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**D1.7**

**Best practice guidelines on the maintenance and  
regular up-date of the biomass cost supply data for  
EU, Western Balkan Countries, Moldavia, Turkey and  
Ukraine**

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## About S2Biom project



The S2Biom project - Delivery of sustainable supply of non-food biomass to support a “resource-efficient” Bioeconomy in Europe - supports the sustainable delivery of non-food biomass feedstock at local, regional and pan European level through developing strategies, and roadmaps that will be informed by a “computerized and easy to use” toolset (and respective databases) with updated harmonized datasets at local, regional, national and pan European level for EU28, Western Balkans, Moldova, Turkey and Ukraine. Further information about the project and the partners involved are available under [www.s2biom.eu](http://www.s2biom.eu).

### Project coordinator



### Scientific coordinator



### Project partners



## About this document

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<b>Editor</b>	Matthias Dees
<b>Authors</b>	Matthias Dees, Pawan Datta, Markus Höhl, Sami Dawar (ALU-FR); Nicklas Forsell, Sylvain Leduc (IIASA); Joanne Fitzgerald, Hans Verkerk, Marcus Lindner (EFI); Berien Elbersen, Igor Staritsky (DLO [Alterra]); Jacqueline Ramirez-Almeyda, Andrea Monti (UniBo); Perttu Anttila, Robert Prinz (LUKE); Martijn Vis (BTG); Heinz Gallaun, Mathias Schardt (JR); Damjan Pantic, Dragan Borota, Branko Glavonjic (University of Belgrade); Daniel Garcia (CIRCE)
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### **Editor contact details:**

#### **Ass. Prof. Dr. Matthias Dees**

*Chair of Remote Sensing and Landscape Information Systems*

*Institute of Forest Sciences*

*University of Freiburg*

*Mailing address: D-79085 Freiburg, Germany*

*Delivery address: Tennenbacherstr. 4, D-79106 Freiburg, Germany*

*Tel.: +49-761-203-3697 // +49-7666-912506*

[matthias.dees@felis.uni-freiburg.de](mailto:matthias.dees@felis.uni-freiburg.de)

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## List of Acronyms and Abbreviations

3D	Three Dimensional
ABA	Area Based Approach
ABC	Activity Based Costing
AEROGRID	AeroGRID Ltd. In United Kingdom
AGB	Above Ground Biomass
Aglink-Cosimo	A partial equilibrium model of world agricultural markets used to generate the OECD-FAO Agricultural Outlook and policy scenario analysis
AIC	Akaike Information Criteria
ALOS	Advance Land Observing Satellite
ALS	Airborne Laser Scanning
Alterra	Alterra Environmental Research institute, Wageningen (From December 2016 called Wageningen Environmental Research)
ANIMAL change	AN Integration of Mitigation and Adaptation options for sustainable Livestock production under climate CHANGE.. EU-FP7 project
AP	Aerial Photographs
BACI	BACI is the World trade database developed by the CEPII at a high level of product disaggregation.
BEE	Biomass Energy Europe, an FP7 project
Bio2Match	S2BIOM tool supporting users to find the best match between biomass conversion technologies and types of biomass. It is accessible via the S2BIOM toolset at: <a href="http://www.biomass-tools.eu">www.biomass-tools.eu</a>
BWI	Bundeswaldinventur (Federal forest inventory, Germany)
CAP	Common Agricultural Policy
CAPRI	Common Agricultural Policy Regionalised Impact
cd	Canopy Density
CEPII	Confederation of European Paper Industries
CHM	Canopy Height Model
CHM <sub>ALS</sub>	CHM generated from Airborne Laser Scanning
CHM <sub>eATE</sub>	CHM generated from Image-Based Point Clouds using eATE
CHM <sub>SGM</sub>	CHM generated from Image-Based Point Clouds using SGM
CIRCE	Research Centre for Energy Resources and Consumption

CLC	CORINE Land Cover
COCO	CAPRI database
COMTRADE	The United Nations Statistical Divisions International Trade statistics (COMTRADE database)
CORINE	Coordination of Information on the Environment
CoSSC	Co-registered Single Look Slant Range
COST	European Cooperation in Science and Technology
COTS	Commercial off-the-shelf
CV	Coefficient of Variation
C <sub>Vol</sub>	Canopy Volume
DBH	Diameter at Breast Height Point
DEM	Digital Elevation Model
DG-ENV	Directorate General Environment of the European Commission
DLR	German Aerospace Center
DM	Dry Matter
DSM	Digital Surface Model
DSM <sub>ALS</sub>	Digital Surface Model Generated from Airborne Laser Scanning
DSM <sub>eATE</sub>	Digital Surface Model Generated from Image-Based Point Clouds using eATE
DSM <sub>SGM</sub>	Digital Surface Model Generated from Image-Based Point Clouds using SGM (A software package for the generation of 3D image-based point clouds)
DTM	Digital Terrain Model
DTM <sub>ALS</sub>	Digital Terrain Model Generated from Airborne Laser Scanning
eATE	enhance Automatic Terrain Extraction (A software package for the generation of 3D image-based point clouds)
EC	European Commission
EEA	European Environment Agency
EFISCEN	European Forest Information SCENario model
EFSOS (I/II) ?	European Forest Sector Outlook Study
ENFIN	European National Forest Inventory Network
EO	Earth Observation
EPIC	Environmental Policy Integrated Climate Model
ESA	European Space Agency
ESRI	Environmental Systems Research Institute, a software company

ETC/SIA	European Topic Centre on Spatial Integration and Analysis
ETM	Enhanced Thematic Mapper
EU	European Union
EuroPruning	7 <sup>th</sup> Framework Programme project (contract-211478). Development and implementation of a new and non existent logistics chain for biomass from pruning.
EUROSTAT	European Commission Statistical Office
EUROSTAT	Eurostat is a Directorate-General of the European Commission
FADN	Farm Accountancy Data Network
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Statistical service of FAO
FAWS	Forests available for wood supply
FISE	Forest Information System of Europe
FRA	Forest Resource Assessment
FSS	Feed stock supply
FVA	Forest Research Station of the federal State of Baden-Württemberg Germany
G4M	Global Forest Model.
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies model is an integrated assessment model dealing with costs and potentials for air pollution control and greenhouse gas (GHG) mitigation, and assessing interactions between policies.
GDP	Gross domestic product
GHG	Green House Gas
GIS	Geographic Information System
GJ	GigaJoule
GLOBIOM	Global Biosphere Management Model
GNSS	Global Navigation Satellite System
H2020	Horizon 2020 - EU Framework <i>Programme</i> for Research and Innovation
HH	Horizontal - horizontal polarisation
HNV	High Nature Value
HR	High Resolution
IACS-LPIS	Integrated Administration and Control System - Land Parcel Identification System
IDEM	Intermediate DEM (Intermediate product level of final TanDEM-X elevation model, provided by DLR for scientific purposes)

IIASA	International Institute for Applied Systems Analysis, Austria
IMPACT	Remote Sensing Software of JR Graz
InSAR	Interferometric synthetic aperture radar
IPCC	Intergovernmental Panel on Climate Change
ISODATA	Iterative Self-Organizing Data Analysis Techniques
ITP	Integrated TanDEM Processor
JR	Joanneum Research Graz
JRC	Joint Research Centre
k-NN	k-nearest neighbour, a classification algorithm
KTBL-online	On-line database & toolset on agricultural management support. At: <a href="https://www.ktbl.de/online-anwendungen0/">https://www.ktbl.de/online-anwendungen0/</a>
KWIN	Kwantitatieve Informatie Veehouderij
LEDAPS	Landsat Ecosystem Disturbance Adaptive Processing System
LGL	Landesamt für Geoinformation und Landentwicklung (German survey administration of the federal state Baden-Württemberg)
LhV	Lower heating Value
LiIDAR	Light detection and ranging (caution differing spelling in the text)
LM	Linear Model
LMH	Lorey's Mean Height
LocalGIStics	S2BIOM tool supporting the design and evaluation of biomass delivery chains accessible via the S2BIOM toolset at: <a href="http://www.biomass-tools.eu">www.biomass-tools.eu</a>
LOOCV	Leave Out One Cross Validation
LUCAS	Land Use and Cover Area frame Survey
LULUCF	Land use, land-use change and forestry, defined by United Nations Climate Change Secretariat
MDF	<i>Medium-density fibreboard</i>
MESSAGE	An energy system model – see Fricko, O., Havlik, P., Rogelj, J., et al., 2016, SSP2: a middle of the road scenario for the 21st century, Global Environmental Change, article in press.

MITERRA-Europe	Model developed for DG-ENV that calculates GHG (CO <sub>2</sub> , CH <sub>4</sub> and N <sub>2</sub> O) emissions, SOC stock changes and nitrogen emissions from agriculture on a deterministic and annual basis. It is based on the CAPRI and GAINS models, supplemented with a nitrogen leaching module, a soil carbon module and a module for representing mitigation activities
MLR	Multiple Linear Regression
MODIS	The Moderate-resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
Natura2000	Natura 2000 is a network of core breeding and resting sites for rare and threatened species, and some rare natural habitat types which are protected in their own right. It stretches across all 28 EU countries, both on land and at sea. The aim of the network is to ensure the long-term survival of Europe's most valuable and threatened species and habitats, listed under both the <u>Birds Directive</u> and the <u>Habitats Directive</u> .
NDSM nDSM in the text	Normalized Digital Surface Model (DSM – DTM), also referred to as forest height model
NDVI	Normalized Difference Vegetation Index
NFI	National Forest Inventory
NIR	Near Infrared
NITRO-Europe	EU-FP6 project (2006-2011) responds to the question of the effect of changes in climate, land use and management on greenhouse gas emissions in both agriculture and non agriculture at different scales from landscape to Europe.
NMAD	normalized median absolute deviation
nPCs	normalized point clouds
NPV	Net Present Value
NRT	Near real time
NUTS	Nomenclature of Territorial Units for Statistics of the European Union
NUTS0, NUTS1, NUTS2, NUTS3	NUTS, the Nomenclature of Territorial Units for Statistics of the European Union structures the territorial units hierarchical, starting with the National level (= NUTS0), followed by NUTS1 and NUTS2 and NUTS3.
NVC	<i>net calorific value</i>
OECD	Organisation of Economic Co-operation and Development
OSB	Oriented strandboard

PAN	Panchromatic
PCA	Principal Component Analysis
PCW	Post-consumer wood
POLES	An energy system Model, see Labat, A., Kitous, A., Perry, M., Saveyn, B., Vandyck, T., and Vrontisi, Z. (2015). GECO2015. Global Energy and Climate Outlook. Road to Paris. JRC Scientific and Policy Reports, EUR 27239 EN.
R <sup>2</sup>	Coefficient of Determination
RCG	Reed Canary Grass
RED	Renewable Energy Directive (2009/28/EC)
REDD	The United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation
RF	Random Forest
RMA	<del>Reduced Major Axis (Regression)</del>
RMSE	Root Mean Square Error
RothC	model of the turnover of organic carbon in non-waterlogged soils that allows for the effects of soil type, temperature, moisture content and plant cover on the turnover process. Version v26.3 utilised in S2Biom.
RS	Remote Sensing
RSG	Remote Sensing Software Package of JR
S2	Sentinel 2
S3	Sentinel 3
SAR	Synthetic Aperture Radar
SD	Standard Deviation
sen2cor	Processor for Sentinel-2 Level 2A product generation and formatting
SFR	Secondary forest residues
SGDBE	Soil Geographical Database of Eurasia
SGM	Semi-Global Matching
SOC	Soil Organic Carbon
SRC	Short rotation coppice
SRTM	Shuttle Radar Topography Mission (also refers to the elevation model derived from the mission)
SVM	Support Vector Machine
SWIR	Short Wave Infrared
UNECE	United Nations Economic Commission for Europe
USGS	United States Geological Survey
VAT	Value-added tax

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VHR	Very High Resolution
VHRS	Very High Resolution Satellite Images
VIF	Variance Inflation Factor
WorldClim	Global Climate Data: WorldClim version 1 has average monthly climate data for minimum, mean, and maximum temperature and for precipitation for 1960-1990.
WorldDEM	World Digital Terrain Model
WP	Work Package
WUR	Wageningen University and Research

## 1 Introduction

This report provides best practice guidelines on the maintenance and regular up-date of the cost supply data base.

It includes a brief summary of the methods and data sets that have been used to establish the cost supply data base, followed by suggestions and recommendations for improvements of methods and data sets.

Updates of the data base are necessary on the one side due to advancement of methods and data sets. Further there is the temporal aspect and the dynamic of changes:

- Many data sources are subject to regular or irregular updates and their quantities may change considerably.
- Some quantities are more stable (e.g. forest area), others change more considerably over time (e.g. availability of land not needed for food and feed, production costs).
- Constraints, e.g. environmental constraints, that need to be considered might be subject to change
- Future projections need to be updated regularly since they need to consider the most recent developments.

The report is structured by major source category. Besides the aspects mentioned per category practical recommendations will be provided concerning data collection, use of models and the organisational & technical setup, e.g. where the involvement of national level organisations as "correspondents" is recommended or a complete change of the data collection by national services and international ones, such as EUROSTAT.

This report further includes the remote sensing studies on the assessment of forest biomass that were conducted with the objective to increase the spatial accuracy of the biomass supply potential maps for European and regional to local scale. Based on these studies a concept a future forest biomass supply mapping concept was developed. .

## 2 Cost supply potential assessment

### 2.1 Primary residues from agriculture

#### 2.1.1 Introduction

The categories of crop residues covered here refer both to straw and stubbles coming from rotational arable crops and to prunings from permanent crops. A more detailed overview of the potential categories covered in this section is given in the Table 1 underneath.

Table 1 Subcategories primary agricultural residues

Third level subcategories		Final level subcategories		
ID	Name	ID	Name	Definition
221	Straw/stubbles	2211	Rice straw	Dried stalks of cereals (including rice), rape and sunflower which are separated from the grains during the harvest. Often these are (partly) left in the field.
		2212	Cereals straw	
		2213	Oil seed rape straw	
		2214	Maize stover	Grain maize stover consists of the leaves, stalks and empty cobs of grain maize plants left in a field after harvest
		2215	Sugarbeet leaves	The sugarbeet leaves and tops are the harvest residues separated from the main product, the sugar beet, during the harvest and (often) left in the field.
		2216	Sunflower straw	Dried stalks of cereals (including rice), rape and sunflower which are separated from the grains during the harvest. Often these are (partly) left in the field.
222	Woody pruning & orchards residues	2221	Residues from vineyards	The prunings and cuttings of fruit trees, vineyards, olives and nut trees are woody residues often left in the field (after cutting, mulching and chipping). They are the result of normal pruning management needed to maintain the orchards and enhance high production levels.
		2222	Residues from fruit tree plantations (apples, pears and soft fruit)	
		2223	Residues from olives tree plantations	
		2224	Residues from citrus tree plantations	

#### 2.1.2 Estimation of supply

##### Summary of the methodology/models used

###### *Assessing the technical potential for straw and stubbles*

In the following a summary description is given of the approach to assessing the potentials for straw and stubble, but for a detailed description we refer to S2BIOM report D1.6 Dees et al. (2016).

For assessing the potential of these residues first the amount of above ground residue is calculated as follows:

$$\text{residue yield} = \text{crop\_area} * \text{yield} * \text{residue2yieldfactor} * \text{DM\_content}.$$

Where:

**crop\_area**: derived from CAPRI per region for 2012, 2020 and 2030

**yield:** this level refers to the yield of the main product (seeds): derived from CAPRI as an average per crop per region

**Residue2yieldfactor:** the factors applied were specific per crop and were derived from Scarlat et al. (2010):

- Soft wheat & durum wheat =  $1.6057 - 0.3629 \cdot \text{LN}(\text{yield})$ , where LN is the natural logarithm<sup>1</sup>.
- Rye =  $1.5142 - 0.3007 \cdot \text{LN}(\text{yield})$
- oats =  $1.3002 - 0.1874 \cdot \text{LN}(\text{yield})$
- Oil seed rape =  $2.0475 - 0.452 \cdot \text{LN}(\text{yield})$
- Sunflower =  $3.2189 - 1.1097 \cdot \text{LN}(\text{yield})$
- Grain maize =  $1.3373 - 0.1807 \cdot \text{LN}(\text{yield})$
- Rice =  $3.845 - 1.2256 \cdot \text{LN}(\text{yield})$

**DM\_content:** Dry matter content is:

- All cereals: 85%
- Grain maize: 70%
- Rice: 75%
- Sunflower: 60%
- Oil seed Rape: 60%

Since the formula provided by Scarlat et al. (2010) applies to the whole above ground biomass a correction factor was additionally applied to assess the straw part only. The straw : stubble ratio can be highly variable, depending on crop type, cultivar and harvest management. Based on Poulson et al. (2011) and Panoutsou and Labalette (2007) a straw stubble ratio of 55% : 45% was used. This implies that the final technical straw potential for all cereals requires the application of the above presented formula times 0.55 to come to a final straw technical potential. For rape, sunflower and grain maize this correction is not applied as not relevant.

#### *Assessing the technical potential for prunings from permanent crops*

The overall calculation of the technical potential of pruning residues follows the same formula as for residues from rotational arable crops:

$$\text{residue yield} = \text{area} * \text{res\_yield} * \text{DM\_content}.$$

Where:

- residue yield = total pruning yield of the crop in Ton/Year in dry mass

<sup>1</sup> If the yield factor of cereals is 2.7 t/ha, then the formula would yield a residue2yield factor of 1.25.

- area = Cultivated area of crop
- res\_yield = Pruning yield Ton/Ha/Year in fresh mass of the crop
- DM\_content= Dry matter content of prunings

The total pruning yield (res\_yield) is derived from an evaluation of maximum pruning yield levels in which a distinction is also made between irrigated and non-irrigated culture. The ratio between irrigation-non-irrigation at NUTS3 region was estimated using a combination of CORINE Land Cover information and statistical sources on permanent crop yields.

The harvest ratios for pruning are to be applied to crop area for the different permanent cropping areas (AREA) from CAPRI baseline runs 2010, 2020 and 2030.

The dry mass content of prunings (DM\_content) differs per type of crop and region. But as an average moisture content a factor of 40% (=0.6 DM\_content) was used for all permanent crops, with the exception of olives where it was set lower at 30% (= 0.7 DM-content).

*Assessing the base potential (=sustainable technical potential) for straw and stubbles*

The aim of S2Biom was to identify the part of the residues that can be removed from the field without adversely affecting the SOC content in the soil. This is calculated by applying the Miterra model and calculating at what removal rates the carbon remains stable in the soil. Miterra model was developed for integrated assessment of Nitrogen, carbon and phosphate balances and emissions from agriculture in EU-27 at Member State and regional levels (NUTS2). The carbon balance module in Miterra that has been further adapted in S2Biom (and Biomass Policies) to take account of removal of straw (and also prunings, see next). This was done by incorporating the RothC model (Coleman and Jenkinson, 1999) into Miterra. RothC (version 26.3) is a model of the turnover of organic carbon in non-waterlogged soils that allows for the effects of soil type, temperature, moisture content and plant cover on the turnover process. It uses a monthly time step to calculate total organic carbon (ton C ha<sup>-1</sup>), microbial biomass carbon (ton C ha<sup>-1</sup>) and Δ14C (from which the radiocarbon age of the soil can be calculated) on a years to centuries timescale (Coleman and Jenkinson, 1999). For this study RothC was only used to calculate the current SOC balance based on the current carbon inputs.

Table 2 Overview of MITERRA-Europe model

Model acronym and name	Relevance	Owner(s) of the model, access conditions and access point	Brief description, related projects (if applies) & references	Model maintenance and development
MITERRA-Europe	Used here to calculate a soil carbon balance with and without removal of straw&stubbles. In this approach	MITERRA-Europe model was developed by Alterra for DG-ENV for integrated assessment of Nitrogen, carbon and phosphate balances and emissions from agriculture in the EU at regional levels (NUTS2). It is based on the CAPRI and GAINS	The project was further developed in several EU projects (e.g. NITRO-Europe, ANIMAL change). References: Velthof et al., 2009;	It is a simple and transparent model applying an uniform approach to assess impacts of changes in policies on the environment, taking

	the sustainably removable straw&stubble amount has been determined for the base potential	models, supplemented with a nitrogen leaching module, a soil carbon module and a module for representing mitigation activities This model is owned by Alterra and cannot be run/used by third parties.	Lesschen et al., 2011; de Wit et al., 2014).	CAPRI output (on changes in management and landuse) as starting point for analysis. Use and maintenance continues through application in new EU projects.
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In Miterra the C input is then quantified for four components:

1. Grain yield at NUTS2 level (Eurostat)
2. Above ground residues (according to Scarlat et al., 2010) as above
3. Straw : Stubble/chaff = 55:45 ratio
4. Belowground C input 25% of assimilated C (based on Taghizadeh-Toosi et al., 2014)

The eventual sustainable straw removal rate is then calculated by taking the balance between the level of carbon input from manure and residues that is needed to keep the SOC at a stable level.

#### *Assessing the base potential (=sustainable technical potential) for prunings*

Like for straw and stubbles sustainable potential was defined by the part of the residues that can be removed from the field without adversely affecting the SOC content in the soil. This is also calculated with the same Miterra model as was used for straw and stubbles. So for the overall methodology and input factors we refer to the former description under straw. The more specific calculation of permanent crop specific removal rates of carbon through prunings was estimated in close collaboration with the EuroPruning project (details available in EuroPruning, 2016). For perennial crops the C input from crop residues was differentiated into prunings, dead fruits (harvest losses in field), litter and belowground C inputs from roots.

#### *Competing use levels (only in user defined potential) for cereal straw*

To determine the user-defined potential for straw that takes account of competing use levels for cereal straw data on current and future livestock uses for straw need to be made. For cereal straw competitive uses are for bedding in specific livestock systems (including horses). The exact quantification is done by using data on livestock type and number data from CAPRI baseline runs.

Factors of straw competing use were calculated following the Scarlat et al (2010) estimates which are:

Dairy cows	0.375 kg straw/day.head
Beef cows	0.375 kg straw/day.head
Pigs	0.0625 kg straw/day.head
Sheep & goats	0.1 kg straw/day.head

### *Competing use levels (only in user defined potential) for prunings*

This information has been assessed in EuroPruning for the most important permanent crop producing countries in Europe. Since the EuroPruning only provided information for a selection of countries the practices for non-covered countries were copied from a neighbouring or similar countries. Prunings are an important source of nutrients and carbon but on the other hand there is also a risk involved when leaving pruning residues in the field as these can be a source of diseases in crops. Other practices quite common are to burn the pruning residues in the field without energy recovery. EuroPruning inventory (EuroPruning, 2015) showed that the way pruning residues are handled is very much dependent on the typical practices per crop and region and the regulations in place.

