project. (adapted from [11]*).*

One of the key perspective goals of the ZAPÁS initiative is to overcome still existing uncertainties in forest resource assessment and forest growing stock volume mapping and carbon accounting.

2. DATA AND METHODS

2.1. Synergistic ESA-ROSCOSMOS Satellite data base

Optical and SAR imagery are acquired basically from ESA and ROSCOSMOS archives (including the ESA Third Party missions of NASA and JAXA) used in a synergistic manner by (1) enhancing the data acquisition by involving the national space agency contacts and (2) combining optical and SAR high and VHR imagery with time series for local and regional scale biomass, forest cover, and forest disturbance mapping.

MODIS time series data are used for the generation of an improved Central Siberian land cover database. Hyper-temporal ENVISAT ASAR imagery is used for regional scale biomass mapping by applying the BIOMASAR algorithm [4]. A reference database was generated in high-priority areas selected by Siberian forestry enterprises of Krasnoyarsk Kray and Irkutsk Oblast. These areas also define the local mapping test sites. By involving recently updated forest inventory data (e.g. growing stock volume, species composition on forest stand level) SAR data is being used for high resolution biomass, forest cover and disturbance, and forest regrowth mapping. Additionally, optical high resolution imagery is used for validation purposes. An overview of the sensors used in the ZAPÁS project and their specifications is given in [12].

2.2. Regional scale forest resource assessment

2.2.1 Land Cover

A Land cover and a forest species map with 250 m spatial resolution (Fig. 2) was developed using time series of spectral reflectance composite images acquired by the MODIS sensor, corresponding to different seasons of the year. Various land cover classes are identified based on the dynamics of their biophysical characteristics, which is reflected in their multi-spectral and multi-temporal class signatures [13]. For the classification of MODIS (MOD09A1) data, composite images for spring (15 April — 15 June), summer (15 June — 15 August), autumn (15 August — 15 October) and winter (1 November — 31 March) seasons of 2010 were generated and classified using the LAGMA approach [14]. The tree species mapping has been performed based on analysis of forest cover reflectance dynamics during the growing season.

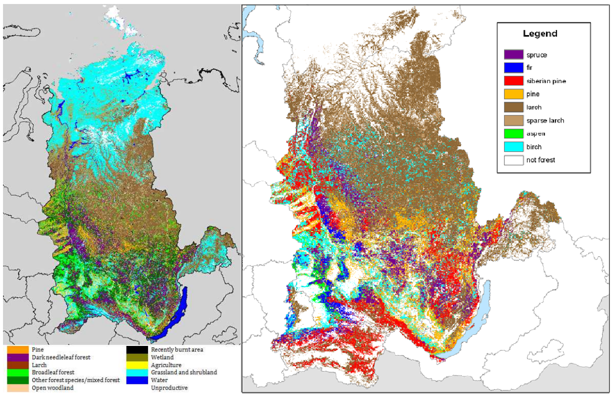


Fig 2: Land cover and forest species map for Central Siberia.

2.2.2 Biomass and improved land cover

A pan-boreal growing stock volume map at 1 km scale was developed using hyper-temporal ENVISAT ASAR ScanSAR backscatter data in the framework of the BIOMASAR-II project [7]. The Central Siberian region of this map was used in this study for cross-validation and comparison with field inventory data. Multi-temporal series of (250 and more) backscatter intensity acquisitions were geo- and terrain-corrected using the SRTM DEM in 1 km pixel spacing. The SAR scenes were tiled in a regular grid of 2 x 2 degree grid cells. Noise and speckle were reduced using a multi-channel approach according to [15]. A detailed description of the SAR processing is given in [7].

The ASAR data derived BIOMASAR-II map along with MODIS surface reflectance products were used as input data to produce improved forest GSV assessment based on locally adaptive estimating approach. The initial forest GSV data have been extracted for the territory of Central Siberia from BIOMASAR-II map of 1 km spatial resolution. MODIS reflectance values of described MODIS winter composite image have a noticeably close to linear relation with GSV values since all land cover classes except for high vegetation (i.e. trees) are mainly covered with snow and have rather homogenous surface reflectance values. This linear relation was applied to the MODIS winter reflectance composites using the LAGMA approach. The resulting product is the Forest GSV Map for Central Siberia with a spatial resolution of 230 m (Fig. 3). This approach allows to enhance the spatial resolution of the initial GSV product as well as to improve the quality of initial product.