Based on the EuroPruning inventory (EuroPruning, 2015) the user defined potential was determined. In this potential the sustainable use which is subtracted refers to the part that is currently shredded and incorporated in the soil. The part that is now removed to the side of the field for energy uses and that is (first piled and then) burned in the field is seen as potential. This potential is expected to be gradually mobilised towards 2020 and 2030. This mobilisation of the unused potential gradually starts with 50% of the unused potential in 2012 and then increases by 10% in 2020 and again an extra increase of 10% by 2030.

### **Summary of main data used**

Since the assessment of agricultural residues and dedicated crops needs to be done for 2012 and for the future land use situations, we rely on economic and land use model output. The most logical model and dataset used as a basis for the estimation of future residual biomass supply from crops is the CAPRI model and related COCO database. The CAPRI model predicts the future market and production responses at the regional level for the whole EU-28, western Balkans, Turkey and Norway. It is therefore the only source of information available that gives a plausible overview taking account of the specific diverse regional circumstances in the EU, of what land-use changes can be expected by 2020 and 2030. In S2Biom, like was also done in Biomass Policies project, we build on the CAPRI model results both for assessing the amount of residues and for assessing competing use levels for straw by livestock. CAPRI forecasts future land use and livestock production changes in the EU-28, most Balkan countries (except Moldova) and Turkey including land demand for domestic biofuels (although NOT for bioenergy crop demand for bio-electricity and heat). Ukraine is not covered in CAPRI (except as part of the rest of the world for import and export relations with the EU).

For the assessment in S2Biom (like for Biomass Policies project) land-use and livestock production levels are used based on the most recent CAPRI baseline run 2008-2050, providing intermediate results for 2010, 2020, 2030 and 2050. This baseline run is seen as the most probable future simulating the European agricultural

sector under status-quo policy and including all future changes in policy already foreseen in the current legislation. It also assumes all policy regarding bioenergy targets as agreed until now and further specified in the *Trends to 2050* report (EC, 2013)<sup>2</sup> for as far as affecting agriculture. For the assessment of residues the CAPRI land use patterns for 2010 were extrapolated to 2012 using FSS farm structural data and calculating relative crop area and livestock number changes between 2010 and 2012 and using these to extrapolate the CAPRI base data 2010 to 2012.

Yields and changes in yield levels per region and country in CAPRI for the conventional crops delivering residues are already included in the baseline scenario of CAPRI. They are derived from the Aglink-Cosimo modelling system of the OECD-FAO (see Britz and Witzke, 2012). The Member States fill in time series on future developments on several variables including yield developments of their main crops. These values are usually based on country specific modelling baselines, expert consultations, historic projections. The national input is then recovered in Aglink-Cosimo by adapting the behavioural equations in the model while at the same time adapting these to joint worldwide future development expectations regarding import/and export relations, worldwide price and technological developments. CAPRI then takes Aglink-Cosimo output as an input. These developments are then further incorporated into CAPRI but tuned where necessary with internal constraints set on yields for both vegetable and animal products. These internal constraints are needed to maintain a consistent and stable relationship between the very influential CAPRI specific yield increase parameters and other factors such as technology development, seed use and losses, land use ratio factors, etc. For further details on this aspect, see Britz and Witzke (2012) and Elbersen et al. (2016ab).

For the assessment of the base potential which refers to the removable straw, stubble and pruning potential while keeping the soil organic carbon content of the soil stable, additional input data were used as specified underneath.

The RothC module integrated in MITERRA-Europe requires the following input data on a monthly basis: rainfall (mm), open pan evaporation (mm), average air temperature (°C), clay content of the soil (as a percentage), input of plant residues (ton C ha<sup>-1</sup>), input of manure (ton C ha<sup>-1</sup>), estimate of the decomposability of the incoming plant material (DPM/RPM ratio), soil cover (if the soil is bare or vegetated in a particular month) and soil depth (cm). Initial carbon content can be provided as an input or calculated according to long term equilibrium (steady state).

The key input data sources used for calculating the soil balance per region and per crop were:

2 EC (2013). *EU Energy, Transport and GHG emissions trends to 2050. Reference Scenario 2013*

- SOC stock based on LUCAS data (0-20 cm) (Land Use/Cover Area frame statistical Survey, is a harmonised survey carried out by EUROSTAT with the aim to gather information on land cover and land use across the EU).
- Missing non-EU countries data for SOC levels were filled with world and EU soil map data on soil properties.
- Climate data: Monthly temperature, precipitation and potential evapotranspiration (derived from WorldClim and FAO)
- Carbon inputs (data for 2010)
  - Manure (based on N flows and CN-ratio). The carbon input from manure, compost and sludge was derived from MITERRA-Europe, following the allocation of manure nitrogen to crops and a livestock type specific CN ratios.
  - Crop residues (NUTS2 yield data (matched with CAPRI), harvest index (Vleeshouwers and Verhagen, 2002)
  - The carbon inputs by permanent crops was differentiated into prunings, dead fruits (harvest losses in field), litter and belowground C inputs from roots. To determine what Carbon input could be assumed from these a literature review was performed in EuroPruning project (EuroPruning, 2016) which is also summarized in S2Biom deliverable 1.6 (Dees et al., 2016). In addition, C input from grassland cover in the permanent crop fields was also included. In order to estimate the grassland cover the LUCAS land use data (Eurostat, 2012) provided useful data. LUCAS provides crop and country specific shares of grass cover in orchards. For the grass yield, it was assumed that it amounted to half of the yield from normal grasslands in the same region which went together with half of the normal permanent grassland C input in the soil.
  - As for the C inputs of fruit losses data was not easily found, but data could be collected from four principal sources:
    - Two studies worldwide orientated from FAO, 2011 and Aulakh, 2013
    - Information gathered from several French data sources by SCDF, 2015
    - A specific study developed in Spain for food losses (MAAM, 2015)

### **Limitations of methodology & data used**

The following limitations can be reported:

- For estimating the technical straw potential the work by Scarlat et al. (2010) has limitations in that it refers to an average grain-to-residues factor. However in an Ecofys study (Spöttle, 2013) a further validation was done of the resulting straw yield based on the grain-to-straw ratios by consulting national experts. Results of this validation suggest that the Scarlat et al. (2010) ratios

are a bit over-estimating the straw potential particularly for Poland, Denmark, Hungary and Romania where the Scarlat et al. (2010) ratio is especially optimistic for wheat. For other countries covered (Netherlands, Germany, Spain, UK, Italy) the ratio estimates are well in line.

- In Scarlat et al. (2010) the grain-to-residue factor is used, but it is important in the case of cereal straw to apply a correction factor to calculate only the straw part of the residue. In S2Biom we follow Poulson et al. (2011) and Panoutsou and Labalette (2007) which recommend to use a straw stubble ratio of 55% : 45%. It should be realised however that straw : stubble ratio can be highly variable, depending on crop type, cultivar and harvest management.
- For estimating the sustainable removal rates of straw & stubbles a carbon balance approach was used. The limitations of this approach are specifically caused by the input data regarding current levels of SOC in the soil, which are very determinant for the final removal rates calculations. The data come from LUCAS and are based on samples in the topsoil (0-20 cm). Based on these data the average SOC stock on arable land was calculated per NUTS2 region. This average was used to calculate the SOC balance and the related sustainable straw removal rates. Since the removal rates are based on regional average topsoil levels it ignores the large variations that can occur in SOC content of soils within regions and also within the same soil varying between top soil and deeper soil levels. The real sustainably removable straw potentials therefore also refer to an average, while within the regions there may still be large variations.
- As for the competing use levels European wide average straw use levels per animal were used, based on Scarlat et al. (2010). These levels vary in reality very strongly per country and region. Furthermore other competing straw uses like for instance in horticulture were ignored while these can be significant in certain regions e.g. flowerbulb production in the Netherlands.
- As to the assessment of biomass potentials from permanent crops it should be realised that the focus was on the pruning material and excluding potential woody biomass existing of trees and stumps that can be removed at the end of a plantation lifetime. Pruning is part of normal practice to enhance and maintain the production of the main fruit and is therefore a cyclical activity delivering a stable amount of biomass every year. Excluding the biomass part that can be derived once every 10 to 20 years at the end of a plantation life time implies a conservative estimation of residues from permanent crops. The EuroPruning project (EuroPruning, 2016) has shown that end of plantation time biomass yield can amount to an extra woody biomass yield ranging between 0.7 to 1.5 t/ha/yr of dry matter (Garcia-Galindo et al., 2016 and u-Pruning Observatory).
- The EuroPruning project report D3.1 (EuroPruning, 2015) contains estimates of pruning residues delivered by the different permanent crops but also

confirms that there is a wide variation in type of trees, shrub forms used, varieties and traditional practices. For these crops there is less understanding of the relation between yield levels of the main crop, 'fruit', and the residue potential. There have been several publications providing residue-to-yield ratios for the different permanent crops, especially covering the Mediterranean region, but the variation is very large and the figures used in S2Biom build on EuroPruning. Although it can be claimed that this last project delivers the most recent European wide overview of pruning yields and practices, it still by far does not cover the very wide variation between and within regions and between different permanent crops.

- The results obtained with RothC and Miterra-Europe models cause the base potential of agricultural pruning to be about 35% of the technical potential as an average in Europe, some countries like Greece, Portugal or Slovenia show an even lower share. In general Mediterranean countries, where the annual rainfall is much smaller, show lower removal rates. In non-Mediterranean countries the relation between the base and the technical potential is in general much larger, averaging between 60% to 70%. The use of water and the low carbon content are limiting factors under rainfed conditions in Mediterranean countries. However, under irrigated regimes, both issues tend to improve. Therefore, the low base potential should be interpreted as an indicator of potential soil vulnerability for permanent crop plantations. A higher share of the base potential can be achieved, but the use of pruning wood should be accompanied with an examination of the soil conditions, and other agronomic practices leading to the maintenance or increase of the soil organic carbon.
- For future residue potentials we relied on CAPRI model output. It should be acknowledged that model outputs, even though coming from a well-documented and validated model, remain highly uncertain and they are always a simplification of the situation. Models cannot take all factors of influence into account, certainly if the future is far away. The future potentials should therefore be interpreted with greater care than the estimates for 2012. The advantage of the S2BIOM use of CAPRI data is that they refer to the intermediate future 2020 and 2030.
- Potentials for non-EU countries covered in S2BIOM have more data limitations. For the Ukraine no future CAPRI land use change results were available. The same applies for LUCAS data on current SOC levels. Because of this biomass potentials for Ukraine for straw and stubbles were kept constant in time. Current SOC estimates used in the calculation for sustainable removal rates are based on rougher low resolution information from the world soil map. The results for Ukraine are therefore less accurate.

## Recommendations on how to address limitations in data & methodology

Recommendations on how to address the limitations are given below.

- If national and regional straw & stubble potentials are to be quantified it is always advisable to take into account regional specific straw ratio factors which take account of local production and varieties used. These regional specific factors can be used to further improve the accuracy of the technical straw potentials.
- For cereals it is important to determine after calculating the residue potential which part of it consists of straw. In S2Biom an average straw : stubble ratio was used of 55% : 45%. However, since this factor can be highly variable between regions it is therefore recommended to check whether regional specific factors are available from local experts which can be applied instead.
- The same applies to the competing use levels for straw, but also prunings. It is always better to apply regional specific competing use factors derived from local experts. Provided the local experts consulted are indeed capable of making good estimates of the situation. The latter is not always the case.
- The quality of input data on current SOC levels for calculation of sustainable removal rates for residues using a carbon balance approach is always challenging. Reliable high resolution data covering the strong diversity in current SOC levels hardly exists. It is therefore recommended to validate the outcomes of the S2BIOM sustainable residue removal rates with observations of experts in the region of interest before the potentials are taken as a start for building a real business case on. Depending on the outcome of the validation, corrections to the data may be needed, at least for the territory of interest covered by the validation.
- Modelling results become less reliable if they refer to far away futures. Potentials used for building up business case should therefore be best based on shorter term land use change predictions not covering more than 10 to 20 years.

### **Recommendations on temporal frequency of updates**

The most recent S2Biom biomass potential estimates are based on agricultural land use figures of 2012. National and European level agricultural statistics are up-dated regularly, usually annually or bi-annually. This certainly applies for IACS-LPIS data since these data need to be reported by farmers on a yearly basis in order to receive CAP payments. This implies that for EU countries agricultural residue potentials can be up-dated yearly provided access to these data is available. Some countries apply very strict disclosure rules to these data, particularly if it involves the data at parcel or municipality level. Crop statistics are up-dated at a yearly basis, but yield data are not collected that frequently.

So with national agricultural statistics the S2Biom 2012 figures can already be up-dated. One can however argue that a yearly up-date of potential calculations is not necessary since large changes in area in 2 years' time cannot be expected. It is

recommended however that a frequency in up-date of 5 years would be a good compromise to detect possible changes in both crop area and yield and this frequency should match well with the statistical data collection frequency in most countries and also with the up-date frequency of European wide statistical sources managed by Eurostat.

### **Practical aspects of the implementation of the up-date**

The calculation of the technical potential of straw and stubbles should be feasible given the information presented in this S2Biom deliverable and also other deliverables. Furthermore national and EU statistics are available, accessible and contain all information to make such calculations. What is more challenging however is to calculate the sustainable removal rates since this requires using a carbon balance approach. Such calculations need to be performed by experts with access to models and high resolution data to perform such calculations which also involve GIS skills. MITERRA-Europe model cannot be used easily by non-expert users because it is complex and there is no open access to the model.

#### **2.1.3 Estimation of cost**

##### **Summary of the methodology/models used**

For the calculation of cost of biomass an excel based activity based costing model was developed to calculate the road side cost of biomass. So the cost from road side for transport and possible in-between treatment to the gate of the conversion installation or the pre-treatment installation are NOT included. The cost for the collection from the road-side to the gate as well as the pre-treatment costs are estimated specific biomass delivery chains further assessed in models (ReSolve) and S2BIOM tools (BeWhere & LocaGIS) included in the S2BIOM toolbox and applied in specific regional case studies.

It involves the whole production process of alternative production routes that can be divided in logical organisational units, i.e. activities. The general purpose of this model is to provide minimum cost prices for the primary production of biomass feedstock at the road side. ABC generates the costs of different components based on specific input and output associated with the choice of the means of production, varying with the local conditions and cost of inputs (e.g. labour, energy, fertilisers, lubricants etc.). Since the production of most biomass is spread over several years, often long term cycles in which cost are incurred continuously while harvest only takes place once in so many years, the Net Present Values (NPV) of the future costs are calculated. This provides for compensating for the time preference of money. To account for the fact that the cost are declining in different periods of time in the future the Net Present Value annuity is applied. In this way annual, perennial crops and forest biomass cost are made comparable (=all expressed in present Euros).

Cost are presented as NPV per annum and expressed in € per ton dm or per GJ.

Net Present Values of all activities are calculated as follows:

$$NPV = Fv / (1+i)^n$$

Where:

NPV = Net Present value  
 Fv = Future value  
 i = the interest rate used for discounting (set to 4%)  
 n = number of years to discount

Then the Net Present Value annuity is applied, assuming that the sum of NPVs cover the annual capital payments attracted against the same interest rate (4%) as the discount rate used for calculating the NPVs.

$$NPVa = \sum NPV * (1 / ((1 - (1+i)^{-n}) / i))$$

Where:

NPVa = Net Present Value annuity  
 $\sum$ NPV = sum of NPVs  
 n = number of years  
 i = the interest rate (set to 4%)

Crop residues also require a separate approach as harvesting cost can usually be allocated to the main products, i.e. grain in the case of cereal straw, and not to the residue. However, the baling of the straw and the collection up to the roadside can be included in the costs.

The cost are determined for 2012, the reference year and are kept constant in the future years 2020 and 2030.

In S2Biom only the costs specifically made to produce the biomass for the non-feed or -food markets are considered. This means that in cases where there is a crop production for human consumption or for feed involved, such as wheat, this production will be considered the main product and the biomass for non-feed or food (e.g. straw in case of wheat) the by-product. All costs of growing the crop are attributed to the main product and consequently these become sunken costs for the by-product and thus excluded. Only activities specifically dedicated to the by-product (e.g. harvesting the straw) add to the (minimum) cost level of the biomass feedstock. Following this reasoning cost associated with land (e.g. land rent) are not attributed to the residual biomass.

This means that in the case of straw and stubbles only the cost of harvesting, fertilization, because of nutrient removal with the straw, and baling and forwarding to the road side/farm gate are included in the calculation.

The cost for fertilization are needed to compensate for the loss of nutrients in the straw itself (i.e. not for the grains). These straw nutrients would otherwise be worked in the soil and act as fertilizer. So the cost for fertilization accounted for cover only part of the total fertilization cost of the cereal crop. For the calculation of cost a detailed selection and characterisation was made of the type of machines used for the harvesting of residues. The larger machines are used in regions where larger fields dominate as identified per region in the Lucas database for the category of arable fields.

In the case of prunings from permanent crops it was assumed that the pruning activity itself is part of normal management of the main crop and the cost are therefore not allocated to the residues. What is included in the cost of pruning is the operations for obtaining the branches left on the soil, as shredded material at road side. For that purpose the operations are based on the existing mechanised technology, consisting of shredders of different types which are able to pick-up the branches, shred them, and convey into a big-bag, a built-in container, or an agrarian trailer towed behind the shredder. In addition the costs of gathering and transporting to the road-side also need to be calculated separately and for these cost levels the row distance between the crops is very influential.

A relationship between field size and row distance was also assumed where larger fields go together with larger row distances and the other way around. The final choice of machinery is determined by the combination of row distance and dominant field size.

### **Summary of main data used**

In the cost calculation a long list of data inputs is required. Firstly the most important group of inputs are needed to allow for a national differentiation in cost levels according to main inputs having national specific prices levels. It refers to detailed information concerning the prices of various resources needed as input for the production process of biomass specific per country. These are specified, either in absolute price levels or as an index related to the known price level in one or two specific countries (mostly Germany). This is necessary as prices of key production factors differ a lot at national level across Europe. National level price data (ex. VAT) included cover cost/prices for labour (skilled, unskilled and average), fuel, electricity, fertilizers (N, P<sub>2</sub>O<sub>5</sub>, K<sub>2</sub>), machinery, water, crop protection and land. Most of these data were gathered from statistical sources such as FADN (Farm Accountancy Data Network), Eurostat and OECD. Most cost levels were gathered for the year 2012.

Next input data the machine input mix which was selected for every activity but specified per management level. So larger machines are generally used in High input systems if these can be operated on the average field sizes encountered in the region under focus. The average field sizes as collected in LUCAS database are guiding in mechanization possibilities. The main source of information used to gather

all financial and functional characteristics of the different machines is the German online database “KTBL-online”. It entails an extensive range of equipment and a similar database is available at WUR (KWIN). Low, medium and high machinery input alternatives from this list have been chosen as typical instances. The following aspects are handled:

- Capacity; the equipment is classified as Low, Medium or High capacity
- Capacity in tonnes (Apt), gives the amount of production per transport operation
- Effective working width in m (We)
- Operating velocity in km/h (V)
- Replacement value in €
- Technical lifetime in years
- Rest value in € (default value is set to 1)
- Average annual costs as a percentage of the replacement value is the sum of:
  - o Depreciation rate (%)
  - o Interest rate (%)
  - o Auxiliary (%) For maintenance & repair, storage, insurance
- Potential use per year (hr) or in case of some parts of the irrigation system per ha. The value is often based on expert judgement, considering the technical lifetime as well as usability during the season.
- Machine cost per hour in €. Calculated from the average annual costs and potential use
- The number of machines involved in a field operation. The default is set to 1
- Energy, Fuel & lubricant costs / hr (€):
  - o Traction fuel (l/hr). Only set when traction is involved, i.e. tractors and self-propelled machines
  - o Traction oil (l/hr). see fuel
  - o Fuel price (€/l). A default value is set
  - o Oil price (€/l). A default value is set
  - o Electricity (kWh)
  - o Electricity price (€/kWh)

In addition to the machinery input information a lot of information was also collected on the amount of time needed to fulfil key activities (field – operations).

Since row distance determines strongly the mechanisation options and thus the pruning harvest time and labour cost in pruning activities much attention was paid in the EuroPruning project to estimate average row distances in different regions in Europe in different permanent crops. Subsequently an estimate needed to be made of the distribution of the different permanent crops over the 3 row size classes. This was done at NUT3 level by combining FSS permanent crop area information with the distribution of the area over different CORINE land cover (CLC) classes. Small fields with small row distances were expected to dominate in mixed CORINE land cover

classes (class 241). The larger row sizes are likely to occur more in the CORINE classes with monocultures of permanent crops mapped separately as CLC classes: 'olives', 'vineyards', 'fruit trees and berry plantations' (classes 221, 222 and 223 respectively). Beside the row distance, estimates were also made of the average field size of the different permanent crops. This was again based on the LUCAS database<sup>3</sup>. Both row distance and field size were taken into account when calculating pruning cost and explain variations in cost between countries beside other national specific cost factors.

### Limitations of methodology & data used

- Although the activity based costing model developed in S2Biom allows for highly detailed cost calculations and national variations in main input cost have been taken into account, it remains an impossible task to cover the wide diversity of harvest and collection practices in Europe. Cost calculations made in S2Biom need to be regarded as average cost which in reality can still range very strongly between countries and regions.
- It should be realized that the cost calculated here only cover the road side cost. These are only part of the cost and one should realize that still many cost need to be made to bring the biomass from the road side to the gate of the conversion plant. So to get a full picture of the at gate cost, more information is required which is chain and location specific and requires additional tools and information.
- Activities related to establishing the contract (transaction costs) and other overheads are not (yet) accounted for. These cost can be quite substantial.
- Cost are calculated here only indicate towards the minimal price that needs to be paid to cover the cost of the residues. In reality there are also biomass types, such as for cereal straw, that have already a large market demand. The road side cost are then less meaningful while the real price setting is to obtain a good idea about cost that need to be made to buy the feedstock.
- In case of pruning, and different to straw, mobilising the biomass for energy is not an "energy" or "demand" driven activity currently. It is stated that there where agricultural pruning wood is being mobilised for energy, there is an advantage for the farmer, who saves some money for the disposal or treatment of the residue. The farmers usually internalise part of the costs of the operations, and collaborate in the value chain. So, for the estimation of costs at regional level it is advised to first assess the most applicable value chains that could be implemented in the area, and then to perform an

<sup>3</sup> LUCAS database, 2013, Eurostat (). LUCAS data used are from the LUCAS 2012 Survey. It provides a distribution of agricultural Corine land cover classes (e.g. arable, permanent crops, olives etc.) over 4 parcel classes: <0.5 ha, 0.5-1 ha, 1-10 ha and > 10 ha.

estimation of costs based on the specific chain, accounting only the costs of operations not internalised by farmers.

### **Recommendations on how to address limitations in data & methodology**

Recommendations on how to address the limitations are given below. The numbers refer to the list of the previous section.