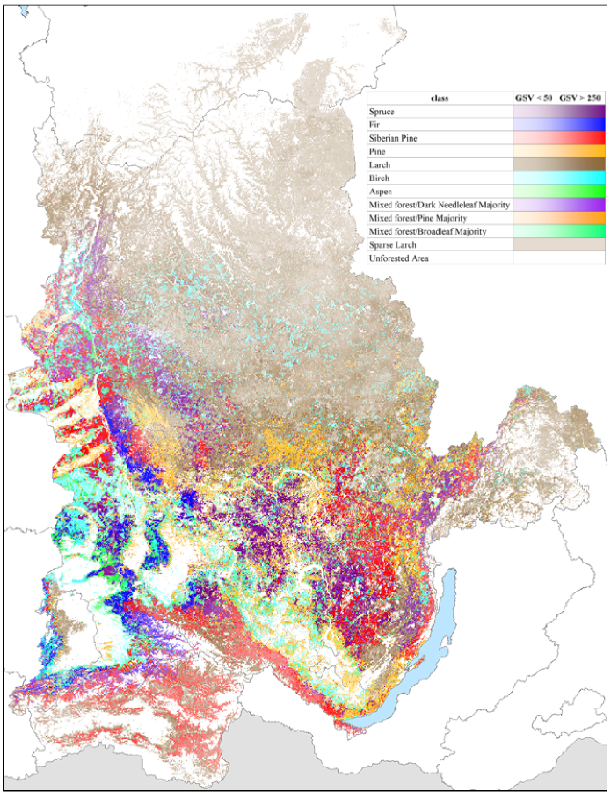


Fig 3: Hybrid Biomass and Land Cover Map for Central Siberia (data available under http://zapas.uni-jena.de*).*

2.3. Local scale forest resource assessment

An orthorectified dual-polarization (HH and HV) mosaic of the Advanced Land Observing Satellite (ALOS) Phased Array type L-band SAR (PALSAR) at 25 m resolution is being developed by JAXA and could be provided through JAXA's Kyoto & Carbon Science Initiative [16]. These annual mosaics covering the time periods of 2007 – 2010 were used for biomass, forest cover and disturbance, and forest regrowth mapping.

2.3.1 Biomass

Using the annual PALSAR mosaics from 2007 to 2010 growing stock volume maps were retrieved based on a supervised random forest regression approach. Non-parametric tree-based ensemble regression techniques are widely used for ecological modelling [17]. Random forest regression models were trained using growing stock information from forest inventory (FI) polygons on forest stand level in m^3 per hectare and the backscatter intensity images of HH and HV polarizations as predictors. To retrieve annual biomass maps for the observation period from 2007 to 2010 the models were run at annual basis.

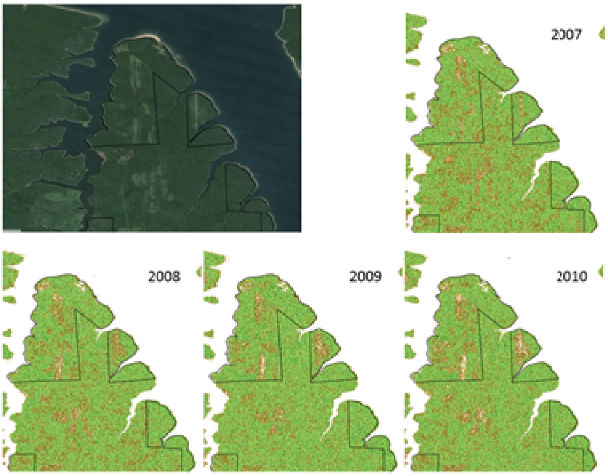


Figure 4: Example of annual growing stock volume mapping (2007 – 2010) for parts of the Padunsk test site in the Irkutsk Oblast. The Google Earth image indicates deforestation patterns, as also tracked in the biomass maps (data available under http://zapas.uni-jena.de*).*