- The cost calculations should be adapted as much as possible to the practices specific to the area of interest. The ABC model leaves large flexibility in adapting all input factors specific to the area of interest practices. If data are available it is easy to adapt the input data in the model.
- In addition to assessing the road side cost it is important to make a good estimate of the cost that need to be made to pre-treat the biomass (e.g. dry, densify, clean, chip, pelletize) and to transport it to the conversion gate. In order to make good estimates of these cost it is helpful to evaluate the area of interest and make specific choices for conversion technologies with help of other tools developed in S2Biom, particularly the Bio2Match tool and the LocaGISTICS tool. All tools are available in the S2Biom toolset available at [www.biomass-tools.eu](http://www.biomass-tools.eu)
- Since transaction cost and other overheads are not (yet) accounted for in the cost model calculations it is recommended to assume a fixed percentage on top of the calculated road side cost price (typically in the range of 20% - 50%).
- For biomass types that already have a large market penetration and can be regarded commodities it is recommended to also collect data of market price levels in order to get a more realistic picture of feedstock cost.

### **Recommendations on temporal frequency of updates**

Statistics on machine price level indices, fuel cost, labour cost and interest rates are published annually. Therefore, the calculations can be updated annually, if drastic changes in cost factors are observed.

### **Practical aspects of the implementation of the up-date**

The ABC cost calculator is freely available and can be used by everybody. However, the current version of the model is not adapted into an easy to use model, so some time investment to understand all calculation modules is required. The most challenging however will be to fill the model with accurate data specific to the area of interest.

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## 2.2 Dedicated cropping of lignocellulosic biomass

### 2.2.1 Estimation of supply

### 2.2.2 Introduction

#### Summary of the methodology/models used

The potential supply of perennial crops and SRC was estimated for the period 2012, 2020 and 2030 for the subcategories presented in Table 3 underneath.

Table 3 Subcategories “Primary production of lignocellulosic biomass crops

Third level subcategories		Final level subcategories	
ID	Name	ID	Name
211	Energy grasses, annual & perennial crops	2111	Sweet and biomass sorghum (Annual grasses)
		2112	Miscanthus (Perennial grass)
		2113	Switchgrass (Perennial grass)
		2114	Giant reed (Perennial grass)
		2115	Cardoon (Perennial crop)
		2116	Reed Canary Grass (Perennial grass)
212	Short rotation coppice	2121	SRC Willow
		2122	SRC Poplar
		2123	Other SRC

The assessment of the land availability and yield potential is challenging and builds on work already performed in several other projects (See D1.6, Table 7). A lot of valuable material is generated in these projects on identifying the best suitable perennial crops for bioclimatic and soil diversity in Europe in experimental fields and wider meta assessments by European crop experts.

Current lignocellulosic and woody crop production areas are low. For the future the likelihood that increased demand for lignocellulosic biomass will lead to large production of perennials on existing good quality arable lands is rather low. Therefore the assessment of the potentials focusses on lands that are current unused or become unused towards 2020 and 2030.

The land no longer used for agriculture, as assessed by the CAPRI model for the baseline scenario, is taken as a potential land resource for woody and herbaceous biomass cropping. Only the land availability for these crops is taken and this is then combined with data generated in the S2BIOM project on biomass crop yield simulations and net present value cost calculations to come to a final biomass potential for these crops in Europe (see Figure 1). The large advantage of using the land claim for these crops from CAPRI is that it has been identified taking account of competing land use claims from other activities, such as for food, feed, and urbanization.

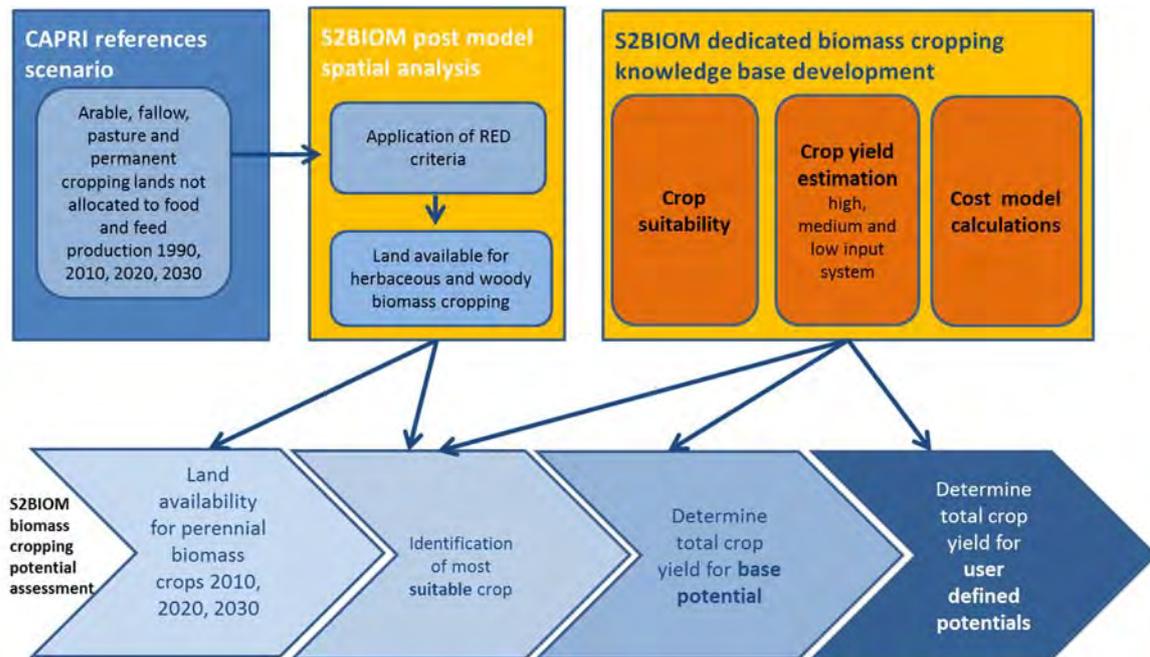


Figure 1 Integration of CAPRI land availability for dedicated biomass crops with S2BIOM yield and cost level assessments to estimate herbaceous and woody biomass cropping potentials

In S2BIOM for the assessment of the base potential, the following criteria are guiding the land suitability and allocation (see also Table 4):

- 1) Avoid competition with food and feed production for the economic and sustainability considerations already discussed in the former. Overall it is clear that mobilisation of perennial biomass cropping is not expected to take off on good agricultural lands.
- 2) Make the sustainability criteria for biofuels applicable to solid and gaseous biomass sources to be used for the generation of bio heat, -electricity and biobased chemicals and materials (see next on application of RED criteria).
- 3) Make suitability masks per crop showing the suitable and unsuitable areas to grow the crop, based on bio-physical limiting factors.
- 4) Integration of CAPRI unused land availability with perennial cropping yields, water requirements and NPV cost levels (see next section on assessment of cost)

Table 4 (RED) sustainability criteria for assessing land available for dedicated biomass crops

RED criteria:	Rules implemented to assess land availability & selection of suitable woody & perennial crops	Technical potential	Base potential	User defined potential
No loss of habitat of high biodiversity value	Exclusion of use of Natura2000 areas & other protected areas		X	X
	Exclusion of use of High Nature Value farmland		X	X
No use of areas of high carbon stock lands	Exclusion of wetlands & peatland areas		X	X
	Only use lands that have been registered as agricultural since 1990 which ensures exclusion of continuous forest lands	X	X	X
	Exclusion of permanent grasslands (even if released from agriculture as assessed by CAPRI)		X	X

RED criteria:	Rules implemented to assess land availability & selection of suitable woody & perennial crops	Technical potential	Base potential	User defined potential
Avoidance of direct land cover changes	Only use lands that have been registered as agricultural since 1990 and marginal and polluted lands (as identified by JRC). This ensures exclusion of continuous forest lands, urban lands, recreational areas etc.	X	X	X
	Avoid conversion of permanent grasslands to arable		X	X
Avoidance of indirect land use changes	Only use surplus (agricultural) lands and marginal and polluted lands	X	X	X
Support agro-biodiversity	Avoid use of Natura2000 & HNV farmland (even if released from agriculture as assessed by CAPRI)		X	X
	Avoid conversion of permanent grasslands to arable		X	X
	No use of fallow land if fallow land share (in total arable land) declines to < 10%			X
	Avoid monoculture choosing mix of at least 3 perennial crops per region (covering both woody and herbaceous crops)		X	X
Avoid negative impacts on soil quality & enhance soil quality impacts	Maximum slope limits to perennial plantations		X	X
	Use perennial plantations to protect soil susceptible to erosion		X	X
	Use perennial plantations for bio-remediation of polluted soils			
Avoid negative impacts on water resources	Only use crops where minimal water requirement is delivered through annual precipitation (so irrigation is allowed but water depletion is avoided)		X	X
	No use of irrigation in perennial crops			X
	Preference for water use efficient crops in drought prone regions			X
Avoid competition with food	Only use surplus (agricultural) lands	X	X	X

For the identification of potentially available lands the following land categories and information layers are used:

- 1) Land availability based on the CAPRI agricultural markets and land use change simulation modelling for the reference scenario (2008-2030). By only taking the released and unproductively used lands from CAPRI it is ensured that the full demand for food and feed is first fulfilled. The following categories of released and/or non-productively used agricultural lands are available from CAPRI per type of potential:
  - a. Technical potential:
    - i. all good and low productive agricultural land released between 2008-2012, 2008-2020, 2008-2030
    - ii. all permanent grassland released between 2008-2012, 2008-2020, 2008-2030
    - iii. All fallow land available in 2012, 2020 and 2030 respectively
    - iv. No limitation of above land categories according to environmental or economic considerations
  - b. Base potential:
    - i. all good and all low agricultural land released between 2008-2012, 2008-2020, 2008-2030
    - ii. All fallow land available in 2012, 2020 and 2030 respectively
    - iii. Limitation of above land categories according to (RED)environmental considerations as specified in Table 4)

c. User Defined potential:

- i. All land available in the base potential for dedicated crops with the exception of fallow land below a 10% fallow share in the arable land area in 2012, 2020 and 2030. Fallow land must first reach 10% of the arable land.
- ii. Only rain fed crop production is allowed. Crops that need irrigation in arid regions cannot be used.

2) Lands excluded because of policy constraints related to RED on the use of high biodiversity and carbon stock lands were translated into maps to identify which shares of the released agricultural land categories should be excluded from use for dedicated biomass cropping.

Table 5 No- go areas according to RED and bio-physical constraints

No-go area consideration per scenario	RED and bio-physical exclusion criteria & assumptions for mapping	Source
High biodiversity lands are excluded from the land availability in the <i>baseline, strict sustainability</i> and <i>realistic mobilisation scenario</i>	HNV farmlands in EU are mapped using agricultural Natura 2000 areas overlapping with CORINE agricultural land cover classes. A likeliness score for HNV farmland has been determined per region (Nuts 2/3) for arable and permanent grassland was mapped. It is assumed that the HNV farmland share for released agricultural land is similar to the average share for a region.	HNV farmland likeliness map: Paracchini et al., 2008; CLC 2012: EEA, 2012.
Land released in the permanent grassland category cannot be used for dedicated cropping because of risk of soil carbon loss in the <i>baseline, strict sustainability</i> and <i>realistic mobilisation scenario</i>	CAPRI land use changes between 2008, 2012, 2020, 2030 can be tracked per land use class by calculating a net land use change balance assuming shifts between good productive lands (used for rotational crops, fruit crops and temporary grassland) and lower productive lands (used for other permanent crops e.g. vineyards, olives, nuts etc. and permanent grasslands). Based on this balance it can be estimated how many permanent grassland areas go out of production between 2008 and 2012, 2020 and 2030 respectively. These releases are not to be used for dedicated cropping.	CAPRI land use change baseline results 2008, 2010, 2020 & 2030.
Fallow land if the total fallow land share in arable land is below 10%	Fallow land share in 2012, 2020 and 2030 can be calculated from CAPRI baseline per NUTS2 region by dividing the fallow land by the total arable land in different years. If the share is below 10% no fallow land can be used for dedicated cropping. If the fallow land share is above 10% the land up to 10% of fallow land share can be used for dedicated cropping.	CAPRI land use change baseline results

3) Land with no or low suitability for one or more types of perennial biomass crops. This requires the elaboration of suitability maps masking (part of) the regions that are not suitable for specific crops because of climatic and or bio-physical limitations. For the elaboration of these spatial masks a matrix was developed matching the classified bio-physical limitations with the specific crop requirements (see D2.6, Tables 10, 11). A differentiation is made between soil and topographic characteristics (slope, soil depth, texture and soil pH) and climatic factors

(temperature, precipitation, maximum and minimum temperature in growing season and killing frost).

#### *Crop yield simulation model description*

For miscanthus, switchgrass, giant reed, reed canary grass, cardoon and SRC willow, poplar and eucalyptus a simple crop simulation model was developed. To assess the yield of the biomass crops the data on daily weather factors (are combined in this model with the phenological factors determining the crop growth of a specific biomass crop. These factors were derived from a wide range of projects and publications on field trial based assessments with lignocellulosic crops under a wide range of soil and climatic circumstances in Europe. For an extensive description of the approach and input data used we refer to D2.6 Chapter 2 (Dees et al., 2016) the section on dedicated crop potentials.

#### *Suitability masks per biomass crop*

Suitability maps were prepared masking (part of) the regions that are not suitable for specific crops because of climatic and or bio-physical limitations. For the elaboration of these spatial masks a matrix was developed matching the classified soil and climate limitations with the specific crop requirements. The selection of parameters and classes builds on the JRC study (Confalonieri et al. 2014) but has been refined using several references (see Table 15 in S2BIOM report D1.6 (Dees et al., 2016). Scores on the parameter classes can be:

- “0” unsuitable,
- “1” Low suitability,
- “2” medium suitable,
- “3” suitable,
- “4” very suitable.

The combination of factors scoring ‘low suitable’ (=0,1) are completely masked out on a map for the specific crop. A differentiation is made between soil and topographic characteristics (slope, soil depth, texture and soil pH) and climatic factors (temperature, precipitation and killing frost). For killing frost a distinction was made between winter frost (when the plant is dormant) and spring frost, when the growing season has started. Frost occurrence in this early growth stage can be particularly harmful for some crops (see Table 16) such as cardoon, giant reed and eucalyptus limiting the area in Europe they can grow significantly as compared to switchgrass and also miscanthus. The latter crop is however not able to cope with too extreme winter colds as it limits strongly the survival rate and prevent enough re-growth in spring. This explains a slightly smaller area suitability coverage for miscanthus as compared to switchgrass or willow.

## Summary of main data used

For the assessment of land availability for dedicated crops the CAPRI baseline run results are again used, like was done for the calculation of the future agricultural residues potentials. Unused lands are estimated in a post model analysis based on the most recent CAPRI baseline run 2008-2050, providing intermediate results for 2010, 2020, 2030 (and 2050). This baseline run is seen as the most probable future simulating the European agricultural sector under status-quo policy and including all future changes in policy already foreseen in the current legislation. It also assumes all policy regarding bioenergy targets as agreed until now and further specified in the *Trends to 2050* report (EC, 2013)<sup>4</sup> for as far as affecting agriculture. By only taking the released and unproductively used lands from CAPRI it is ensured that the full demand for food and feed is first fulfilled. How this is done is further explained in the former Section.

Data to map No-go areas are specified in the Table 5 in the former and include:

- The HNV farmland likeliness map (Paracchini et al., 2008)
- Corine Land Cover 2012 (EEA, 2014)
- CAPRI baseline run land use 2008, 2012, 2020 and 2030.

The suitability masks per crop were elaborated for a wide range of data on soil and topographic characteristics (slope, soil depth, texture and soil pH) and climatic factors (temperature, precipitation and killing frost).

Main data sources used to elaborate the maps are the following:

- 1) The meteorological data were derived from the JRC-MARS database from European Commission-Joint Research Centre (JRC). The daily long-term data average (since 1975) were used: (i) temperature (minimum, average, maximum in °C), (ii) rainfall (in mm), (iii) reference evapotranspiration ( $ET_0$  in mm) available on grid cells of 25x25 km.
- 2) the Soil Geographical Database of Eurasia (SGDBE) at scale 1:1,000,000 from the European Soil Database version v2.0 produced by JRC. The soil features: soil depth and soil texture were taken from Miterra data, no data were available for Western Balkans, Turkey and Moldova.
- 3) The steep slope data was derived from Global Terrain Slope and Aspect Database<sup>5</sup>. This database comprises of the following elements.

4 EC (2013). *EU Energy, Transport and GHG emissions trends to 2050. Reference Scenario 2013*

- i. Elevation (median)
- ii. Slope gradient: Distributions of nine slope gradient classes are available for each grid-cell: 0–0.5%, 0.5–2%, 2–5%, 5–8%, 8–16%, 16–30%, 30–45%, and > 45%.
- iii. Slope aspects: Slope aspect data is stored in distributions of five classes namely: Class 1: slopes below 2% undefined aspect; Class 2: slopes facing North (315°–45°); Class 3: East (45°–135°); Class 4: South (135°–225°), and Class 5: West (225°–315°).

To elaborate the masks four slope classes were extracted and elaborated from this database, namely: 0-4%, 4-8%, 8-15%, 15-25%, and >25%.

The data collected specifically on the phenological factors determining the crop growth of the specific biomass crops, were derived from a wide range of projects and publications. For an extensive overview of the input data used we refer to D2.6 Chapter 2 (Dees et al., 2016) the section on dedicated crop potentials.

### **Limitations of methodology & data used**

Of all biomass types the potentials for dedicated crops are likely to be most uncertain for several reasons.

- Firstly, current lignocellulosic and woody crop production areas are very small. Whether the potential from these crops will really be mobilized depends on many factors which could not all be taken into account in the assessment of the potential. Some of the main factors determining future mobilization are summarized underneath:
  - a. access rights to lands;
  - b. uncertainty about establishment cost, particularly on the more marginal lands
  - c. uncertainty about economic returns as experience with growing these novel biomass crops is very limited and is mostly in the stage of field trials. Some European wide scattered commercial experiences exist which so far have not been proven very successful (e.g. RCG production in Finland). Uncertainty about economic returns is influencing the interest of land owners and/or investors;
  - d. loss of flexibility by the farmer to decide on his/her cultivation plan as the plantations usually have a lifetime of between 10 to 20 years

- e. unclear arrangements regarding CAP payment rights in certain EU countries when agricultural land is planted with SRC crops for a longer period of time
- f. opportunity to set-up optimal logistical biomass delivery chains making collection cost effective requires cooperation between different actors in the supply chain not only several biomass providers (farmers), but also the conversion industries
- g. ensure minimal feedstock delivery and security of supply which can only be realized if several farmers together invest in dedicated biomass cropping activities.

In the potential assessment most of these factors were not taken into consideration because they are difficult to predict.

- The experience with growing biomass crops in Europe is still limited and crop simulation input data were mostly based on field trial information from a limited number of locations. The yield simulation work done in this project was based on data available, but much more experience and field trialling is necessary to obtain more reliable crop yield response understanding, particularly in more marginal circumstances in Europe.
- The land availability estimates referring to unused lands potentials are based on many assumptions. All these assumptions are uncertain including the ones based on CAPRI post-model assessments. It should be acknowledged that model outputs, even though coming from a well-documented and validated model, remain highly uncertain and they are always a simplification of the situation. Models cannot take all factors of influence into account, certainly if the future is far away.
- For the post-model evaluation of land availability, the mapping of no go areas and the elaboration of the crop specific masks for land suitability we had to work with rather coarse data (low resolution data). The exact location of the unused land within every region for which CAPRI provided results, was not known. The match with no go areas (according to RED) and also with climate and soil characteristics was not known and had to be estimated. An area share was assumed that matched with the regional area share, for typical soil and topographic characteristics and also overlap with e.g. HNV farmland areas. So, if a share of the arable agricultural land was overlapping with HNV farmland, we assumed that the same area share applied to the released agricultural land resource. For the weather data available at 25\*25 km resolution, we first recalculated average Nuts 3 region levels before they were used as input into the crop simulation model and to generate the mask of suitable areas per crop. Because of these scale and lack of knowledge on the exact location, the results take less account of extremes and are likely to be less accurate for certain regions where unused land resources are unevenly spread or where soil and weather factors are strongly diverse within one Nuts 3 region.

## Recommendations on how to address limitations in data & methodology

Recommendations on how to address the limitations are given below.

- Estimations of future biomass potentials should consider additional socio-economic factors (e.g. owner or societal attitude towards intensified use of forest resources) and should be based on bottom-up approaches. Through these local case studies can be performed with involvement of land managers, potential investors and local governments to identify real interest in and opportunities and limitations of setting up large scale dedicated cropping activities;
- Estimates of cost and yields for dedicated biomass crops should be based as much as possible on larger scale field experiences in the relevant bio-climatic circumstances. The more field experience there is, the more reliable yield estimates can be made for the whole European territory using crop yield simulation models.
- In this study no attention was paid to performance differences for different varieties of the same crop. The simple assumption was made that the crop used in every region was chosen according to best performing varieties of the crop. So for example for southern Finland a switchgrass a variety was chosen that proved to be best surviving in cold winters and short growing season. For the crop simulation work crop phenological parameters were taken that refer to an average crop performance not taking account of all variety characteristics that may exist.
- Land availability estimates made in this study should be validated as much as possible with local land use and other spatially explicit information to determine whether the identified unused land estimates really overlap with identifiable unused land resources at local level. For these unused lands' it should be well evaluated what the current land owner and access status is, what the reasons are behind leaving land unused and whether the taking into use of this land through dedicated biomass cropping is indeed an option for local actors given both biophysical, technical and socio-economic limitations.

## Recommendations on temporal frequency of updates

The most recent S2BIOM biomass potential estimates are based on post model processing of CAPRI model output and on accessible and available information on crop performance of different biomass crops from existing projects, mostly working with field trials.

It is recommended to use new CAPRI model runs for new scenario runs to up-date the land availability results over the next years. It is also recommended to improve the data on crop performance further by continue the collection of information in this field both from published material and new projects where practical experience with the production of these crops is gained. Based on the additional collection of this

information further validations and where necessary corrections can be made to the yield simulation results in S2BIOM.

### **Practical aspects of the implementation of the up-date**

The estimation of the land availability and total dedicated cropping potential is challenging and likely to be difficult to be repeated by groups not involved in this work. Updates, improvements and further validations need to be performed by experts with access to models and high resolution data and can best be done in close collaboration with the researchers who performed the S2BIOM potential assessment estimates.

#### **2.2.3 References**

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## 2.2.4 Estimation of cost

### Summary of the methodology/models used

For the assessment of the cost of dedicated biomass crops the same activity based costing model (ABC) was used as for agricultural residues. The ABC model assesses the road side Net Present Value (NPV) Cost of biomass. The model calculations for road side cost of dedicated crops are more extensive than for residues as more activities are covered which need to be allocated to the final biomass cost.

In order to assess the cost of a dedicated crop per location in Europe, 8 interrelated excel work sheets in the ABC model need to be filled. This enables calculation of dedicated biomass Net Present (NPV) cost per type of crop, in a 60 year cycle for every Nuts 3 region in Europe for 3 management systems: low, medium and high input management systems. The low input systems are tuned with low productive soils in more marginal conditions, while the high input systems are tuned with higher quality soils where input limitations are expected to be more limited because higher yields are possible.

Plantation life time per crop type assumed is as follows:

- 12 years for SRC willow, poplar and eucalyptus and cardoon.

- 15 years for perennial grasses

In the Figure 2 an overview is given of the 8 model modules involved in the calculation of the dedicated cropping cost. These 8 include:

1. **Crop input 1** module sheet gathers the potential yield level of the selected crop and water use combination at national or nuts3 level from the crop yield simulation model for dedicated crops as discussed in the former.
2. **Crop inputs 2** module sheet gathers the condensed information of the selected crop covering information on inputs specific to the yield type, yield level and input level selected in the case input sheet.
3. In the module **Crop inputs 3** the different crop management activities are gathered according to the crop management selection in the case input. In order to make crops with different cropping intervals comparable through time, activities are set on or off per year over a 60 year cycle. With a total cycle of 60 years complete cycles of 1,2,3,5,10,12,15,20 or even 30 and 60 year intervals can be covered by the model.
4. In the '**Country inputs**' module detailed information concerning the prices of various resources needed as input for the production process of biomass are gathered specific per country. These are specified either in absolute price levels or as an index related to the known price level in one or two specific countries (mostly Germany).
5. The '**Machinery inputs**' module contains extensive information about different aspects of mechanized equipment involved in field operations.
6. In the '**Task Time Activity**' module for a number of activities (field – operations) the amount of time needed to fulfil the operation is calculated with a model from De Lint et al (1970).
7. All modules described in the former then transfer the parameters to the **Calculus** module. This module consists of 2 calculation sheets which are linked.
  - a. The first is the '**Activity cost calculus**'. In this module all activities cost are gathered from the different input sheets to calculate the total cost of all activities involved in terms of machinery, labour input and energy input requirements.
  - b. The time consumption per activity is gathered from the '**Task Time Activity**' module as discussed above.

## Flowchart Activity based costing model

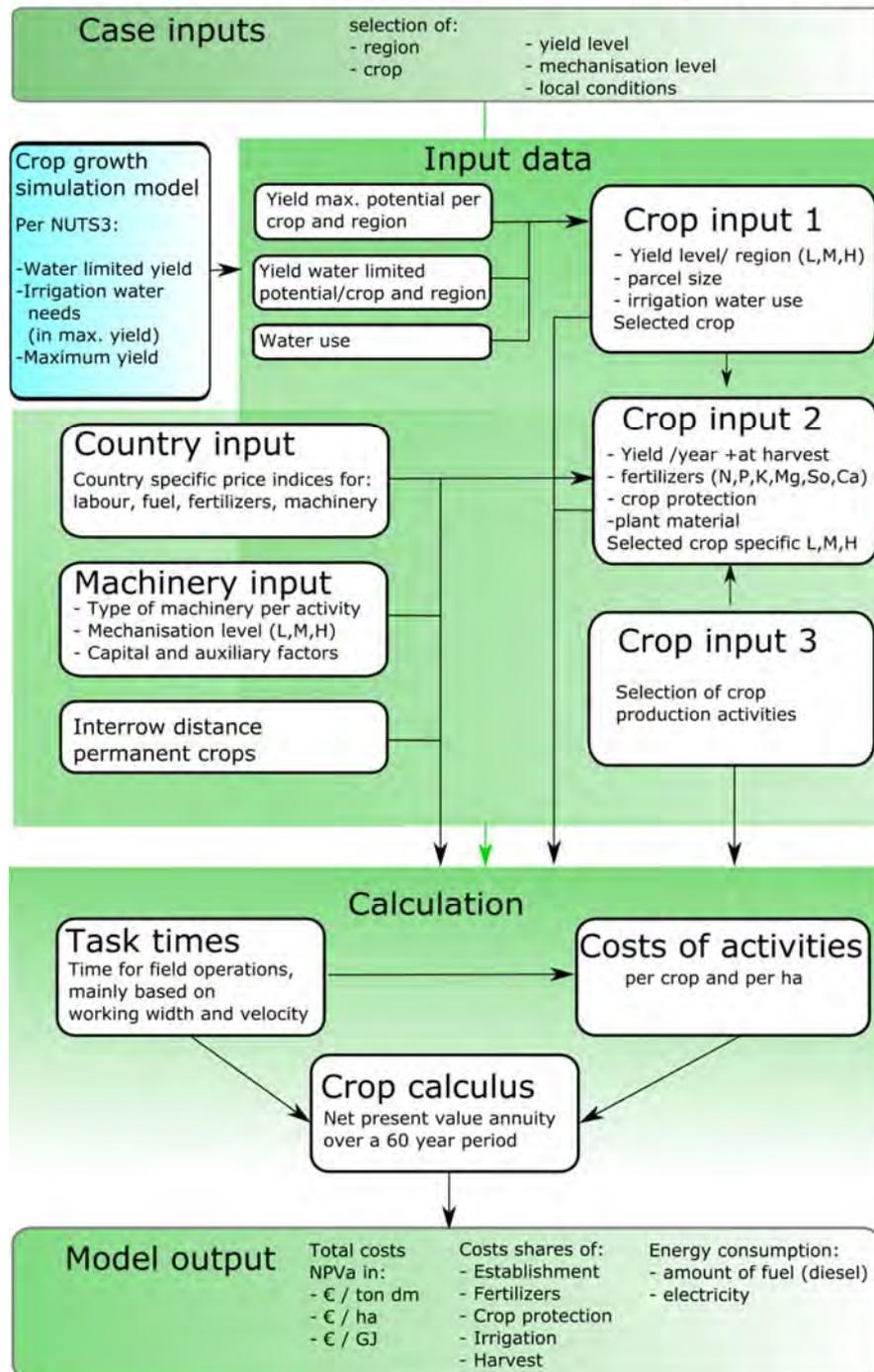


Figure 2 Overview of ABC cost calculation model for dedicated biomass crops

- The final calculation worksheet which generates the final cost is the '**Crop calculus**' module. In this final worksheet all the costs associated with the selected crop in the specified region are expressed in a net present annuity, making each crop comparable through time. It adds up for the specific case input selection all activity cost, and all input cost per year, for the total lifetime of the plantation and repeats this until it reaches a total of 60 years. Then the

Net Present Value annuity is applied assuming that the sum of NPVs cover the annual capital payments attracted against the same interest rate (4%) as the discount rate used for calculating the NPVs. The total sum of NPVs over all 60 years can then be divided by the biomass harvested to express the NPV value in €/ton dm. By multiplying this with the energy contents (lower heating value, LhV) a conversion to GJ is made to come to the cost expressed in €/GJ.

### **Summary of main data used**

An extensive explanation of the main data gathered and the sources used is given in the former Section 2.1.2 where the ABC model application is described for calculation of cost of agricultural residues.

### **Limitations of methodology & data used**

The limitations of the cost calculations are the same as already described in the former Section 2.1.2 for agricultural residues. For the dedicated cropping cost calculations it can be added that calculation of these cost are even more challenging because:

- 1) There is still relatively limited experience in Europe with producing these crops. This does not happen much at a large commercial scale. The field activities and also the machinery available are still limited and in development. Exact knowledge on management of the dedicated cropping systems can be improved when field experience is further incorporated in the cost calculation.
- 2) Another limitation is that currently limited cost are made for the preparation of the field before establishing the crop, while this could be very challenging in lands that have gone out of production for a longer period of time and/or are marginal or low productive.

### **Recommendations on how to address limitations in data& methodology**

Here the same recommendation as for cost calculations of agricultural residues apply as discussed in Section 2.1.2. In addition to these recommendations the following apply specifically for dedicated crops:

- 1) Any further crop management information that can be gathered from field experience in specific biomass crops is useful for further improving the ABC model in order to generate improved cost-levels.
- 2) Expert information on preparation of low productive lands that have gone out of agricultural use for a middle to longer period of time are needed to improve the cost estimates in the ABC model covering field preparation.

### **Recommendations on temporal frequency of updates**

Here the same recommendation as for cost calculations of agricultural residues apply as discussed in Section 2.1.2.

### **Practical aspects of the implementation of the update**

Here the same recommendation as for cost calculations of agricultural residues apply as discussed in Section 2.1.2.

#### **2.2.5 References**

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## 2.3 Unused grassland cuttings

### 2.3.1 Estimation of supply

### 2.3.2 Introduction

#### Summary of the methodology/models used

The grassland cuttings potential assessed refers to biomass derived from grasslands that are part of the farming area, so not abandoned officially, but underused.

The potential calculation was done using the Miterra-Europe model (Velthof et al., 2009; Lesschen et al., 2011; de Wit et al., 2014) and builds on two main assessments. The core of the analysis is the calculation of a feed balance at regional level covering the total grass use for feed in every region. This approach is described in Hou et al. (2016) and is the basis for the assessment of the nitrogen excretion of livestock in the EU-27 at regional level (Nuts 2). In this assessment the total grass production is based on grassland yields of Smit et al. (2008) and grassland areas based on 2010 Eurostat data both at Nuts 2 level.

For the calculation of the unused grassland resource potential the total of Hou et al. (2016) ‘perennial forages (= *grass harvested by grazing and grass harvested for silage and hay*)’ was used. This total was then subtracted from the ‘total biomass production from perennial forages’ to come to a net unused grassland biomass availability. So the following formula was applied:

Unused grassland yield = (perennial forage cropparea \* yield \* DM\_content) – (perennial forage intake by animals).

Where:

- Perennial forage area: derived from CAPRI per country for 2012, 2020 and 2030
- Yield levels: derived from Eurostat (2014) and Smit et al. (2008)
- Dry matter (DM) content is:
  - Managed grass: 20%
  - Natural grass/rough grazing land: 20%

#### Summary of main data used

In this assessment the total grass production is based on grassland yields of Smit et al. (2008) and grassland areas based on 2012 Eurostat data both at Nuts 2 level.

#### Limitations of methodology & data used

The 2 main limitations specifically related to the calculation of cost of unused grassland cuttings are:

- 1) The approach could only be applied to EU-27 countries (so excluding Croatia, western Balkans, Ukraine, Turkey and Moldova). Extrapolation of the

methodology to the other non-EU countries was not possible given data limitations and time constraints to extend the Miterra Europe model application.

- 2) The calculation was made for the year 2012 as the calculations were too complicated to also be made for future years as this would involve incorporation of many additional uncertain parameters. The potentials for 2012 are assumed to remain stable toward 2020 and 2030 which is very unlikely as livestock numbers will change in the future as will the feeding practices.
- 3) The calculation of the whole unused grassland potential builds on a very large number of assumptions and ignores largely differences in farming practices within regions.

### **Recommendations on how to address limitations in data & methodology**

- 1) It is recommended to extend the calculation of this unused grassland resource particularly for countries in Europe where grazing land abandonment has been significant as this biomass type could be a promising resource. This requires additional data collection and adaptation of the Miterra-Europe model and can only be done in collaboration with Miterra-Europe modellers.
- 2) For the main parameters in Miterra-Europe that need to be taken into account to make the potential calculations for 2020 and 2030 need to be parameterized with experts in the field. This may be challenging, but it is crucial to make realistic assumptions about future developments in livestock feeding practices. In this data gathering improvements can be made by taking account of different livestock management systems in regions.
- 3) Validation of the results with local experts are useful to further improve the quality of the potential estimates.

### **Recommendations on temporal frequency of updates**

The 2012 biomass potential estimates are partly based on grassland area estimates based on FSS data. Up-dates of these data become available at a 1 or 2 yearly basis from national and European wide statistics. Further data on grassland productivity are becoming increasingly available from other sources too, such as from remote sensing information. If data from such assessments become available the potential estimate calculations can be further improved. The improvement requires access to the model Miterra-Europe though.

### **Practical aspects of the implementation of the update**

It is challenging to calculate the unused grasslands potential since this requires using the Miterra-Europe model. Such calculations need to be performed by experts with access to this model and high resolution data to perform such calculations which also

involve GIS skills. Miterra-Europe model cannot be used easily by non-expert users because it is complex and there is no open access to the model.

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### 2.3.4 Estimation of cost

#### Summary of the methodology/models used

Also for the calculation of road side cost of unused grassland cuttings the ABC model is applied. For the most detailed explanation of the model and all the different modules it consists of we refer to the descriptions in the former Sections where the cost calculations are explained for agricultural residues and dedicated biomass crops.

The cost allocated to unused grassland cuttings consist of:

- 1) Mowing
- 2) Racking which is needed to dry the cuttings before baling
- 3) Baling
- 4) Collection and loading at the road side

All activities require calculations in the modules **Crop inputs 1, 2 and 3, Country inputs, Task time, Costs of Activities** and **crop calculus**. In comparison to the calculation of dedicated cropping cost, the number of activities allocated to unused

grassland cutting are much smaller. They only include the activities of cutting, baling and collecting the grass to road side (or farm gate). Although unused grassland needs to be fertilized occasionally this activity is not included because of unknown, but assumed relatively large time intervals which would make the influence on the outcome marginal anyway.

The establishment of the grassland as a crop is not allocated either, because it can be assumed that the grassland is already there and that the establishment was done under the assumption to use it for livestock grazing or cutting for feed. However, in time the feed balance of the farm changed and the grassland remained unused. To keep it in good farming condition, as prescribed by the CAP, mowing/cutting remains necessary.

### **Summary of main data used**

The same data inputs are required as for cost calculations of agricultural residues and dedicated crops.

### **Limitations of methodology & data used**

Here the same recommendation as for cost calculations of agricultural residues apply as discussed in Section 2.1.2.

### **Recommendations on how to address limitations in data & methodology**

The same recommendation as for cost calculations of agricultural residues apply as discussed in Section 2.1.2.

### **Recommendations on temporal frequency of updates**

Here the same recommendation as for cost calculations of agricultural residues apply as discussed in Section 2.1.2.

### **Practical aspects of the implementation of the update**

Here the same recommendation as for cost calculations of agricultural residues apply as discussed in Section 2.1.2.

## **2.3.5 References**

None.

## **2.4 Wood production and primary residues from forests**

### **2.4.1 Estimation of supply**

#### **Summary of the methodology/models used**

The potential availability of woody biomass from forests is estimated by calculating the theoretical potential of forest biomass supply and reducing this potential by taking into account constraints that reduce the potential supply (Vis and Dees 2011). For a detailed description of the methodology see Dees et al. (2017).

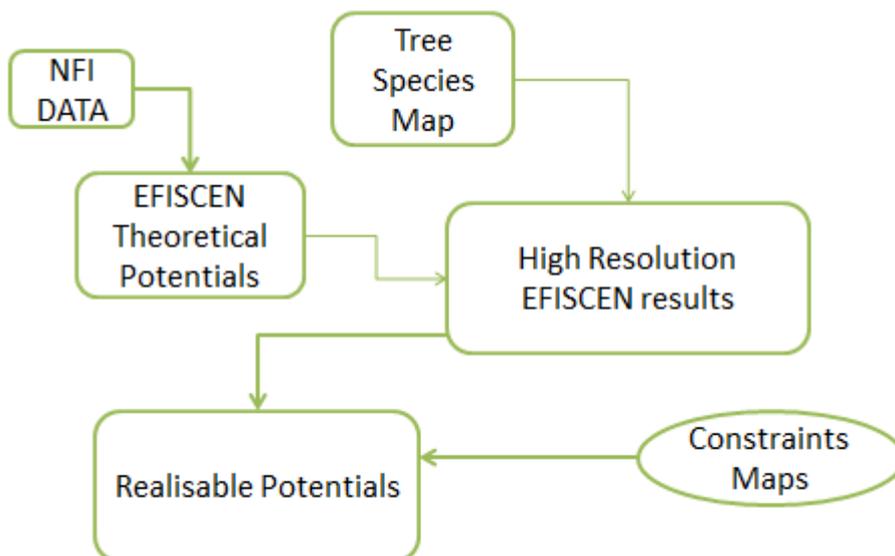


Figure 3 General work flow of the forest biomass supply calculations.

### Summary of main data used

National forest inventory data on area, growing stock and net annual increment are used to initialize the EFISCEN model. The forest area was scaled to match the forest area available for wood supply (FAWS) as reported by Forest Europe (2015). Where NFI data was not available, woody biomass potentials were estimated as described in the biomass handbook developed in BEE (Vis and Dees, 2011). Age-limits for thinnings and final fellings were based on conventional forest management according to handbooks at regional to national level (Nabuurs et al. 2007) and by consulting national correspondents (UNECE-FAO 2011). Climate change is included using results from Sitch et al. (2003) and Bondeau et al.(2007); data are an average for several climate models for the A1b SRES scenario.

A spatially explicit approach was used to quantify environmental and technical constraints. These constraints were quantified using spatial datasets. The following constraints and datasets were used:

- site productivity, soil surface texture, soil depth and soil bearing capacity (EC 2006b)
- natural soil susceptibility to compaction (Houšková 2008)
- Natura 2000 sites (EC 2009b)

- fire weather index (average for summer months June, July, August over the period 1975-2005; Marco Moriondo, pers. comm.)
- terrain ruggedness index (Riley et al 1999)

Table x Data sources to estimate high-resolution biomass potentials using EFISCEN

Dataset	Description	Sources
National forest inventories	Data on area, growing stock, increment by region, owner type, site-class, species and age-class	<a href="http://www.efi.int/portal/virtual_library/databases/efiscen/inventory_database/">http://www.efi.int/portal/virtual_library/databases/efiscen/inventory_database/</a> ; national/regional forest inventories <sup>1</sup>
Management regimes	Region- and species-specific recommendations on thinning ages and rotation lengths	national/regional guidelines (e.g. Yrjöla 2002), handbooks
Biomass distribution functions	Species-specific and age-dependent biomass distribution functions to convert stem biomass to whole tree biomass	Vilen et al. 2005; national greenhouse gas inventory reports; scientific publications
Wood density	Wood density (t dry matter/m <sup>3</sup> fresh volume)	IPCC 2003
Harvest losses	Factor to be used to convert wood removals into fellings	UNECE-FAO 2000
Tree species distribution	Maps describing the distribution of tree species (to be used for disaggregation)	Brus et al. 2012

<sup>1</sup>More recent national forest inventory data were used compared to what is available in this database (cf. comments on restricted data availability below).

### Limitations of methodology & data used

The following limitations of methodology can be identified:

1. NFI data was not always easily available and some variations in methodology of collection mean it is not always uniform or comparable between countries. Also the time reference of the inventories varies and for several countries data had to be projected to 2012 with additional uncertainties.
2. EFISCEN was designed for even-aged, single species forests and so may not be able to accurately model other forest types e.g uneven-aged systems. Furthermore, a 5-year time-step is typically applied in the model, which make assessments of biomass potentials from fast growing plantations (e.g. Eucalypt plantations) less reliable;
3. The estimated potentials (and their costs) do not consider the attitude of forest owners or society as a whole (or other socio-economic factors that limit mobilisation of forest biomass) towards a more intensive use of forest resources;
4. The future potential biomass supply is likely to be affected by climate change, especially in the longer term. A review of climate change on productivity suggests that productivity may increase in the northern part of Europe and that there are mixed projections for other parts of Europe (Reyer 2015). The projected impacts of climate change depend on the climate model and scenarios used (Reyer et al. 2014). Climate change is expected to lead also to increased disturbances (fire, wind, beetles; Seidl et al. 2014), which may affect biomass potentials and supply costs at the regional level;
5. Regional and spatially explicit biomass potentials were estimated by disaggregating EFISCEN results using trees species maps from Brus et al. (2012). Improved tree species maps are now available (San Miguel Ayanz et al. 2016), which may improve the quality of disaggregation results.

### **Recommendations on how to address limitations in data& methodology**

Recommendations on how to address the limitations are given below.

1. Harmonisation efforts would improve the comparability of the estimated biomass potentials between countries. Efforts are already in progress to harmonise NFI data collection across Europe in the DIABOLO project;
2. Biomass potential assessments at European level would benefit enormously from improved access to detailed and latest national forest inventory results (i.e. public access to detailed and updated databases) for all European countries;
3. Estimations of future biomass potentials should consider the additional socio-economic factors (e.g. owner or societal attitude towards intensified use of forest resources);
4. The assessment of future biomass potentials should consider climate change impacts (productivity changes, disturbances) from a range of climate scenarios and models;

5. An alternative source of biomass information would be to make use of the high-resolution forest cover maps provided by the Copernicus programme and to generate large-scale forest biomass maps that could be provided with the methodology and concept described in chapter 4.4. These information sources provide high-resolution information on current actual biomass potentials;
6. The rise of remote sensing offers great opportunities for developing new models to assess future forest resource development and biomass potentials. While traditional resource models rely on NFI data carried out in cycles of 5-10 years, remote sensing offers the possibility to get up-to-date, European wide-data in much shorter cycles. New large-scale forest resource models are needed that can build on such remote sensing information.

### **Recommendations on temporal frequency of updates**

NFIs are typically completed every 5-10 years. International reporting on forest resources (e.g. FAO Forest Resource Assessments, Forest Europe's State of European Forest reports) are published every five years. Taking into account these cycles, it is recommended that estimations of biomass potentials are updated every five years. Improved access to national forest inventory results (i.e. public access to detailed and updated databases) is needed to facilitate such assessments.

### **Practical aspects of the implementation of the update**

EFISCEN is now an open source model. However, the collection and interpretation of NFI data can be time consuming.

## **2.4.2 Estimation of cost**

### **Summary of the methodology/models used**

The supply costs were estimated up to the roadside including chipping or crushing, but excluding road transport and production cost. The methodology of cost estimation consists of two main components: 1) the estimation of hourly machine costs, and 2) the estimation of work productivity (Figure 4).