2.3.2 Forest cover and disturbances

The ALOS-PALSAR HH and HV backscatter mosaics and the biomass map for the related year were implemented in three different forest cover and disturbance mapping frameworks. In a first framework, an object-based image analysis (OBIA) was developed for a fully automated wall-to-wall mapping of forest disturbance classes in all local test sites for 2007 and 2010. Using eCognition several multi-scale image segmentation runs were performed. A multi-stage threshold-based classification process tree was developed by (first) classifying *Forest* and *Non-Forest* based on HH backscatter thresholding, followed by the class definition of the *Forest Regrowth* class based on a biomass threshold (lower 100 m^3/ha). The result is a segment-based forest cover and disturbance map for the years 2007 and 2010. Another biomass map product was generated using an image differencing approach applied on the annual growing stock volume maps. A combination of image differencing and standard deviation thresholding resulted into an image mask of disturbed forest areas in terms of loss of biomass. The difference images from 2007 to 2010 were combined in order to derive a biomass disturbance map (2007-2010). An example is shown in Fig. 5 near the Angara River. The forest cover and disturbance map and the biomass disturbance map are covering all local test sites of the ZAPÁS project in Central Siberia. For further map exploration, the reader is referred to the SIB-ESS-C geoportal (http://www.sibessc.uni-jena.de/).

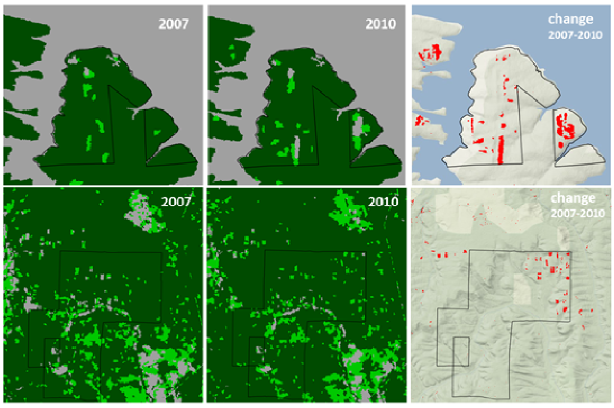


Figure 5: Example of local scale forest cover and change mapping in the Padunsk test site. The forest cover and disturbance classifications for 2007 (right) and 2010 (middle) indicate changed patterns in the forest stages (green = forest, grey = non-forest, light green = forest regrowth). This agrees to the biomass disturbance map (2007 - 2010) on the left where changes are indicated in red.

2.3.3 Abandoned land and Forest Regrowth Mapping

Time series of annual ALOS PALSAR HH and HV backscatter mosaics and the retrieved biomass layers from 2007 to 2010 were integrated as predictor variables in a random forest regression model. An example of continuously increasing biomass levels is shown in Fig. 6. A supervised modelling approach was set up in order to detect possible areas of forest regrowth due to agricultural abandonment processes or forest regrowth (such as logging and wildfires). The regression model was trained with samples of undisturbed forest areas and areas where a significant increase of biomass could be detected. For the model calibration, the undisturbed areas were set to the value 0 and re-growing areas were set to the value 100. This defines the target value range for the rescaling process. The application of the random forest regression model results in a continuous scale image layer of potential forest regrowth areas. Values from 0 to 100 indicate the probability of the occurrence of such areas with a strong forest succession.

Using multi-temporal Landsat acquisitions and forest inventory a threshold adjustment was conducted. From the continuous field product a reforestation area probability threshold of 69.3 % was estimated and applied on the probability map. The final result indicated all as potential re-growing forest lands with a probability higher than 69.3%. As shown in Fig. 6, the map covers all local test sites with a spatial resolution of 25 m.

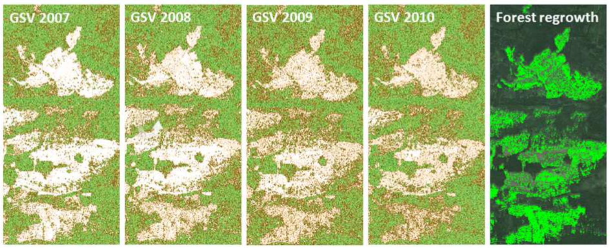


Figure 6: Biomass distributions from 2007 to 2010 indicate recent increasing forest cover on former agricultural areas in the Abansk region. The increasing biomass rates of the annual GSV layers were the input for the mapping of re-growing forest areas. The mapping result is shown in green (right).

3. RESULTS

3.1. Forest GSV assessment

Comparisons of the 25 m and 1 km scale GSV products inventory showed comparable agreements of the ASAR and PALSAR GSV maps ranging within 16 % and 23 % (except of Siberian Pine).