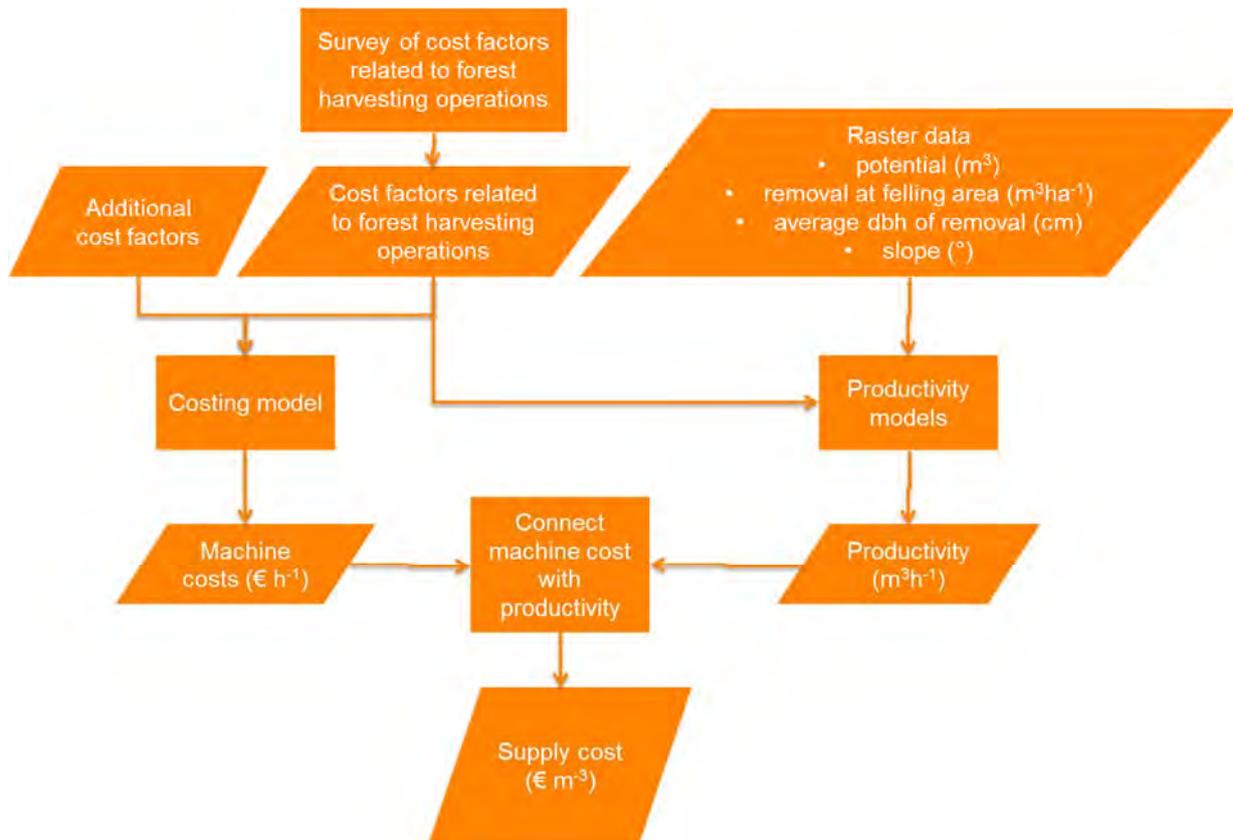


Figure 4 General work flow of the forest biomass cost calculations.

In order to enable better comparison of costs between regions, supply chains were standardised. The dominant supply chain for stemwood in Europe is the chain based on roadside chipping. In the chain felling and bunching are carried out by a harvester, off-road transport by a forwarder and chipping by a mobile chipper. For logging residues the chain is otherwise similar except for the missing felling phase. Instead, piling of logging residues by the harvester is considered to belong to logging residue supply chain. Stumps are extracted by an excavator, forwarded to roadside and crushed by a mobile grinder.

The COST model for calculation of forest operations costs (Table 6) was utilized when calculating the hourly machine costs for each machine type and country.

In the estimation of productivity a set of productivity models were selected for the following work phases: mechanized felling and bunching, integrated bunching while felling with a harvester, forwarding, chipping, stump lifting, and crushing.

Finally, the supply cost in  $\text{€ m}^{-3}$  was obtained by multiplying the machine costs by the productivities.

All the cost estimations pertain to the cost level of 2012.

For a detailed description of the methodology see Dees et al. (2017).

Table 6 Models relevant for the estimation of cost of wood supply

Model acronym and name	Relevance	Owner(s) of the model, access conditions and access point	Brief description, related projects (if applies) & references	Model maintenance and development
The COST model for calculation of forest operations costs	It will serve the purpose of calculating harvesting machine costs per cubic meter (m <sup>3</sup> ), Productive Machine Hour (PMH), Scheduled Machine Hour (SMH), day, week, month or year.	The Costing Model was developed for the European Cooperation in Science and Technology (COST) Action FP0902 (“Development and harmonization of new operational research and assessment procedures for sustainable forest biomass supply”)  <a href="http://www.forestenergy.org/pages/costing-model---machine-cost-calculation/">http://www.forestenergy.org/pages/costing-model---machine-cost-calculation/</a>	A description and user guide for the The “COST” model for calculation of Forest Operations Costs is published in International Journal of Forest Engineering (IJFE). The model should be referred to as:  Ackerman, P., Belbo, H., Eliasson, L., de Jong, A., Lazdins, A. & Lyons, J. 2014. The COST model for Calculations of Forest Operations Costs. Int.J.For.Eng. 25(1): 75-81.	The model is comprehensive and will serve the purposes of both experienced foresters and contractors alike. The model requires specific cost-related inputs from which it generates relevant costing information.

### Summary of main data used

In the estimation of machine costs both machine-level and country-level input data were used as explanatory variables in the costing model applied in the study. The applied machine-level data is shown in Table 7. The full country-level data can be found in Dees et al. (2016) and included variables like purchase price, fuel cost and labour cost.

Table 7 Machine-level input data.

	Harvester	Excavator	Forwarder	Chipper	Grinder
Machine utilisation	80 %	88 %	85 %	65 %	65 %
Fuel consumption (lh <sup>-1</sup> )	11.0	18.0	9.5	45.0	68.6
Insurance (€)	3750	1800	2500	5400	7300
Oil and lubricant cost (% of fuel cost)	15 %	5 %	5 %	15 %	15 %
Maintenance and repair cost (% of fuel cost)	51 %	34 %	34 %	41 %	41 %

Data describing the operating environment were collected and used as explanatory variables for the productivity models. The data included the intensity of harvesting (m<sup>3</sup>ha<sup>-1</sup>) for final fellings and thinnings separately for broadleaves and conifers as well as the average diameter (cm) of removed trees for the same classes in a 1 km x 1 km grid. The grid data were aggregated to NUTS3 level to be used as input parameters for productivity models. The effect of slope was considered by multiplying the time consumption of forwarding by a driving speed factor determined by the steepness of slope. The slope values were calculated by using the Digital Elevation Model over Europe in a spatial resolution of 25 m.

### Limitations of methodology & data used

The following limitations of methodology can be identified:

1. The cost of stemwood production is not included. As logging residues and stumps are by-products of roundwood, their production costs can be allocated to roundwood. However, for stemwood from final fellings and thinnings production costs should be covered in order to be consistent with dedicated cropping of lignocellulosic biomass. Due to the vast number of alternative management regimes in the European forests a complete assessment of production costs was not possible.
2. Only one supply chain per biomass category was determined. Although the dominating chains in Europe were chosen their feasibility varies from country to another. However, choosing different chains for the countries would impair the comparability of the costs between the countries.
3. Part of the machine-level input data were assumed constant among the countries. In reality there are differences between countries in, e.g., utilization rate.
4. Labour costs are based on Eurostat data where the work categories are rather broad. E.g. the real labour cost of a harvester operator may differ from labour costs of class "Industry – except construction".
5. Only one productivity model per biomass category and work phase was applied. The reason for this was, again, the attempt keep the costs comparable between the countries.
6. The accuracy of the intensity and average diameter data is unknown.
7. Estimation of stem, crown and stump volumes was simplified so that only one species for each of the four country categories was selected. The grouping of

the countries was more or less arbitrary and the selection of species depended on the availability of volume and biomass functions.

8. Generally much of the input data is difficult to obtain at regional or even country level. E.g. in most of the countries there exist no statistics on forwarding distances, but the answers given in the survey were mostly educated guesses.

### **Recommendations on how to address limitations in data & methodology**

Recommendations on how to address the limitations are given below. The numbers refer to the list of the previous section.

1. Estimate stemwood production data for a smaller area of interest.
2. Add more supply chains. E.g. on mountainous regions a supply chain based on cable yarding could be considered.
3. Collect country-level machine data, if exist.
4. Check the Eurostat data against country-level survey data.
5. Compare the results with additional models. In the comparison it should be noted that often the models are based on a very limited number of operators. It is however well known, that the effect of an operator on productivity is large. Therefore studies with extensive data should be preferred.
6. Validate the estimations with measured data.
7. Add models for the countries and species where available.
8. Collect relevant data at country level.

### **Recommendations on temporal frequency of updates**

Statistics on machine price level indices, fuel cost, labour cost and interest rates are published annually, whereas the harvesting intensity and average diameter of removal change more slowly. Therefore, the calculations can be updated annually, if drastic changes in cost factors are observed.

### **Practical aspects of the implementation of the up-date**

The machine cost calculator is freely available. However, the rest of the calculation consists of a number of spreadsheet calculators and GIS models which have not been published.

### 2.4.3 References

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## 2.5 Other land use: road side verge grass

### 2.5.1 Estimation of supply

#### Summary of the methodology/models used

The only category covered in the other land use category in S2BIOM is the road side verge grass category.

The assessment of potential biomass from road side verges builds on the assessments already done as part of the Biomass Futures (Elbersen, et al., 2012) and Biomass Policies (Elbersen et al., 2016) projects and the results of this assessment were further refined and extrapolated to 2012, 2020 and 2030 in S2BIOM.

For the assessment EU-wide road network maps combined with a more precise national road network map (for The Netherlands) was used. This was necessary because the European-wide data sources only contain the main roads, the more detailed information from The Netherlands could be used and extrapolated European wide using road density relations between the 3 data sources to the EU-wide data layer. A 10 meter boundary was assumed along both sides of the road and along the total road length in every region for which an average grassland potential was calculated. For the estimation of the grassland yield we build on Smit et al. (2008) who estimated average grassland productivity factors for different types of grassland per environmental zone in Europe. The type of grassland used in this map was assumed to be the most extensive grassland type assuming no fertilisation and poor soils. The environmental zonation ensures that grassland productivity is directly linked to climatic factors such as rainfall, evapotranspiration and length of growing season.

For future assessments it is assumed that the road network and thus the road side verge grass potential will increase according to GDP growth. As growth in the GDP will be reflected in extra investments for increasing the road network in a country. The road side verge grass yield levels were kept constant in time.

#### Summary of main data used

For the assessment an EU-wide road network map (ESRI roads (Europe Roads represents the roads (European Highway System, national, and secondary roads) and de roads network database, Eurostat 2010) was used as a basis. It was combined with a more precise road network map for The Netherlands (TOP10, Kadaster) because the European-wide data sources only contain the main roads, the more detailed information from The Netherlands could be used and extrapolated European wide using road density relations between the 3 data sources to the EU-wide data layer. A 10 meter boundary was assumed along both sides of the road

and along the total road length in every region for which an average grassland potential was calculated. The average road verge size estimation was made based on an analysis of aerial photographs (AEROGRID) and Google Maps.

For the estimation of the grassland yield we build on Smit et al. (2008) who estimated average grassland productivity factors for different types of grassland per environmental zone in Europe.

### **Limitations of methodology & data used**

There are many limitations connected to the assessment:

- 1) The road density could not be assessed with high resolution information on national road networks, instead the Dutch density of primary, secondary and tertiary road was applied to all countries, which is a very rough estimation.
- 2) The general assumption was made that all roads have a road side verge covered with grass, which does not necessarily need to be the case. In reality there are also shrubs or trees growing along roads.
- 3) A 10 meter boundary of grass cover was assumed along all roads, which is a very rough average estimate since it is impossible to measure real verge width for all roads. In reality this width can be larger or smaller, and a real average will be impossible to detect.
- 4) The increase in roads is assumed to have a relationship with development in GDP. This is a very rough assumption likely to not be applicable to all countries in Europe.

### **Recommendations on how to address limitations in data& methodology**

- 1) The current road side verge potential can be improved by adding national and regional high resolution data on road networks.
- 2) If the focus area is smaller it is possible to make a representative sample of road networks boundaries and collect additional information on vegetation along roads and also average width of the vegetated verge.
- 3) Future developments in road side network are now assumed to be related to GDP development, but it would be better to also check historic developments in road side network and extrapolate these historic developments to the future.

### **Recommendations on temporal frequency of updates**

Since road networks grow it is recommended to up-date the assessment once every 5-10 years with updated road network data.

### **Practical aspects of the implementation of the update**

The calculation of the road side verge grass potential is relatively easy to repeat by a specialist GIS person. No complicated modelling is involved.

## 2.5.2 Estimation of cost

### Summary of the methodology/models used

The cost for the type 'road side verge grass' falling in this other land use category has been assessed using the same ABC model as applied for agricultural biomass (see Sections 2.3.2 and 2.4.2). The cost allocated consist of:

- 1) Mowing
- 2) Racking which is needed to dry the cuttings before baling
- 3) Baling
- 4) Collection and loading at the road side

Although the cost for mowing is part of normal road side management we still allocate these cost to the cuttings because we expect higher mowing frequency if cuttings have a use. Collection and loading at the road side can be a time consuming activity because it needs to be done along a road, where traffic can be busy and space to work limited.

### Summary of main data used

Same data used as for assessment of cost of agricultural biomass.

### Limitations of methodology & data used

One can argue whether cost for traffic management and road blocking need to be incorporated. In this calculation we have not done it.

### Recommendations on how to address limitations in data& methodology

Evaluation of cost with local road side management organisations would be a valuable validation. Based on the outcome of the evaluation further improvements of the cost calculations could be made.

### Recommendations on temporal frequency of updates

Same recommendations as in former descriptions of agricultural biomass calculations.

### Practical aspects of the implementation of the update

Same as in former descriptions.

## 2.5.3 References

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## 2.6 Secondary residues from wood industry

### 2.6.1 Estimation of supply

#### Summary of the methodology/models used

Secondary forest residues (SFR) comprise

- Residues from saw mills,
- Residues from industries producing semi -finished products and wood based panels
- Residues from further wood processing
- Residues from pulp and paper industry

The general approach, applied for the residues from saw mills, industries producing semi -finished products and wood based panels and from pulp and paper industry, is based on the production quantity per industry sector (partly per subsector) per country and the ratio of residues to the production quantity per industry sector/subsector per country. The estimate of the amount or residues per sector (partly per subsector) results from a multiplication of the production quantity and this ratio.

In the sector of further wood processing comprising of the subsectors construction, furniture industry, packaging industry and other (summarising all other types of further wood processing) an approach used is that is based on the number of employees per sector per country (partly per subsector) and on an estimate of the round wood input per employee and the fraction of residues of the round wood input.

The estimates of totals at NUTS3 level result from a spatial disaggregation of the totals at country level using variables for proportional allocation at NUTS 3 level that are assumed to be highly correlated. The variables used for the spatial disaggregation per sector/ subsector are listed in Table 8.

Table 8 Spatial disaggregation approach by sector

Category, category group	Approach
Saw mill residues, conifers	Forest cover of conifer forests using the Copernicus high resolution forest type layer of Europe.
Saw mill residues, non-conifers	Forest cover of broad leaf forests using the Copernicus high resolution forest type layer of Europe.
Residues from industries producing semi -finished products and wood based panels	<i>National level to Nuts 2:</i> Employees of the wood industry sector retrieved from EUROSTAT. Nuts 2 to Nuts 3: Land area.
Residues from further wood processing	<i>National level to Nuts 2:</i> Employees per sector "Construction", "Furniture", "Packaging", "Other" retrieved from EUROSTAT applied on residues of the respective sectors. Nuts 2 to Nuts 3: Land area
Secondary residues from pulp and paper industry	Number of pulp and paper mills per NUTS3 area.

Future projections are using projections from EFSOS II, except for pulp a paper where it was assumed that the production level remains unchanged vs. the status in 2012.

Production quantities and employee statistics used for 2012 are 5 year averages (2010-2014). For future projections it was assumed that the ratios and factors applied on production quantities and employee statistics remain unchanged.

### **Summary of main data used**

Data on production originate from FAOSTAT and in single cases from national level statistics. Data on the number of employees originate from EUROSTAT and in case of the Non-EU countries from a national level data collection of national level sources.

For countries where production statistics have not been available or have been regarded highly uncertain an approach utilising national level statistics on apparent consumption, imports and exports was used, that was also applied by the study "The Sector Study on Biomass-based Heating in the Western Balkans" (World Bank 2016).

Ratios and factors applied originate mainly from UNECE FAO (2010).

S2BIOM Deliverable D1.6 provides a detailed description of the methodology and data sets used.

### **Limitations of methodology & data used**

Critical uncertainties are originating from a likely considerable underestimation of the real production in the statistics for many countries. Estimates of the amount of underestimation exist for Germany (Jochem et al. 2015) and for several Balkan countries, which was the reason to apply in the study mentioned in the previous paragraph the approach based on apparent consumption, imports and exports (World Bank, 2016).

Product to residues ratios depend on the technology and the assortment structure of the round wood input, both change over time and are country specific, whereas country specific original values exist for a limited number of countries only (UNECE FAO, 2010). Uncertain are further several other ratios and factors applied, especially those used for the estimation of residues from further wood processing.

The spatial disaggregation is for the NUTS3 level (a further factor of uncertainty).

### **Recommendations on how to address limitations in data & methodology**

It is recommended to conduct national level studies on the amount of underestimation of the production statistics and to develop a methodology to address

these either already on national level or in form of adjustments of the available national level statistics.

Further studies on factors and ratios on national level and repeated updates of the collection of such factors as was provided by UNECE FAO (2010) would increase the quality of the estimates. Specifically the estimation of residues from further wood processing deserves special attention.

The uncertainties resulting from spatial disaggregation could be reduced by integration of subnational data and by spatially explicit information on industry locations.

### **Recommendations on temporal frequency of updates**

The major factors that determine the amount of secondary residues are the production quantities and the residues shares. Since the production in all wood industry sectors is subject to considerable annual changes it is recommended to update these data every two to three years.

### **Practical aspects of the implementation of the up-date**

The current future projections in S2BIOM are based on EUwood (Saal 2010) and EFSOS II data (UNECE FAO 2011) - the best available data within the time and budget limitations of the S2BIOM project. However, a new EFSOS study is currently prepared and, once available, it is recommended to utilise this study for an update, accompanied by regular updates based on most recent production statistics.

## **2.6.2 Estimation of cost**

The assumption used for the current status of the data base is, that all costs that occur in the wood industry sector are motivated by the aim of producing the main product. Residues in the wood industry sector are used in the most economical way, thus either traded or utilised for heat and power internally rather than regarded as waste and entered into the waste stream, which would be the costly alternative.

If a cost values would be attributed to secondary forest residues, these would be relative low and would not have an impact on the estimate of cost-supply potentials are reasonable cost respectively price levels.

Thus the issue estimating the costs of secondary forest residues is not regarded of high importance for a cost-supply data base.

## **2.6.3 References**

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## 2.7 Secondary residues of industry utilising agricultural products

### 2.7.1 Estimation of supply

#### Summary of methodology used

All the secondary agricultural residues included in the potential calculation refer to residues of crops that are mostly grown and processed in the S2BIOM countries. The residues covered in S2BIOM include olive stones, rice husk, pressed grape residues and cereal bran.

For the calculation of the amounts of secondary residues produced, there are 2 options:

- 1) The area of the crop delivering the residue is multiplied with a residue factor expressing the per hectare delivery of the residue amount (for olive stones)
- 2) The total yield of the main crop is multiplied with a factor expressing the residue to yield factor (for rice husks, grape dreg and stalks and cereal bran)

Table 9 Specifications on the residue factor

Biomass type	Potential assessed	Area / Source	Residue factor
Olive-stones	Technical potential = Base potential	CAPRI & national statistics: Area with all olive trees (table=oil olives) 2012, 2020, 2030	Olive pits make up between 10%-12.5% of the weight of olive according to Garcia et al. 2012 and Pattarra et al., 2010)
Rice husk		CAPRI & national statistics: Area with rice in Europe 2012, 2020, 2030	Rice husk is approximately 20% of the processed rice, with average moisture content of 10% ((Nikolaoy et al. 2002)). It is assumed that all rice produced in the S2BIOM countries is locally processed
Pressed grapes residues		CAPRI & national statistics: Area with vineyards in Europe 2012, 2020, 2030	Of the processed grapes 4.6% consists of residues and 1.5% of stalks (FABbiogas 2015, Italian country report)
Cereal bran		CAPRI total estimate of tons processed cereals per EU country	In wheat processing 20% to 25% wheat offals (Kent et al., 1994). Wheat bran represents roughly 50% of wheat offals and about 10 to 19% of the kernel, depending on the variety and milling process (WMC, 2008; Prikhodko et al., 2009; Hassan et al., 2008). ). So the residue to yield factor used is 10% of cereals processed domestically.

The overall calculation of the technical potential of secondary residues follows the same general formula as for residues from rotational arable crops :

$$\text{RESIDUE\_YIELD}_i = \text{AREA}_i * \text{RES\_YIELD}_i * \text{DM\_CONTENT}_i.$$

or

$$\text{RESIDUE\_YIELD}_i = \text{MAIN PRODUCT yield}_i * \text{RES\_YIELD}_i \text{ ratio} * \text{DM\_CONTENT}_i.$$

Where:

- RESIDUE\_YIELD<sub>i</sub> = total residue yield of crop i in Ton/Year dry mass
- AREA<sub>i</sub> = Crop area of crop i
- RES\_YIELD<sub>i</sub> = Secondary residue yield Ton/Ha/Year in fresh mass of crop i
- DM\_CONTENT<sub>i</sub> = Dry matter content of residue of crop i
- MAIN PRODUCT yield<sub>i</sub> = this is the yield of the main product i which in the processing at the mill delivers the secondary by-product

For the calculation of the olive stones, rice husk and pressed grapes residues we assumed that all domestic production would also be processed locally and that is no further processing of imported olives, rice and grapes. This implied that the residues would be available locally and that the regional distribution of the processing residues is a direct outcome of the cropping area distribution over regions in every country.

For cereal bran it is more logical to assume that the basis should be the total amount of cereals processed in every country. This implies that cereal bran needs to be calculated for a total net domestic cereal production and imports:

$$\text{Domestic production cereals} - \text{export cereals} + \text{import cereals}$$

## Summary of main data used

Data on area and total production (Area\*yield) can be derived from Eurostat and national agricultural statistical sources.

The data on total domestic production, exports and imports levels are more difficult to derive, but are generally published in European and national statistics.

In S2BIOM we used data on imports and exports available from CAPRI for 2010, 2020 and 2030 for all S2BIOM countries except for Ukraine.

To come to a regional distribution of the cereal bran potentials in every S2BIOM country 2 assumptions were made:

- 1) The bran based on the net domestic production (=domestic production – exports) is distributed regionally according to cereal production area share.
- 2) The cereal bran based on processing of imported biomass is distributed over largest (port) cities per country as it is expected that processing industries are there where imports enter the country and where population is concentrated. The residues were spatially distributed to regions with the large and medium sized cities (>100,000 inh.), every city was equally weighted.

For Ukraine there were no CAPRI data available on domestic production of cereals, nor imports and exports. Instead we used data from the statistical yearbook "Agriculture of Ukraine" for 2013, Data of State Statistics Committee of Ukraine. This implied data were only available for one year. For the 2020 and 2030 situation the Ukraine potential is assumed to be stable.