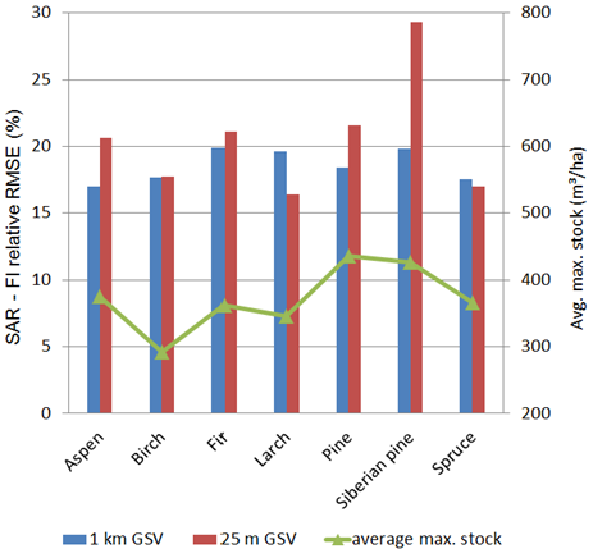


Figure 7: Relative RMSE of SAR – forest inventory comparisons of dominant forest species (mean values of all test sites). The 1 km GSV map better agrees with FI in the high biomass levels and vice versa.

Fig. 7 shows the summary statistics for inter-comparisons of the local and regional scale biomass products against forest inventory data. In general, the 1 km ASAR map shows lower RMSE than the 25 m PALSAR GSV map. However, it is obvious that the 25 m product has better agreements to forest inventory when comparing with the average maximum stocking. Examples are given with Larch, Spruce, and Birch. Areas where dark coniferous species are dominating show lower RMSE between forest inventory and SAR using the 1 km GSV maps. Reasons for this constellation can be the occurring saturation effect at the high biomass levels by using Radar imagery for growing stock volume estimation [18]–[20]. Due to different data and methods used the hyper-temporal approach of the BIOMASAR-II approach showed less sensitivity to saturation than the mono-temporal random forest method used for the PALSAR mosaic modelling.

3.2. Assessment of forest cover change dynamics

Analyzing the effects of landscape fragmentation and forest cover area changes has been conducted comprised the derivation of landscape metrics according to [21]. The fragmentation analysis has been conducted using the forest cover and disturbance maps of 2007 and 2010. Fig. 8 and 9 visualizes the change of patch density and area for the classes *Forest*, *Non-Forest*, and *Forest Regrowth* in the Abansk and Dolgomostovsk test site (698.479 ha).

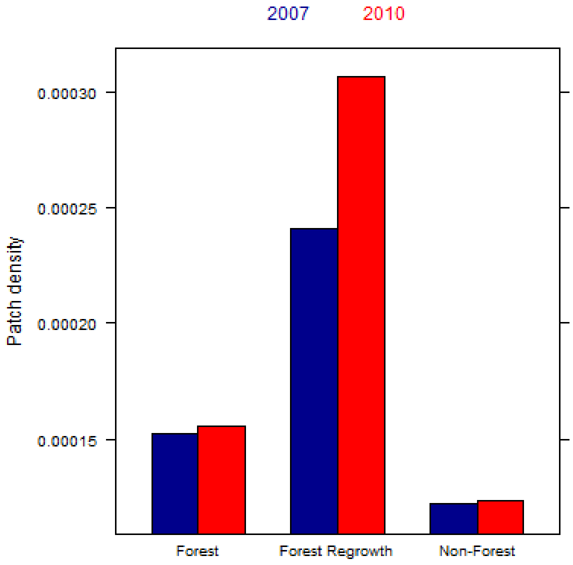


Figure 8: Patch density change between 2007 and 2010 for the Padunsk test site resulted by processes of forest regrowth and logging activities.

Temporal comparisons of the fragmentation indices indicated that there are complex processes of forest regrowth ongoing, e.g. on abandoned agricultural fields and, former forest fires and logging areas. This is shown by increasing patch density and area in the forest regrowth class. However, ongoing forest cover loss is indicated by decreasing forest area and increasing non-forest area.

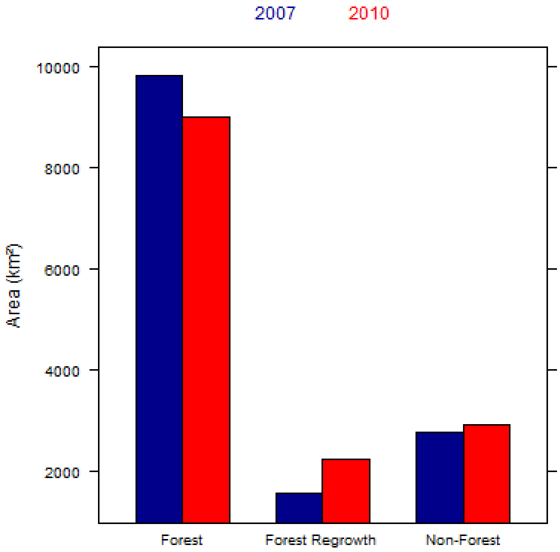
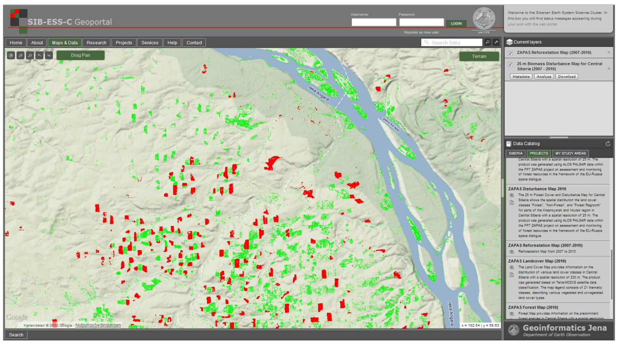


Figure 9: Area change between 2007 and 2010 for the Padunsk test site resulted by processes of forest regrowth and logging activities.

4. SUPPORTING A FOREST OBSERVATION SYSTEM FOR SIBERIA

The ZAPÁS team consists of a consortium of EU-Russian scientists and space agencies. To achieve the overall goal – prototyping and supporting a forest observation system for Siberia – an intelligent data distribution chain is needed. This means that the link between earth observation data (and related products) and national and local users has to be designed as fast and easy-to-use as possible. Here, a data processing middleware is proposed as a technical solution to improve interdisciplinary research using multi-source time-series data and forest resource maps, standardized data acquisition, pre-processing, updating and analyses [22]. This solution is being implemented within the Siberian Earth System Science Cluster (SIB-ESS-C), which combines various sources of EO data, climate data and analytical tools. The development of this spatial data infrastructure (SDI) is based on the definition of automated and on-demand tools for data searching, ordering and processing, implemented along with standard-compliant web services. These tools, consisting of a user-friendly download, analysis and interpretation infrastructure, are available within the SIB-ESS-C geoportal for operational use. The mission of SIB-ESS-C is to provide a web-based infrastructure and comprehensive information products derived from Earth Observation that support environmental and earth system research in Siberia. The ZAPÁS project is closely linked to the SIB-ESS-C developments and uses its capabilities by integrating local and regional scale forest resource maps and land dynamics analyses tools (Fig. 10).

After developing regional and local scale forest resource maps based on optical and SAR satellite data, all geo-information products are integrated in the geoportal. The portal is designed as an infrastructure for the so-called multi-concept in earth observation. In the case of forest resource assessment and monitoring in the EU-Russian ZAPÁS project, state and dynamics of forest resources can be assessed for the Central Siberian test region. The complete set of EO-based forest resource maps related to biomass and forest cover tracking is accessible under http://www.sibessc.uni-jena.de. The basic functions are explained in a tutorial [23].



Welcome to the Siberian Earth System Science Cluster. In this box you will find status messages appearing during your work with the web portal.

Central Siberia with a spatial resolution of 25 m. The product was generated using ALOS PALSAR data within the FP7 ZAPAS project on assessment and monitoring of forest resources in the framework of the EU-Russia space dialogue.

ZAPAS Disturbance Map 2010

The 25 m Forest Cover and Disturbance Map for Central Siberia shows the spatial distribution the land cover classes "Forest", "Non-Forest", and "Forest Regrowth" for parts of the Krasnoyarsk and Irkutsk region in Central Siberia with a spatial resolution of 25 m. The product was generated using ALOS PALSAR data within the FP7 ZAPAS project on assessment and monitoring of forest resources in the framework of the EU-Russia space dialogue.