## Limitations of methodology & data used

- 1) Product to residues ratios also depend on technologies used, so the average residue ratios used may differ per country, region and industrial process.
- 2) The assumption made that all crops produced are also processed locally can not always be made. This depends very much on the crop type and the country and region. In S2BIOM only for cereal bran imports and export numbers were taken into account.
- 3) The spatial disaggregation is for the NUTS3 level (a further factor of uncertainty).

## Recommendations on how to address limitations in data & methodology

It is recommended to conduct national level studies on the type of industrial processes involved and the amounts of crop products processed.

Further studies on factors and residue ratios on national level and repeated updates of the collection of such factors is always useful, particularly if the focus is on one country or a limited number of countries/regions.

## Recommendations on temporal frequency of updates

The major factors that determine the amount of secondary residues are the production quantities and the residues shares. Since the production and trade of agricultural crop products is subject to annual changes it is recommended to update these data every two to five years.

## Practical aspects of the implementation of the up-date

The current future projections in S2BIOM are based on the best available data within the time and budget limitations of the S2BIOM project. However, it is recommended to utilise national expertise and factors published in other studies for an update, accompanied by regular updates based on most recent production statistics and expertise of industrial processes.

### 2.7.2 Estimation of cost

#### Summary of methodology used

This study follows the activity-based costing approach. In principle, the costs of harvesting, collection and forwarding to the roadside are considered, not the market value of the biomass. In case of secondary agricultural residues, it makes no sense to estimate the activity based costs at roadside in detail, as explained in the following sections.

The cost to put the residues at roadside is assumed to be zero. The cost of further collection and processing is allocated to the main product processed at the mill.

Secondary residues are not only collected for energy generation, but often for feed. Getting all the cost information on “at roadside” collection costs will not contribute to any purpose.

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## 2.8 Waste collection/ tertiary residues

### 2.8.1 Estimation of supply

#### Summary of the methodology/models used

In this report we focus on two relevant waste biomass categories, namely biowaste and post-consumer wood.

Biowaste is defined as “biodegradable garden and park waste, food and kitchen waste from households, restaurants, catering and retail premises and comparable waste from food processing plants”, following the Waste Framework Directive (2008/98/EC). Biowaste is part of biodegradable municipal waste as defined in the landfill Directive (99/31/EC), but it excludes textile and separately collected paper and paperboard. The availability of biowaste in year x on NUTS3 level can be established as: municipal solid waste generated per capita (kg/capita) x biowaste fraction (%) x population of the NUTS3 area (persons).

Post-consumer wood includes all kinds of wooden material that is available at the end of its use as a wooden product (“post-consumer” or “post-use” wood). Post-consumer recovered wood mainly comprises packaging materials (e.g. pallets), demolition wood, timber from building sites, as well as fractions of used wood from residential (municipal waste), industrial and commercial activities (e.g. used wooden furniture). A further distinction between hazardous and non hazardous fractions, or a categorisation in waste classes (e.g. A: clean wood; B: painted wood; C: impregnated wood) can be useful for analysis of possible (bioenergy) applications.

A further description of the methods is provided in Annex A3 & A4.

#### Summary of main data used

European statistics provide information on the amounts of municipal solid waste generated per capita in a country. The biowaste fraction has to be collected from statistical information and sorting analyses on national level. Arcadis and Eunomia

(2010) have analysed literature on the share of biowaste in municipal waste in all the EU27 countries. For a year in the past population data on NUTS3 level can be taken from Eurostat (see Eurostat database code demo\_r\_gind3). Projections on the development of the total quantity of biowaste are assumed to be proportional to population growth. The main scenario on population development from Eurostat has been used to predict the population in 2020 (see proj\_13npms).

Eurostat gives data on “wood waste”, but this includes several types of processing and post consumer waste types, for which Eurostat data cannot be used to determine the potential of post-consumer wood. Only used packaging wood can be obtained directly from Eurostat (env\_waspac). This means that data needs to be collected from literature or from primary research. In S2BIOM, data on post-consumer wood was obtained from forest biomass resource assessments done for the EUwood and EFSOS II studies (Mantau et al. 2010; UN-ECE/FAO 2011<sup>6</sup>).

### **Limitations of methodology & data used**

The method to determine the biowaste potential has the following limitations:

- The quantities of biowaste known at country (NUTS0) level are distributed proportionally based on the population at regional (NUTS3) level. This ignores differences in the production between urban and rural areas, and between regions in general. Site specific data of waste availability is not available, the lowest level is NUTS3.
- The varying composition of biowaste between regions and seasons is not addressed. The method uses one biowaste fraction for a whole country for all years.
- The method distinguishes between separately collected and integrally collected biowaste as these have different possibilities for energy application, e.g. biowaste as integral part of municipal waste can be combusted, and separately collected biowaste can be digested before composting. This distribution is based on a detailed analysis of Arcadis and Eunomia (2010), but this study will probably not be updated regularly.
- In order to convert volumes to energy potentials, conversion factors are introduced, which are based on the experts' selection of literature. Possible fluctuations in moisture content and biogas yield of the waste can easily introduce a substantial error (say 10-15%).
- A common issue with statistics is that the definition of biowaste can be interpreted differently between Member States (See Eunomia and Arcadis 2010, chapter 4).

6 UNECE (United Nations Economic Commission for Europe), FAO (Food and Agricultural Organization of the United Nations) 2011: The European Forest Sector Outlook Study II; Geneva

The method to determine the post consumer wood potential has the following limitations:

- With the exception of wooden packaging waste, data on post-consumer wood cannot be obtained from Eurostat, meaning that in practice resource assessments depend on study reports<sup>7</sup> that will rely on sector information and expert opinion.
- There is no harmonised classification of post-consumer wood quality classes throughout the EU; each member state has its own classes (e.g. A: clean; B: painted; C; impregnated wood), some member states only distinguish between hazardous and non hazardous wood.
- The spatially disaggregated information on regional (NUTS1-3) level is based on population distribution, but the actual resource depends on among other the location of building and demolition activities, which can vary per region.
- Competing uses differ per regions; in some regions there is substantial demand from the particle board industry, in other regions not.
- In order to go from volumes to energy potentials, conversion factors are introduced, which are based on the experts' selection of literature, it can easily introduce an error in the order of 10-15%.

### **Recommendations on how to address limitations in data & methodology**

Recommendations on addressing limits in data and methodology of biowaste:

- In a number of Member States information on biowaste or at least municipal solid waste generation is available at regional (NUTS3) level, it is recommended to apply NUTS3 level data collection throughout the EU, and include this data in Eurostat.
- It would be helpful if the average composition of municipal solid waste is available at Member State level, reported to Eurostat and updated every two years. This way the biowaste fraction of municipal solid waste can be monitored and updated regularly.
- It will be difficult to take into account varying compositions of biowaste at NUTS3 level, except if a dedicated study is carried out on a specific region; this will not be feasible at EU28 level.
- The conversion factors between volumes and energy content can be improved if more data would be available on the moisture content, composition and

<sup>7</sup> Eurostat provides information on “wood waste” (Cat 07.5 of EWC-Stat/Version 3) generation by NACE\_R2 sector (see env\_wasgen in Eurostat), but it does not show information at the level of subcategories, such as wood packaging, sawdust and shavings, and other wood wastes) (see Commission Regulation (EC) No 574/2004 for the full classification. Wood packaging data can be obtained separately (env\_waspac), but nothing can be found in Eurostat on construction and demolition wood, nor the wood content in municipal solid waste.

potential biogas yield of biowaste. Given the varying composition of biowaste between regions and seasons this would require substantial effort.

Recommendations on addressing limits in data and methodology of post-consumer wood:

- First of all it is recommended that Eurostat publishes not only information on main category “wood wastes” (07.5), but also on its sub-categories: wooden packaging (07.51) sawdust and shavings (07.52), waste bark, wood waste from mechanical waste treatment (Eural 19 12 07), separate collected waste wood (Eural 20 01 38), and the hazardous fractions thereof<sup>8</sup>. Because of this mixture of several types of secondary wood processing wood and tertiary post-consumer wood within one main category, Eurostat data cannot be used to determine the potential of post-consumer wood. This recommendation requires additional efforts from Member States to collect this data separately.
- A EU standardisation of wood waste assortments would help to improve the sharing and trade in wood resources across the EU, improve understanding of potential end-uses and lead to new market developments (Vis et al 2016). This standard could subsequently be introduced in statistics.
- The coming years statistics will not provide sufficient insight into the resource potential of the different assortments of post-consumer wood and their current applications. Therefore, it will be necessary to keep performing studies like EU wood (Mantau 2010). It would be even better if a detailed dedicated study on waste wood availability and use would be carried out.

### **Recommendations on temporal frequency of updates**

Part of the S2BIOM database on biowaste could be updated yearly, by using the most recent statistics on municipal solid waste generation and population. It is recommended that the biowaste fractions and conversion factors to energy are updated least once per five years and preferably every two years.

Post-consumer wood data relies only partly rely on statistics and largely on separate studies. Currently, only the availability of the packaging waste wood could be updated each year. It is recommended to carry out an in depth study to the waste wood supply and demand preferably every two years, or at least once in the five years.

### **Practical aspects of the implementation of the update**

The current S2BIOM database on post-consumer wood is based on EU wood and EFSOS II data, the best available data, within the time and budget limitations of the

8 See Commission Regulation (EC) No 574/2004.

S2BIOM project. However, these studies are already 5 years old; therefore, a new study to the demand, supply and application of post-consumer wood supply is recommended, followed by an update of the S2BIOM database on short term.

### 2.8.2 Estimation of cost

This study follows the activity-based costing approach. In principle, the costs of harvesting, collection and forwarding to the roadside are considered, not the market value of the biomass. In case of biowaste and post-consumer wood, it makes no sense to estimate the activity based costs at roadside in detail, as explained in the following sections.

#### **Cost supply methodology biowaste**

The cost to put the biowaste in a container at roadside is assumed to be zero. The cost of further collection and processing is covered by the households and organisations that need to discard the biowaste, regardless its possible further application for energy production. Waste collection and treatment is part of the public tasks and the cost for it cannot be allocated to the processor of the waste. In case of biowaste we could define the municipal collection point as “at roadside”. From this municipal collection point, the municipality can select which waste treatment option is preferred, within the framework of European and national policy, considering costs and sustainability of the treatment methods. In short, in this study the biowaste costs at roadside (at the waste treatment plant) are assumed zero.

Although the cost of (separate) collection of biowaste is relevant for municipalities and regions that have to organise it, the added value of obtaining this information at NUTS3 level for 28 Member States can be questioned. Again, biowaste is not solely collected for energy generation, but primarily to process it centrally, with or without energy generation. Getting all the cost information on “at roadside” collection costs will not contribute to the estimation whether it is feasible to produce energy with biowaste.

#### **Cost supply methodology post-consumer wood**

The cost of discarding post-consumer wood in a container at roadside is regarded zero. For instance, demolition activities are performed to make space for another building, and not with the purpose to generate wood waste. Demolition activities will follow legal instruction, i.e. put waste wood fractions in separate containers if this is required by law. For other sources of post-consumer wood such as packaging materials or household waste a similar approach can be applied. Packaging waste is of no value to organisations and they just want get it disposed of. Consumers bring wooden furniture to a central collection point, or put it at roadside for pick-up, not for the sake of providing energy wood, but to get rid of it. Once collected and sorted, waste wood fractions have an economic value, which can be considerable if there is sufficient demand. However, as said, S2BIOM follows an activity based costing

approach, considering the costs, not the economic value of the material. In short, the roadside cost of demolition wood is assumed zero.

The costs of collection of post-consumer wood to the roadside is not an important barrier to the utilisation of post-consumer wood for material and energy applications, and it is not recommended to put substantial efforts in identifying these costs at NUTS3 level in all the EU28 Member States and beyond. The logistic costs of further transport to the users of the post-consumer wood are more relevant (see S2BIOM WP3). Other important issues are for instance the implementation of legislation that promotes separation of the different waste wood qualities at the source and the organisation of a corresponding infrastructure. There is an existing market for clean and dry waste wood fractions in both the particleboard industry and the energy sector, and, given the emphasis on cascading use and circular economy, other material applications could be developed as well in the coming years. For more information see Vis et al (2016)<sup>9</sup>.

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### 3 Regular future update of the determination of imports

#### 3.1 Summary of the methodology/models used

The trade related cost supply curves for lignocellulosic biomass has been estimated utilizing a full economic equilibrium model known as GLOBIOM<sup>10</sup> (Global Biosphere Management Model) and a global forest model known as G4M<sup>11</sup> (Global Forest Model). The two models have been developed at the International Applied Systems Analysis (IIASA) and has along history of being used in a policy context and in consultation with EU member state countries to provide projections that are validated by country experts. The fact that the models are also being used and applied in multiple key global countries improves the representation of international linkages. Part of the strength of the model is that it is global and explicitly links countries and regions through trade of commodities. Thus, the model can consider demand and supply developments on a global level and can assess the impact of national policies in terms of trade, leakage and rebound effects.

The Global Forest Model (G4M) (Kindermann et al. 2008; Gusti 2010) was developed by IIASA in 2008 to assess the mitigation reduction potential from halting deforestation activities. By comparing the economic value of alternative land uses, the model simulates the impact of wood demand projections and carbon prices on forestry activities (afforestation, deforestation and forest management). Because the G4M model lacked the capability to project market developments (external projections of wood demand are required) the Global Biosphere Management Model (GLOBIOM) (Havlik et al. 2014) was developed in 2011 at IIASA, providing market developments and a fully integrated forest and agricultural sector modelling framework. In its core, the GLOBIOM model is a geographically explicit land use model that projects the developments of the forestry and agricultural markets, international trade, impacts on land use, and CO<sub>2</sub> emissions for the LULUCF sector. It is as such an economic model that jointly covers the forest, agricultural, livestock, and bioenergy sectors, inherently allowing it to consider a range of direct and indirect implications of biomass use and trade implications. Nowadays, the GLOBIOM and G4M models are used in conjunction to benefit from their respective strengths.

The G4M and GLOBIOM models are currently used to study the effects of climate change and adaptation of management on forests (Kindermann et al. 2013), forest resource developments over time (Böttcher et al. 2012), EU wide LULUCF developments (Commission 2013), soil organic carbon mitigation potentials (Frank et al. 2015), and woody biomass energy potentials (Lauri et al. 2014). The models have a long history of use in a policy context and providing EU member state projections of

10 See also:

11 See also:

forest harvest levels and LULUCF projections. As an example, the models have been used to develop the EU28 wide LULUCF reference scenario, in consultation with national experts and cross-checked per country through a consultation process (Commission, 2013). The two models have also been used for Reducing Emissions from Deforestation and forest Degradation (REDD) assessments in tropical forest regions (Herrero et al. 2013), bioenergy sustainability assessments (Forsell et al. 2016), and even represent the land use part of the IIASA integrated assessment modelling framework MESSAGE-GLOBIOM (McCollum et al. 2014).

Table 10 Models relevant for the estimation of import supply potentials

Model acronym and name	Relevance	Owner(s) of the model, access conditions and access point	Brief description, related projects (if applies) & references	Model maintenance and development
G4M (Global Forest Model) and GLOBIOM	The interlinked GLOBIOM and G4M models was in this project used to create cost supply curves of biomass trade between countries and regions of interest	IIASA	G4M (Global Forest Model) is a global forest model that was developed by IIASA to provide estimates of availability and cost of woody biomass resources and is used in conjunction with GLOBIOM to estimate the impact of forestry activities on biomass and carbon stocks.	The G4M and GLOBIOM models are both being maintained and further developed by IIASA through a number of ongoing projects and research developments at IIASA. Ongoing updated throughout a full range of ongoing projects that the models are being used for.

### 3.2 Summary of main data used

Overall, all processes and management options within the models that have been used are represented at a high level of regional detail and built on trustworthy databases. GLOBIOM is based on EU data regarding area, yields, production etc. at NUTS 2 level. The market balances calculated for the 53 regions worldwide rely on EUROSTAT accounts and on FAOSTAT for outside EU. Land cover is dealt with in a geographically explicit way. The land cover description for the EU28 is based on CORINE/PELCOM cover maps, which ensure a great level of detail in land cover. The land cover for the rest of the World is based on Global Land Cover 2000 (Bartholome et al. 2002).

Biomass use for large-scale energy production is commonly based on the POLES or MESSAGE energy sector models (Havlík et al., 2011; Reisinger et al., 2013), but

other estimates can also be utilized. For forests, mean annual increments and growing stocks for GLOBIOM are obtained from G4M. For the agricultural sector, GLOBIOM draws on results from the crop model EPIC (Environmental Policy Integrated Climate Model)<sup>12</sup>, which provides the detailed biophysical<sup>13</sup> processes of water, carbon and nitrogen cycling, as well as erosion and impacts of management practices on these cycles. GLOBIOM therefore incorporates all inputs that affect yield heterogeneity and can also represent a different marginal yield for different crops in a same grid cell.

In term of trade of the considered feedstocks, processed, and final commodities from the forest, agriculture, and livestock sectors are computed endogenously within the GLOBIOM model between geographical regions. Trade of commodities is as such modelled following the spatial equilibrium approach so that bilateral trade flows between individual regions can be traced for each commodity. For the calibration of trade flows within endogenously within GLOBIOM, 2000 year bilateral trade flows are first taken from BACI database which is an initiative of the CEPII (Fontagné L. et. al. 2008) to provide reconciled values and quantities of COMTRADE annual trade statistics at the HS6 product level<sup>14</sup>. A trade calibration method (Jansson and Heckelej, 2009) is applied to reconcile bilateral trade flows with net trade as computed as the difference between the production in a region minus all domestic uses reported by the FAO. In addition, the trade calibration approach ensures that when two regions trade together, their prices only differ by the trading costs for the base year of 2000.

### Limitations of methodology & data used

Like all modelling framework, there are limitations to methodologies and data available for making scenario based projection. These limitations include:

- As always in scenario analysis, the study results critically depend on the assumptions and constraints of the modelling framework.
- There are limitations to the data sources available concerning the current use of feedstocks for wood pellets production in countries such as USA, Canada, and Russia. Some studies have recently been made public showcasing the

<sup>12</sup> See also:

<sup>13</sup> Biophysical means related to living (animals, plants) and non-living (light, temperature, water, soil etc.) factors in the environment which affect ecosystems

<sup>14</sup> BACI provides the historically trade flows where the trade between countries is fully reconciled such that reported imports for country A from country B, fully match that of reported export from country B to country A.

feedstock use in particular regions<sup>15</sup>, but further data sources would improve modelling efforts.

- Some features are challenging to capture within a modelling framework: For instance, how land owners and biomass producers react to changes in policies and prices; and the institutional and infrastructural barriers to the mobilization of biomass feedstocks.
- There are inevitable uncertainties in projecting the development of new goods, new markets, new trade routes, new technologies and changes in end-consumer consumption patterns. These are all aspects where large changes may occur in the future that influence future developments.

### 3.3 Recommendations

#### Recommendations on how to address limitations in data & methodology

The main recommendation would be to update the cost-supply curves on a regular basis such that new developments and new data sources that have become available can be reflected upon.

#### Recommendations on temporal frequency of updates

Bi-annual updating of trade related biomass supply curves are recommended, especially given the fast development of the wood pellets sector and political decision concerning demand biofuel and bioenergy production within the EU. As such policies can have a large impact on trade flows, it is highly recommended that updates are done on a regular basis.

#### Practical aspects of the implementation of the up-date

Updates of data can be provided by IIASA-ESM by contacting the lead developers of the models used for the production of the data GLOBIOM and G4M.

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## 4 Options for large and regional scale high resolution wood volume and woody biomass maps

### 4.1 Introduction

Given the increased temporal availability of high resolution remote sensing data and of remote sensing based options to estimate forest height substantial advancements will be possible in future and will be available for future updates of biomass cost supply potentials from forests and have therefore been subject to dedicated studies that explore these options.

The studies presented here explore the generation of wood volume and woody biomass maps and focus on

- Using high resolution optical time series data for mapping at European scope – time series of Sentinel 2 and Landsat data offer new opportunities for timely updated large scale biomass maps
- The use of vegetation height estimates from SAR interferometry for mapping at European scope – TandemX based digital surface models offer new opportunities for large scale biomass maps using SAR interferometry
- The use of vegetation height estimates from aerial photography for mapping at local, regional and possibly in the long term even to European scope— whereas airborne LiDAR can provides most accurate vegetation height mapping, airborne LiDAR are not yet regularly updated by national survey agencies, whereas for digital aerial photography this is the case in the majority of European countries and thus this technical option is of high relevance

### 4.2 Estimating woody biomass and stem volume using time-series of optical satellite imagery

#### 4.2.1 Introduction

For spatial explicit estimating woody biomass and stem volume at the European scale with optical imagery, mainly medium resolution satellite imagery from MODIS were used up to now (compare e.g. Gallaun et al., 2010). Because of the coarse spatial resolution in the range of 0.5 km by 0.5 km per pixel, these estimations provide only limited information content for cost estimation and biomass availability models. This is especially the case when it comes to monitoring of changes which are typically characterised by small patterns, e.g. sizes of management units are often below one hectare.

However, with increased availability of temporally and spatially high resolution optical satellite imagery and availability of fully automatized pre-processing chains, wall to wall spatial explicit estimation of woody biomass and stem volume becomes feasible. In the following, the data sources and data availability which are a main factor for operational roll-out of such European-wide assessments are therefore described in a first chapter. Applicability of large area estimation of woody biomass and volume is then described in the next chapters mainly on the basis of results achieved for a demonstration site located in Southwest Germany and Eastern France as for this demonstration site, comprehensive reference data was provided by the Forest Research Station of the Federal State of Baden-Württemberg as well as from the Public Forest Administration of the Federal State of Baden-Württemberg, which allowed an independent accuracy assessment.

#### 4.2.2 Availability of high resolution optical satellite time series imagery

The main limiting factor for high resolution estimation of woody biomass and volume at the European level is the availability of appropriate satellite time series imagery. In the following, main findings regarding availability of optical time series satellite imagery from Hirschmugl et al. (2017) are summarized which are relevant for estimating woody biomass and stem volume. In the context of a future operational applicability at the European level, appropriateness relates in this respect not only to the spatial and temporal resolution, but also to data acquisition and data processing cost. A further criterion is that only HR satellites with a regular nadir acquisition scheme can be considered suitable for regular and continuous monitoring. Since the satellites from the Landsat series and Sentinel-2 fulfil this condition, and also provide open and cost free access to archives and new acquisition images, these satellites can be the backbone for a future operational application. The spectral capabilities of these two satellite missions complement each other (Figure 5) and, as shown in Figure 6, increased density of the time series can be expected in the future.