ZAPAS Reforestation Map (2007-2010)

Reforestation Map from 2007 to 2010

ZAPAS Landcover Map (2010)

The Land Cover Map provides information on the distribution of various land cover classes in Central Siberia with a spatial resolution of 230 m. The product was generated based on Terra-MODIS satellite data classification. The map legend consists of 21 thematic classes, describing various vegetated and unvegetated land cover types.

ZAPAS Forest Map (2010)

Forest Map provides information on the predominant

Figure 10: Visualization of deforestation (red) and reforestation patterns (green) based on annual biomass maps derived from ALOS PALSAR (25 m mosaics provided by JAXA's Kyoto and Carbon Science Initiative). The example of the SIB-ESS-C shows a visualization of two forest change maps indicating the state and dynamics between 2007 and 2010 of a massive Central Siberian deforestation area near the Angara River.

The presented maps and statistics demonstrate, beside numerous other studies, ongoing processes of forest degradation in the boreal zone in terms of large scale logging and forest fires. Most of them are of anthropogenic origin [24]. But also forest regeneration processes are visible. Forest succession is often observed on abandoned agricultural lands due to post-Soviet land use conversions [25]. Understanding, observing and managing Siberian forests is challenging. Using multi-sensor and multi-agency satellite data demonstrated the capabilities for the implementation in national management bodies. However, the biggest obstacle is how to get data (including long time series, SAR and optical high resolution maps at different thematic information levels) and maps or forest change statistics for regional and national authorities. The state of the art satellite based forest monitoring techniques, as assessed and cross-compared within the ZAPÁS framework, highlight the potential for implementation in the national forest management. Fast and easy to use web-based middleware geoportals can play a central role for this process.

REFERENCES

1. White, M. A. (2005). A global framework for monitoring phenological responses to climate change. *Geophys. Res. Lett.*, **32**.

2. Dolman A. J., A. Shvidenko, D. Schepaschenko, P. Ciais, N. Tchebakova, T. Chen, M. K. van der Molen, L. Belelli Marchesini, T. C. Maximov, S. Maksyutov, and E.-D. Schulze. (2012). An estimate of the terrestrial carbon budget of Russia using inventory-based, eddy covariance and inversion methods. *Biogeosciences*, vol. **9**, no. 12, pp. 5323–5340.

3. Goetz, S. J., A. Baccini, N. T. Laporte, T. Johns, W. Walker, J. Kellndorfer, R. Houghton, and M. Sun (2009). Mapping and monitoring carbon stocks with satellite observations: a comparison of methods. *Carbon Balance Manag*., vol. **4**, p. 2.

4. Santoro, M., C. Beer, O. Cartus, C. Schmullius, A. Shvidenko, I. McCallum, U. Wegmüller, and A. Wiesmann. (2010). Retrieval of growing stock volume in boreal forest using hyper-temporal series of Envisat ASAR ScanSAR backscatter measurements. *Remote Sens. Environ.*, vol. **115**, no. 2, pp. 490–507.

5. Cartus, O., J. Kellndorfer, M. Rombach, and W. Walker. (2012). Mapping Canopy Height and Growing Stock Volume Using Airborne Lidar, ALOS PALSAR and Landsat ETM+. *Remote Sens*., vol. **4**, no. 11, pp. 3320–3345.

6. De Grandi, G. D., A. Bouvet, R. M. Lucas, M. Shimada, S. Monaco, and A. Rosenqvist. (2011). The KC PALSAR Mosaic of the African Continent: Processing Issues and First Thematic Results, vol. 49, no. 10. IEEE, pp. 3593–3610.

7. Santoro, M., C. Schmullius, C. Pathe, and J. Schwilk. (2012). Pan-boreal mapping of forest growing stock volume using hyper-temporal Envisat ASAR ScanSAR backscatter data. *Geoscience and Remote Sensing Symposium (IGARSS)*, pp. 7204 – 7207.

8. Seifert, F. (2012). GlobBiomass - User Consultation Meeting. 2012. [Online]. Available: http://due.esrin.esa.int/meetings/meetings283.php. [Accessed: 25-Jul-2013].