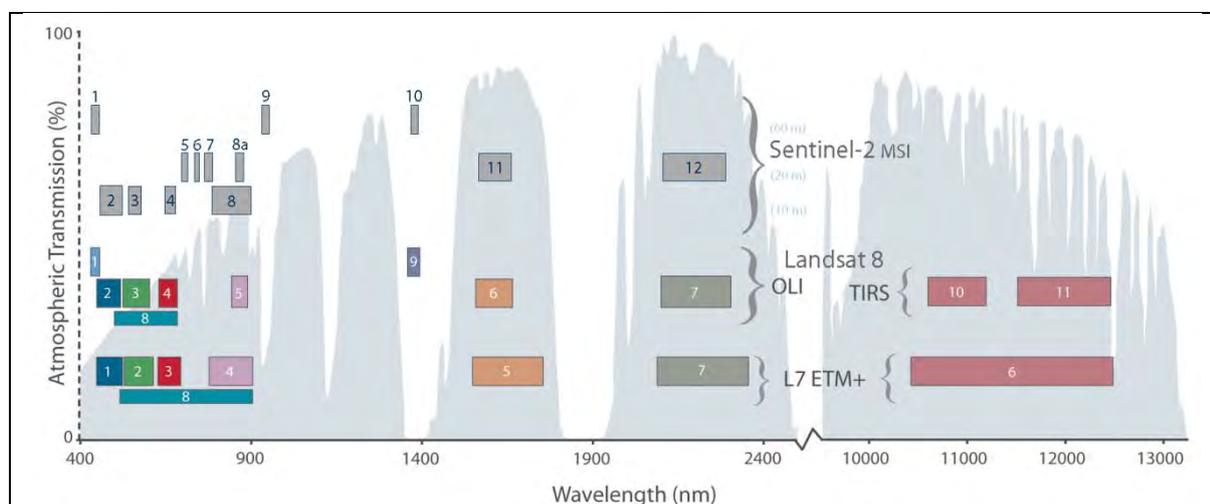


Figure 5 Comparison of Landsat 7 and 8 bands with Sentinel-2. Source: <http://landsat.gsfc.nasa.gov>.

Very high resolution (VHR) sensors are of high relevance for estimating woody biomass and volume based on ordering and tasking (e.g. Worldview, Geoeye, RapidEye or SPOT). They can, thus, complement Landsat and Sentinel-2 assessments especially at the local to regional level, whereas the regular continuous wall-to-wall monitoring from national to continental or even global scale can be based on Sentinel2 and Landsat satellites with a regular nadir acquisition scheme.

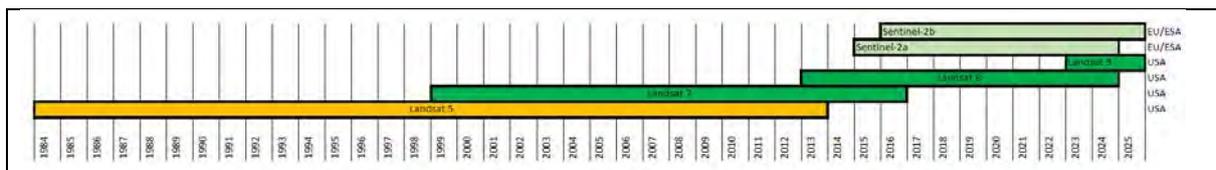


Figure 6 Temporal aspects of sensors suitable for a European wide applicability in the next years. Assumptions: Lifespan of Senitel 2a & b of 12 years, Landsat 7 termination in 2016, Landsat 8 lifespan of 12 years, Landsat 9 lunch in 2023

The Landsat program has been providing continuous multispectral data since 1972 and this data is available from USGS archives. In addition to the Landsat Level 1 standard data products, higher level science data products (e.g. surface reflectance) can also be ordered through a number of data access sites (URLs: <http://earthexplorer.usgs.gov>, accessed 4<sup>th</sup> January 2017; <http://glovis.usgs.gov>, accessed 4<sup>th</sup> January 2017). The current operational satellites are Landsat 7 and Landsat 8; the long term continuity of data from the program is foreseen to continue well into the future, with Landsat 9 planned for launch in 2023.

Sentinel-2 is planned as two satellite missions: the first, Sentinel-2A, was launched June 23<sup>rd</sup>, 2015 (full operational readiness is planned for July 2016) and Sentinel-2B is planned for launch in mid-2017. The operational lifespan of the Sentinel-2 mission is 7.25 years, while the consumables can last for up to 12 years (source: ESA, <https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/sentinel-2>, accessed 4<sup>th</sup> January 2017). Available Sentinel-2 images can be downloaded at the Scientific Data Hub and are provided in the form of a “rolling archive”. In addition, there are initiatives to provide full-scale archives.

Table 11 presents main technical specifications for Landsat and Sentinel2 data sources.

Table 11 Technical specifications of Sentinel-2a & b and Landsat optical sensors.

Satellite system	Mission start/ completion	Spectral characteristics [in μm]	Orbit height	Swath width	Resolution	Repeat Cycle
Landsat 5 (NASA, USA)	1984 - 2013	TM: 0.45 – 0.52 (blue) 0.52 – 0.60 (green) 0.63 – 0.69 (red) 0.76 – 0.90 (NIR) 1.55 – 1.75 (SWIR) 2.08 – 2.35 (SWIR) 10.4 – 12.5 (TIR)	705 km	185 km	TM: 30m	16 days

Satellite system	Mission start/ completion	Spectral characteristics [in $\mu\text{m}$ ]	Orbit height	Swath width	Resolution	Repeat Cycle
Landsat 7 (NASA, USA)	1999 - ongoing	ETM+: 0.52 – 0.90 (PAN) 0.45 – 0.52 (blue) 0.53 – 0.61 (green) 0.63 – 0.69 (red) 0.78 – 0.90 (NIR) 1.55 – 1.75 (SWIR) 2.09 – 2.35 (SWIR) 10.4 – 12.5 (TIR)	705 km	185 km	PAN: 15m TIR: 60m Others: 30m	16 days
Landsat 8 (NASA, USA)	2013 - ongoing	OLI: 0.50 – 0.68 (PAN) 0.433 – 0.453 (deep blue) 0.45 – 0.515 (blue) 0.525 – 0.60 (green) 0.63 – 0.68 (red) 0.845 – 0.885 (NIR) 1.36 – 1.39 (SWIR) 1.56 – 1.66 (SWIR 2) 2.10 – 2.30 (SWIR 3) TIRS: 10.3 – 11.3 (TIR 1) 11.5 – 12.5 (TIR 2)	705 km	185 km	PAN: 15m TIR1&2: 100m Others: 30m	16 days
Sentinel-2 (ESA, EU)	2015 – planned 2027	0.443 (center wavelength): 0.02 (band width) – Band 1 0.490: 0.065 – Band 2 0.560: 0.035 – Band 3 0.665: 0.03 – Band 4 0.705: 0.015 – Band 5 0.740: 0.015 – Band 6 0.783: 0.015 – Band 7 0.842: 0.115 – Band 8 0.865: 0.02 – Band 8a 0.945: 0.02 – Band 9 1.375: 0.03 – Band 10 1.610: 0.09 – Band 11 2.190: 0.180 – Band 12	786 km	290 km	B2,B3,B4,B8: 10m B5,B6,B7,B8a,B11,B12: 20m B1,B9,B10: 60m	10 days (Sentinel-2A); 5 days (Sentinel-2A & 2B)

For continuous monitoring over Europe, it is the cloud free coverage of the combination of Sentinel-2 and Landsat that is crucial. This coverage differs considerably by region, as shown in following figure.

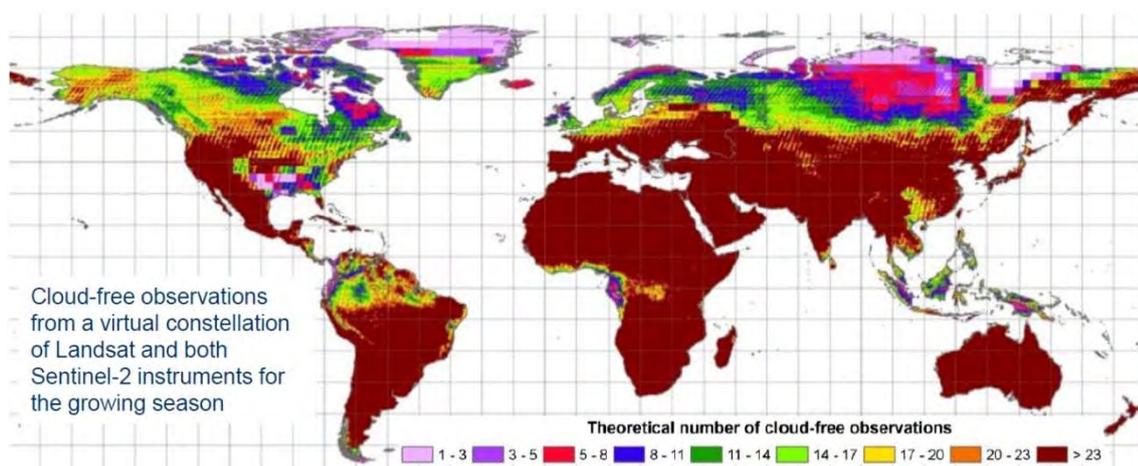


Figure 7 Estimated number of cloud-free observations from Landsat and both Sentinel-2 instruments for the vegetation season (Hostert et al., 2015).

### 4.2.3 Demonstration sites

The German/France demonstration site is located in Southwest Germany to Eastern France (center at  $48^{\circ} 40'$  north and  $8^{\circ}$  east) and covers an area of 57.000 km<sup>2</sup>. The

site is characterised by diverse forest ecosystem conditions ranging from flat terrain of the Upper Rhine Valley to mountainous terrain of the Black Forest in Southern Germany and the Vosges in eastern France (see following figures).

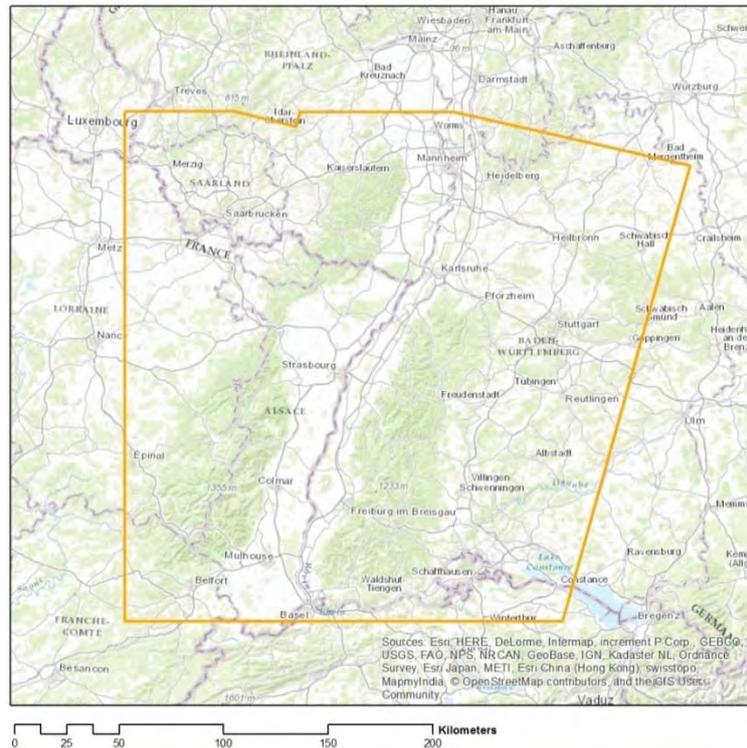


Figure 8 Demonstration site in Southern Germany – Eastern France.

The main criterion for selection of this demonstration site was because comprehensive field inventory data was available for this site.

The location of the Serbian demonstration site is drawn in below figure.

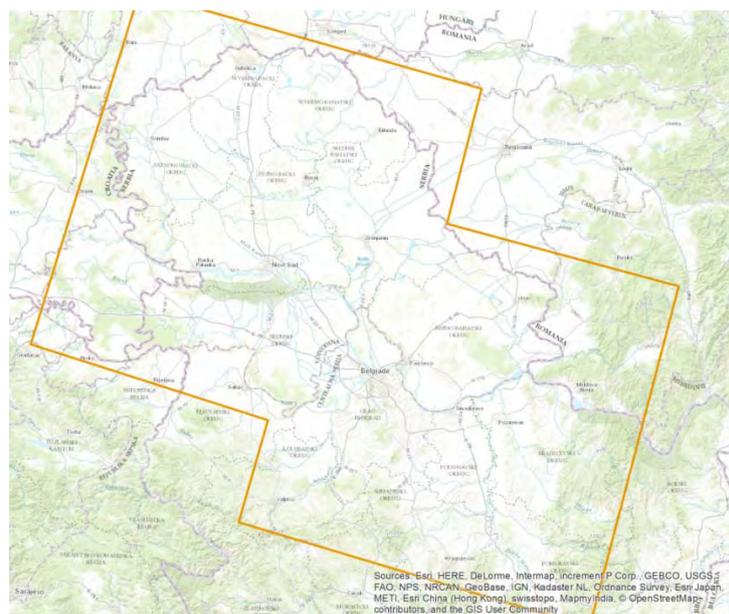


Figure 9 Demonstration site in northern Serbia covered by four Landsat frames.

#### 4.2.4 Field Inventory Data

The Baden Württemberg forest administration provided comprehensive field inventory data from the second and third national forest inventories of Germany. The location of the field plots is shown in following figure.

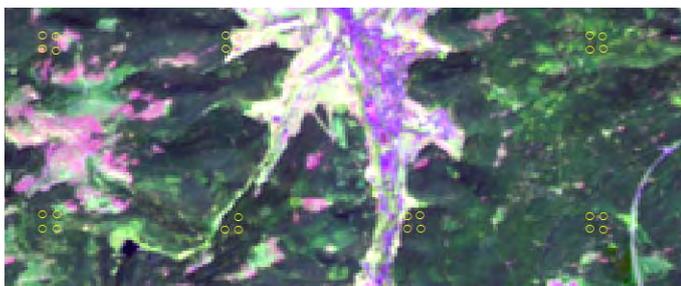
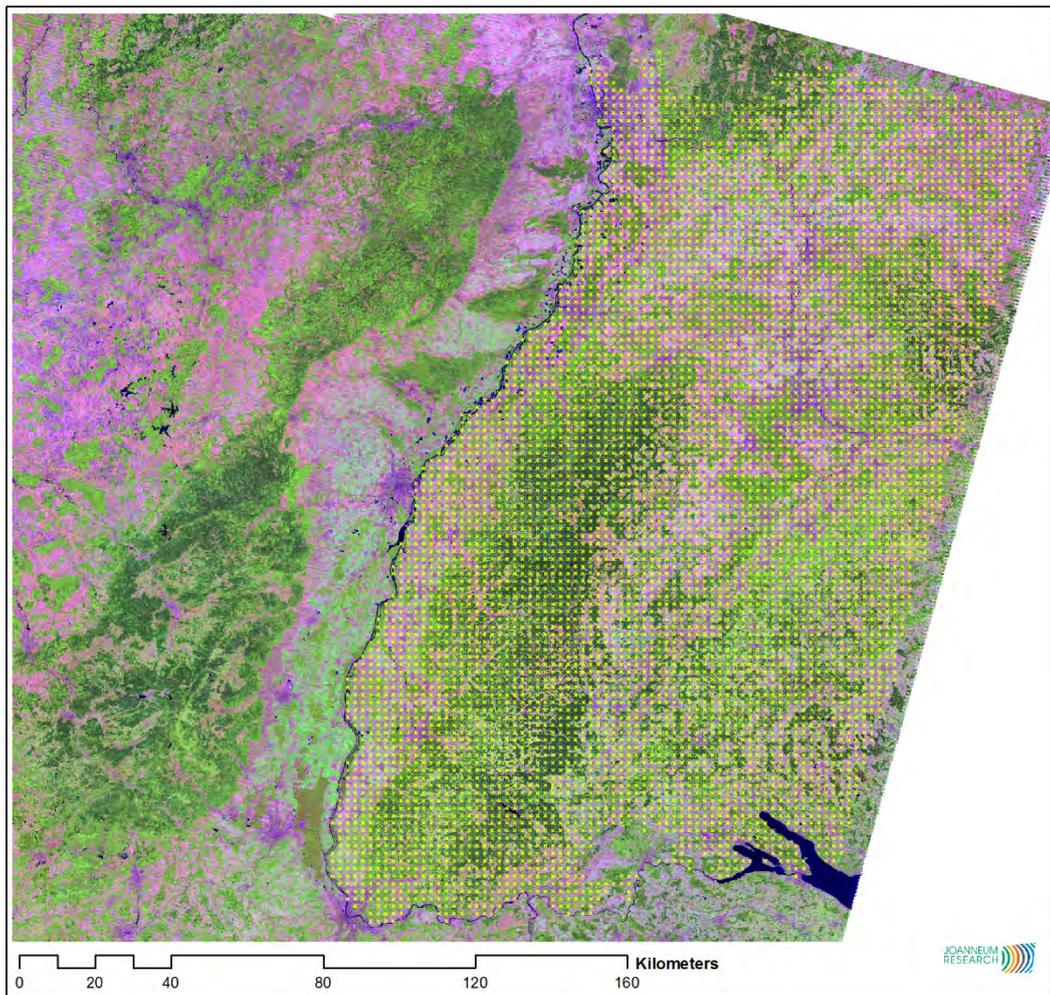


Figure 10 Distribution of plots of the second and third national forest inventories of Germany within the demonstration site (full site shown above, and part of the site drawn below). Sampling locations are in 2 x 2 km grid (indicated with yellow dots) with each sampling location covering a maximum of 4 plots. The distance between the individual sampling plots is 150 x 150m.

In total, 25.000 plots were available for the project, where for each plot detailed attributes derived from the field measurements were provided by the forest administration of Baden Württemberg. The main attributes used for the project were “above ground woody biomass” in t/ha and “stem volume over bark” in m<sup>3</sup>/ha.

Also for the Serbian demonstration site, comprehensive field inventory data was provided by the Forest Faculty, University of Belgrade. Whereas for the German/France site, field inventory was available for two periods, for Serbia, only data from one period as provided.

For the German/France demonstration site, this allows an independent accuracy assessment, as data from the BWI-II was used for estimation and calibration only, and data from BWI-III was used for the independent accuracy assessment only. Therefore, in following chapters, estimation, calibration as well as the independent accuracy assessment is described for the German/France demonstration site.

## 4.2.5 Time series data

### 1.1.1.1 High resolution optical time series

#### German/France demonstration site:

As the field inventory data from the second national forest inventory of Germany BWI-II is from the period 2001-2002 and from the third inventory BWI-III from 2011-2012, the time series was generated with multispectral data from Landsat 5, 7 and 8, but without Sentinel-2 imagery. As from 2015 onward Sentinel-2 imagery is available, the temporal resolution of future time series will increase (compare chapter 4.2.2). Below figures show the Landsat coverage of the demonstration sites German/France and Serbia.

From the Landsat archive, all scenes acquired in the vegetation period from 2000 to 2015 with cloud cover below 40% were downloaded. After a visual check, e.g. regarding remaining dust over the demonstration site after atmospheric correction, a large number of scenes were processed for generating the time-series:

- 132 scenes for path 195 / frame 26
- 118 scenes for path 195 / frame 27
- 105 scenes for path 196 / frame 25
- 106 scenes for path 196 / frame 27

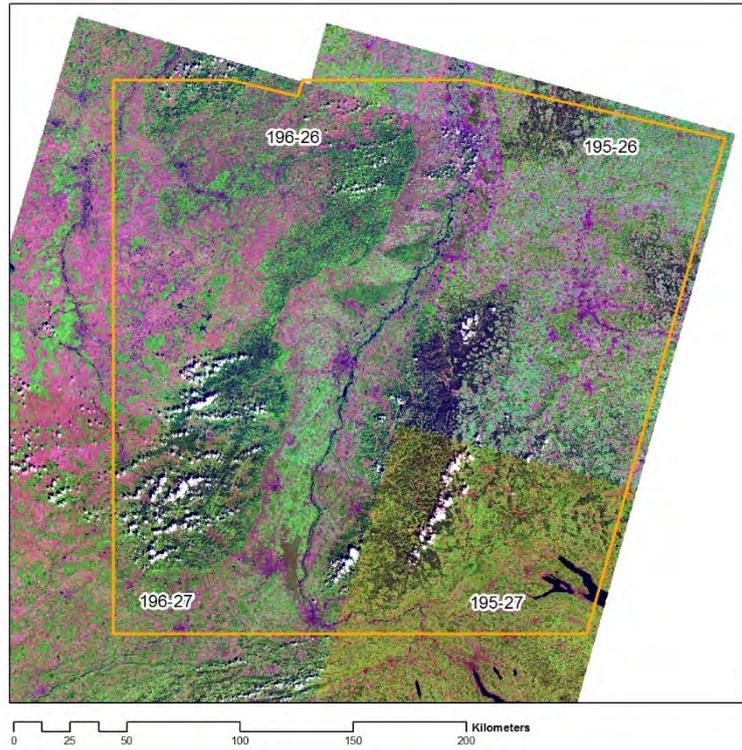


Figure 11 Location of the Landsat frames covering the German/France demonstration site

Serbian demonstration site:

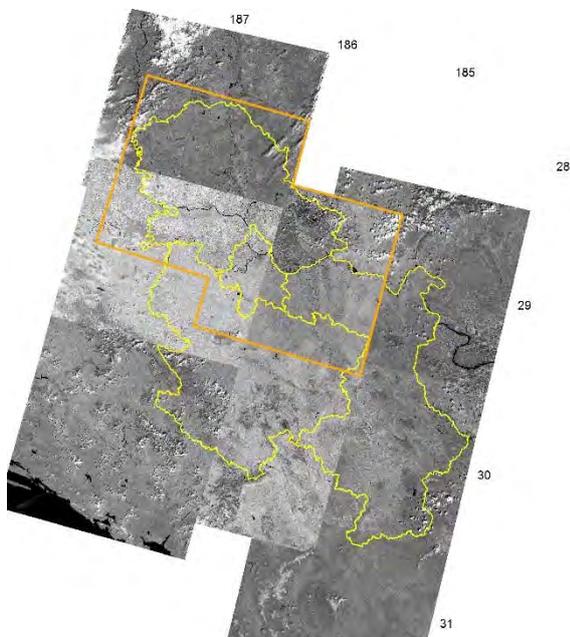


Figure 12 Location of the Landsat frames selected for the Serbian demonstration site (selected frames are drawn in orange, administrative boundaries in yellow, Landsat frame numbers are given at the border).

As for the German/France demonstration site, also for the Serbian site a visual check was performed as a first step, e.g. regarding remaining dust over the demonstration site after atmospheric correction. A large number of scenes were then processed for generating the time-series:

- 128 scenes for path 185 / frame 29
- 141 scenes for path 186 / frame 29
- 138 scenes for path 187 / frame 28
- 128 scenes for path 187 / frame 29

As the USGS archive allows automated downloading and the pre-processing steps implemented at Joanneum Research are automated, these processing steps can be applied operationally for large area assessments. Details on the pre-processing and processing methods are described in next chapter.