9. Hüttich, C., C. C. Schmullius, C. J. Thiel, C. Pathe, S. Bartalev, K. Emelyanov, M. Korets, A. Shvidenko, and D. Schepaschenko (2012). “ZAPÁS. Assessment and Monitoring of Russian Forest Resources in the Framework of the EU – Russia Space Dialogue.,” in. *Let’s Embrace Space. Space research achievements under the 7th Framework Programme*, European Commission.

10. B. Ryan, “Introduction to GEO,” in UNFCCC COP-18, 26 November - 07 December 2012, Doha, Qatar, 2012, p. 10.

11. M. Herold, C. E. Woodcock, T. R. Loveland, J. Townshend, M. Brady, C. Steenmans, and C. Schmullius, “Land-Cover Observations as Part of a Global Earth Observation System of Systems (GEOSS): Progress, Activities, and Prospects,” IEEE Syst. J., vol. 2, no. 3, pp. 414–423, 2008.

12. C. Hüttich, C. Schmullius, C. Thiel, C. Pathe, M. Urbazaev, M. Korets, S. Bartalev, E. K., A. Shvidenko, and D. Schepaschenko. (2012). ZAPÁS - Assessment and Monitoring of Forest Resources in the Framework of EU-Russia Space Dialogue. Progress Report I,” Jena.

13. Bartalev, S., A. Belward, D. Erchov, and A. Isaev (2003). A new SPOT4-VEGETATION derived land cover map of Northern Eurasia. *Int. J. Remote Sens.*, vol. **24**, no. 9, pp. 1977–1982.

14. Uvarov, I. A., and S. A. Bartalev. (2010). The Algorithm and Software Suite for Land Cover Types Recognition Based on Locally-adaptive Supervised Classification of Satellite Imagery. *Actual Probl. Remote Sens. Earth from Sp.*, vol. **7**, no. 1, pp. .353–365.

15. Quegan, S., and J. J. Yu. (2001). Filtering of multichannel SAR images, *IEEE*, vol. **39**, no. 11, pp. 2373–2379.

16. Rosenqvist, A. T., Ogawa, M. Shimada, and T. Igarashi. (2001). Initiating the ALOS Kyoto & Carbon Initiative, IEEE, vol. **1**, pp. 546–548.

17. Prasad, A. M., L. R. Iverson, and A. Liaw. (2006). Newer Classification and Regression Tree Techniques: Bagging and Random Forests for Ecological Prediction. *Ecosystems*, vol. **9**, no. 2, pp. 181–199.

18. Imhoff, M. L., Radar backscatter/biomass saturation: observations and implications for global biomass assessment, *IEEE*, vol. 1., 1993, pp. 43–45.

19. Wagner, W. (2003). Large-scale mapping of boreal forest in SIBERIA using ERS tandem coherence and JERS backscatter data, *Remote Sens. Environ*., vol. **85**, no. 2, pp. 125–144.

20. Santoro, M., A Shvidenko, I. Mccallum, J. Askne, and C. Schmullius. (2007). Properties of ERS-1/2 coherence in the Siberian boreal forest and implications for stem volume retrieval, *Remote Sens. Environ.*, vol. **106**, no. 2, pp. 154–172.

21. McGarigal, K., S. A. Cushman, M. C. Neel, and E. Ene. (2002). FRAGSTATS: Spatial Pattern Analysis Program for Categorical Maps. Computer software program produced by the authors at the University of Massachusetts, Amherst. *Analysis*, vol. **3**.

22. Eberle, J., S. Clausnitzer, C. Hüttich, and C. Schmullius. (2013). Multi-Source Data Processing Middleware for Land Monitoring within a Web-Based Spatial Data Infrastructure for Siberia. *ISPRS Int. J. Geo-Information*, vol. **2**, no. 3, pp. 553–576.

23. Eberle, J. 2013. Sib-ESS-C Tutorial, Report, [Online]. Available: http://www.sibessc.uni-jena.de/doc/Tutorial_v1.pdf. [Accessed: 18-Nov-2013].

24. Mollicone, D., H. D. Eva, and F. Achard. (2006). Ecology: human role in Russian wild fires. *Nature*, vol. **440**, no. 7083, pp. 436–437.

25. Prishchepov, A. V., D. Müller, M. Dubinin, M. Baumann, and V. C. Radeloff. (2013). Determinants of agricultural land abandonment in post-Soviet European Russia, *L. Use Policy*, vol. **30**, no. 1, pp. 873–884.