#### **1.1.1.2 Low resolution optical time series**

Methodological testing was performed in the first project phase based on dense time series from MODIS, as dense time series with high spatial resolution based on Sentinel-2 and Landsat 8 are only recently available. We used the so-called MCD43A4 product from USGS, which provides 500 meter reflectance data adjusted using a bidirectional reflectance distribution function. The German/France demonstration site was covered and the focus was on detection of storm-damages as described below. However, for future operational application, we recommend to use high resolution time series from Sentinel2 and optionally in addition Landsat 8 data in areas characterized by frequent cloud cover.

#### **4.2.6 Methods**

In the last years, free availability of Landsat imagery, advances in image pre-processing and classification methods, as well as increase in computational capacity have stimulated the development and application of time series methods for forest monitoring based on high resolution time series. The next chapters focus on those methods which are directly relevant for estimating above ground woody biomass and stem volume at a yearly basis as well as changes of these important forest parameters over time.

#### **1.1.1.3 Pre-processing of optical time series**

A pre-requisite for application of time series based methods is that the image data is precisely geometrically as well as radio-metrically pre-processed. The general pre-processing workflow is outlined in following figure.

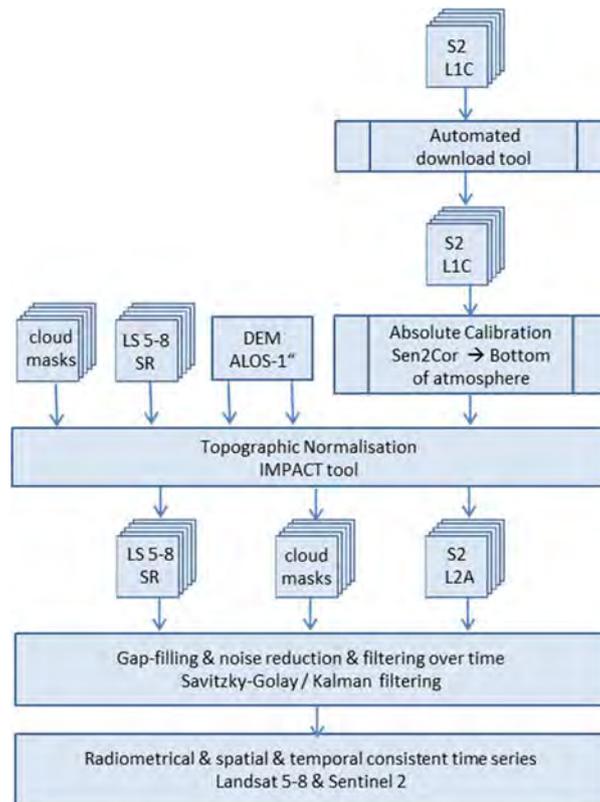


Figure 13 General pre-processing workflow, based on optical time series imagery for Landsat and Sentinel 2.

Within the project, Sentinel-2 processing was successfully tested. For the generated time series however, only Landsat 5, 7 and 8 multispectral imagery were used, because at the respective project phase, only Sentinel2 imagery from the “ramp-up” phase were available but no finally calibrated S2 imagery, and because the available field reference data was from 2002 to 2012 period (prior to the launch of S2 in 2015).

**Geometric pre-processing** is in general performed by fully automated ortho-rectification. Landsat as well as Sentinel-2 time series are already provided ortho-rectified with subpixel-accuracy over Europe. Optionally, co-registration can be applied to reduce remaining geometrical inconsistencies by application of image matching algorithms. COTS software is operationally available for this processing step.

For **radiometric pre-processing** of time series in a first step, absolute atmospheric correction is applied. For atmospheric correction of Landsat imagery, the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) software can be applied which is freely available at the USGS website (URL: <http://landsat.usgs.gov>), or already atmospherically corrected imagery can be downloaded e.g. file-List based tools via <https://earthexplorer.usgs.gov/filelist> (accessed 4th January 2017).

For atmospheric correction of Sentinel 2 imagery to bottom of atmosphere reflectance, ESA provides the tool sen2cor which is freely available from the ESA servers. In general, tools for atmospheric correction of optical data are continuously

improved by organisations such as ESA (for Sentinel2 imagery) or USGS/NASA (for Landsat imagery).

In addition to atmospheric correction, **topographic normalisation** is applied to reduce the impact of different solar illumination depending on the local topography in hilly to mountainous terrain.

For **noise reduction and gap-filling**, Savitzky Golay filtering is applied, which filters the time-series imagery based on polynomial interpolation. As this pre-processing step includes filtering over time, also remaining differences caused by varying phenology, such as different wetness conditions over time are reduced.

The results of above pre-processing steps are wall-to-wall radiometrically and geometrically consistent mosaics of bottom of atmosphere reflectance time series as shown in Figure 15.

#### ***1.1.1.4 Estimating above ground woody biomass stocks and stem volume***

The implemented workflow for estimating above ground woody biomass and stem volume including derivation of changes over time is outlined in Figure 14.

First, pre-processing is applied as described in the previous chapter. The resulting calibrated time series are then used to derive yearly maps of stocked areas by rule based classification. The yearly maps are then aggregated over the monitoring period to derive a forest - non-forest mask. Estimation of the forest parameters is then only performed within this forest- non-forest mask.

As the spatial assessment units for the national forest inventories (which are based on the so-called Winkelzählprobe measurements) differ from the satellite data resolution, an automatic up-scaling approach which was developed by Gallaun et al. (2010) was applied. As opposed to conventional classification methods such as k-NN classification (Tomppo et al., 2002) which relate the plot measurements directly to remote sensing data, this approach has the main advantage that it is not sensitive to a mismatch between the area represented by the individual plot measurements and the area covered by each pixel.

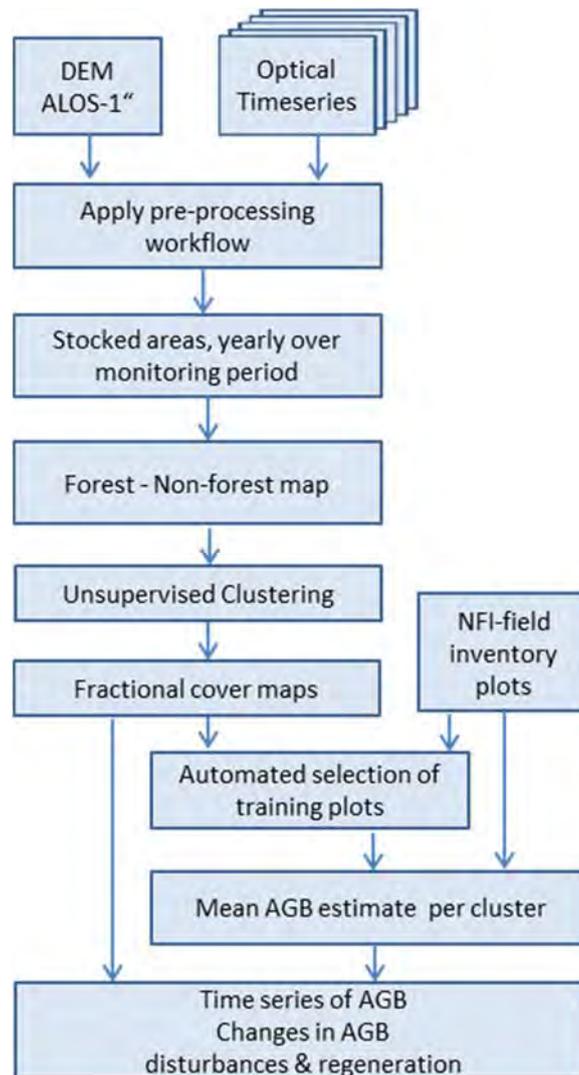


Figure 14 Workflow for estimating above ground woody biomass and stem volume based on optical time series imagery and field inventory plots.

#### *Unsupervised clustering:*

Clustering is performed by applying the Iterative Self-Organizing Data Analysis Techniques (ISODATA) algorithm within the forest – non-forest mask. In the next step, fractional cover maps are calculated for each cluster category. To measure the fractional coverage of the different land cover categories within each pixel, the posterior probability of class membership is calculated (Foody et al., 1992; Häme et al., 2001). The posterior probability was calculated according to Strahler (1980) with:

$$\Phi_k(\mathbf{X}_i) = \frac{1}{(2\pi)^{\frac{p}{2}} |\Sigma_k|^{\frac{1}{2}}} \exp\left\{-\frac{1}{2}(\mathbf{X} - \mu_k)^T \Sigma_k^{-1} (\mathbf{X} - \mu_k)\right\}$$

With:

$p$	Number of features used to characterize each observation.
$\mathbf{X}_i$	Vector of measurements on $p$ variables associated with the $i^{\text{th}}$ observation
$\Phi_k(\mathbf{X}_i)$	Probability density value associated with observation vector $\mathbf{X}$ for class $k$ .
$\Sigma_k$	Variance-covariance matrix associated with the $k^{\text{th}}$ class.
$\mu_k$	Parametric mean vector associated with the $k^{\text{th}}$ class.

The result of this processing step is one layer for each cluster with posterior probability of membership to the respective cluster.

#### *Automatic selection of training plots:*

For each cluster, the pixels selected for training are the ones that include NFI sample plot data and that show a high posterior probability of membership to the respective cluster (Foody and Arora, 1996). Contrary to conventional classification, where homogeneous training areas are often used as reference data, this approach produces one training set for each cluster composed of dispersed pixels.

Estimate mean biomass stock / stem volume for each cluster:

The NFI plots located within each training set are then used to calculate mean above ground woody biomass stock or stem volume for each cluster. Since the mean values are determined by sampling, the method is not sensitive to mismatch in spatial scale between the plot measurements and the pixel size. This is the main advantage of this approach compared to conventional classification methods. As the pre-processed time series are absolutely calibrated, this estimation is only performed once, with the reference data and the satellite imagery taken from the same period.

#### *Time series estimation for the whole area:*

The estimation of the above ground woody biomass stock or stem volume is performed by weighting the cluster mean values with the posterior probability of membership of the respective class (Foody et al., 1992; Häme et al., 2001). The results of this processing step are yearly maps of estimated biomass stocks and stem volume. As the estimates are derived from one reference set and the pre-processing includes filtering over time of the yearly image mosaics, changes are derived by directly calculating the differences between the respective yearly estimates.

In the next chapter, the processing steps are discussed on the basis of the application within demonstration sites in Germany/France and Serbia.

## 4.2.7 Results

In the following, the results achieved within the German/France and the Serbian demonstration sites are discussed. Within S2BIOM all field inventory reference data were within the period 2002 to 2012. As Sentinel-2 is available from 2015 onward, only Landsat time-series were generated within the current project, however, for future applications, Sentinel-2 will be the main data source.

### 1.1.1.5 Pre-processing of optical time series

No **geometric pre-processing** needed to be applied, as the Landsat time series data are provided by USGS with sub-pixel location accuracy over the demonstration sites.

For **radiometric pre-processing** the LEDAPS software which is provided by USGS was applied. In the last project months, the Landsat time series were densified, because the USGS archive is currently in an updating process, where additional scenes are provided which were not included previously (e.g. further scenes from ESA archives are included). These scenes were already provided absolutely calibrated to bottom of atmosphere reflectance. For Sentinel-2, an automated pre-processing chain was implemented and tested successfully which includes the software sen2cor. Further, co-registration of Landsat and Sentinel-2 time series was tested with the software RSG which is developed by Joanneum Research. The tests showed, that geometric mismatches were reduced, however, USGS as well as ESA recently announced an optimized geometric pre-processing based on co-registration and it can be expected, that for a future operational implementation, the within-sensor relative geometric accuracy of Landsat time series as well as Sentinel-2 time series will significantly increase. For a future operational application, the co-registration accuracy between Landsat and Sentinel-2 should therefore be analyzed, specifically regarding remaining systematic offsets between Landsat and Sentinel-2 time series.

The absolutely calibrated time series were **topographically normalized** by application of the IMPACT software, which is developed by Joanneum Research. In this tool a so-called Minnaert-correction model is implemented. As input, digital elevation models were generated by combining the “best-off” available models. For the German/France test site the ranking in the mosaicking was a LIDAR based model (which covers part of the demonstration site in Germany, which was provided by the University of Freiburg that utilised data provided from the Forest Research Station of the Federal State of Baden-Württemberg), the ALOS 1” model and the SRTM 1” model. For the Serbian test site, no LIDAR model was available, and the ALOS 1” model was used with gap-filling with SRTM 1” model.

**Yearly mosaics** over the vegetation period were then generated by calculating the median reflectance of the pre-processed scenes over the vegetation period. Compared to the mean-value, the median is less sensitive to outlier-observations which still remain after the fully automated pre-processing. Such outlier-observations are e.g. caused by not detected clouds or cloud-shadows, or by imperfect atmospheric corrections, caused by regionally varying atmospheric conditions. The results of above pre-processing steps are yearly mosaics over the vegetation period for 2000 to 2015 of bottom of atmosphere reflectance derived from Landsat observations.

For a cost-effective future operational applicability at the continental scale, it is of main importance, that spectral libraries, which need to be developed only once for each bio-geographic region are used as basis for the estimation. As varying phenological conditions are present in the yearly mosaics, such as for example draught period over central Europe in 2003, a further “normalization” of the yearly mosaics over longer time intervals is required. This is achieved in the course of the **noise-reduction and gap-filling** process. Savitzky-Golay polynomial filtering was applied for this processing step. For future applications however, also other filtering approaches could be applied e.g. based on Kalman filtering. Below figure shows for a subregion within the German/France demonstration site the effect of this filtering process.

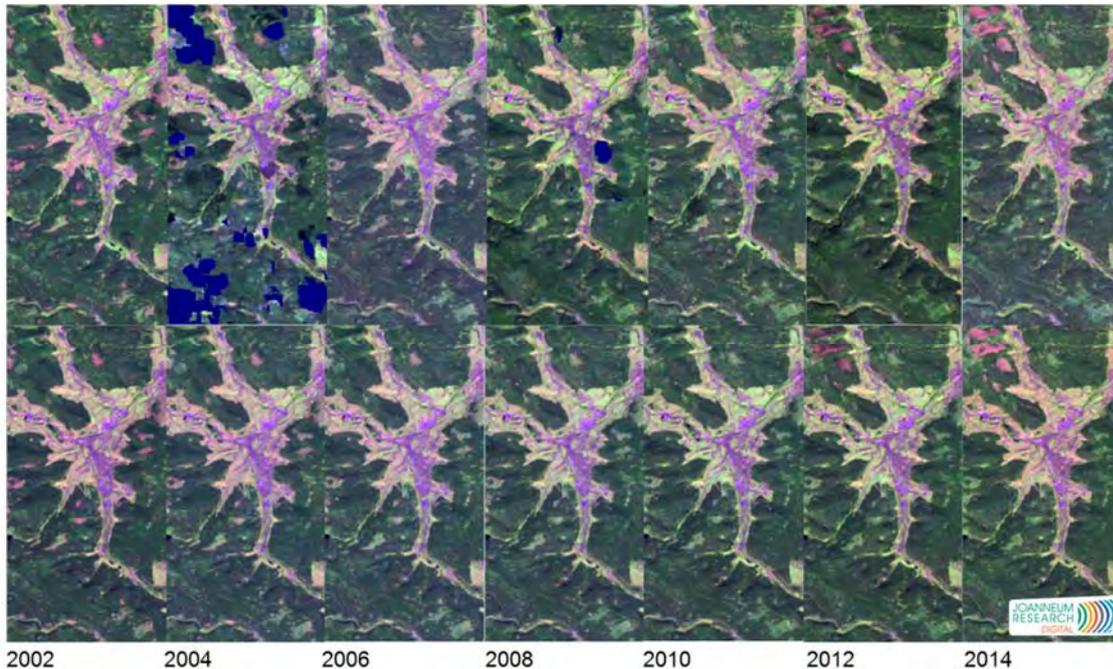


Figure 15 Result of noise-reduced and gap-filled time series (second column) compared with the input atmospherically corrected time series (first column) for a sub-region in the German demonstration site. Areas not covered by satellite measurements in the respective year are drawn in blue in first row.

In next figures, the coverage of the German/France and the Serbian test site with yearly mosaics is shown for the year 2014.

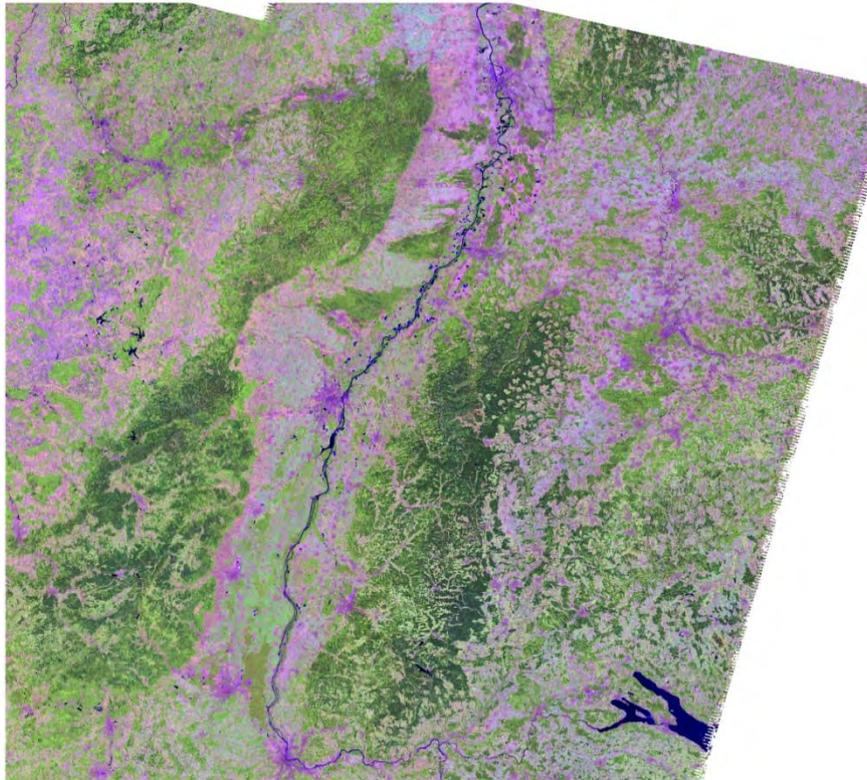


Figure 16 Resulting noise-reduced and gap-filled mosaic for the German/France demonstration site for the year 2014 (SWIR, NIR and Green drawn in RGB).

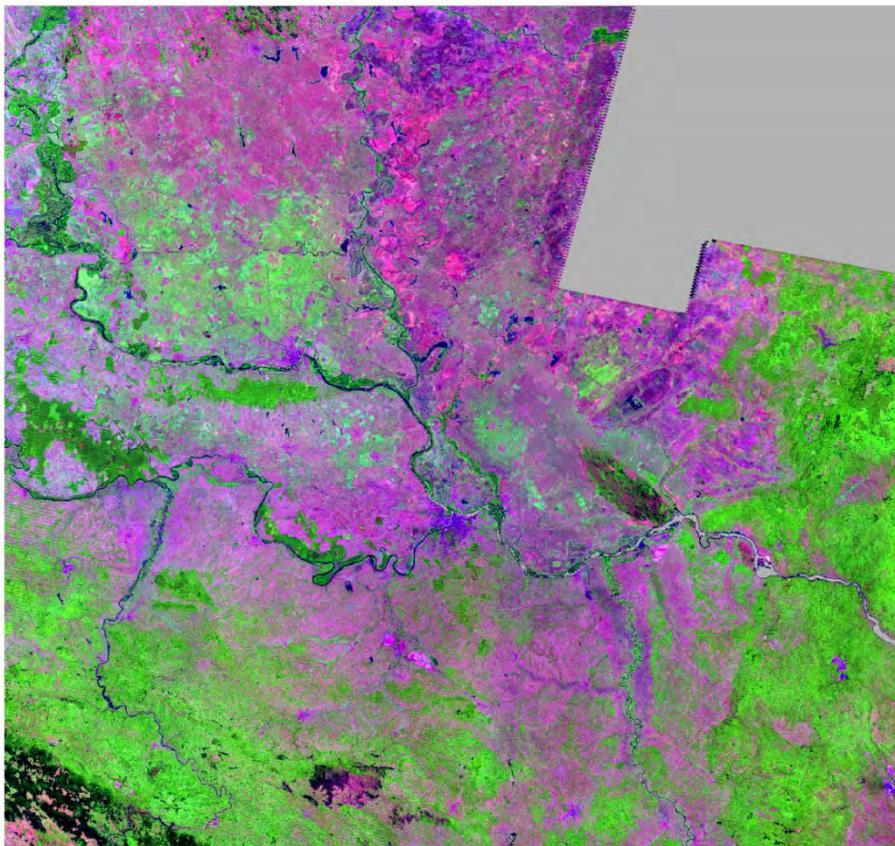


Figure 17 Resulting noise-reduced and gap-filled mosaic for the Serbian demonstration site for the year 2014 (SWIR, NIR and Green drawn in RGB).

### 1.1.1.6 Estimating above ground woody biomass stocks and stem volume

The methods described in the previous chapter were applied to estimate above ground woody biomass and stem volume based on the field inventory plot data. The estimations are derived at a yearly basis for the period 2000 to 2015. As the estimations are based on absolutely calibrated time series, reference data is only required for one period, and the derived signature libraries are directly applied for estimating the forest parameters for the other years. For the German/France demonstration site, field inventory data from the BWI-II from the period 2001-2002 was used as reference data. Data from the BWI-III from the period 2011-2012 was only used for an independent accuracy assessment as described in next chapter.

As the field measurement assessment units deviate from the satellite based pixel measurements, the plot level data were aggregated to the so-called sampling locations or clusters, each consisting of a maximum of four plots with a between distance of 150m. To reduce noise, only those sampling locations were used, for which all four plot measurements per cluster were available.

#### *Calibration of the estimation results:*

Based on the aggregated mean value of four plots for each sampling location, the cluster based estimates were calibrated by linear regression. BWI-II data which was also used in the cluster based estimation was used for calibration. Only sampling locations where all four plots lie within forest were used for calibration, which results in a total number of n=1228 sampling locations. The resulting functions are:

$vol\_cal = 1,17 * vol\_est - 67,9$  for calibrating stem volume and

$agb\_cal = 1,31 * agb\_est - 64,8$  for calibrating woody biomass.

As for the cluster based estimation, the same functions were applied for calibration of all yearly estimates. Whereas for the independent accuracy assessment (see next chapter) only data from BWI-III (from the period 2011-2012) was used, below figures show the scattergrams and linear trend lines for BWI-II data (from the period 2001-2002) which was also used in the cluster based estimation process. Whereas the determination of the calibration function was based on sampling locations where all four plots lie in the forest, following figures show the scattergrams and trend-lines for all sampling locations (also including plots out-site of forests). As not forested areas are classified in general with high accuracy, this leads to a significant increase of the correlation as following figures show. For below assessment, all sampling locations for which data from all four plots was available were used, which resulted in a total of n=5172 sampling locations or n=20.688 plots.

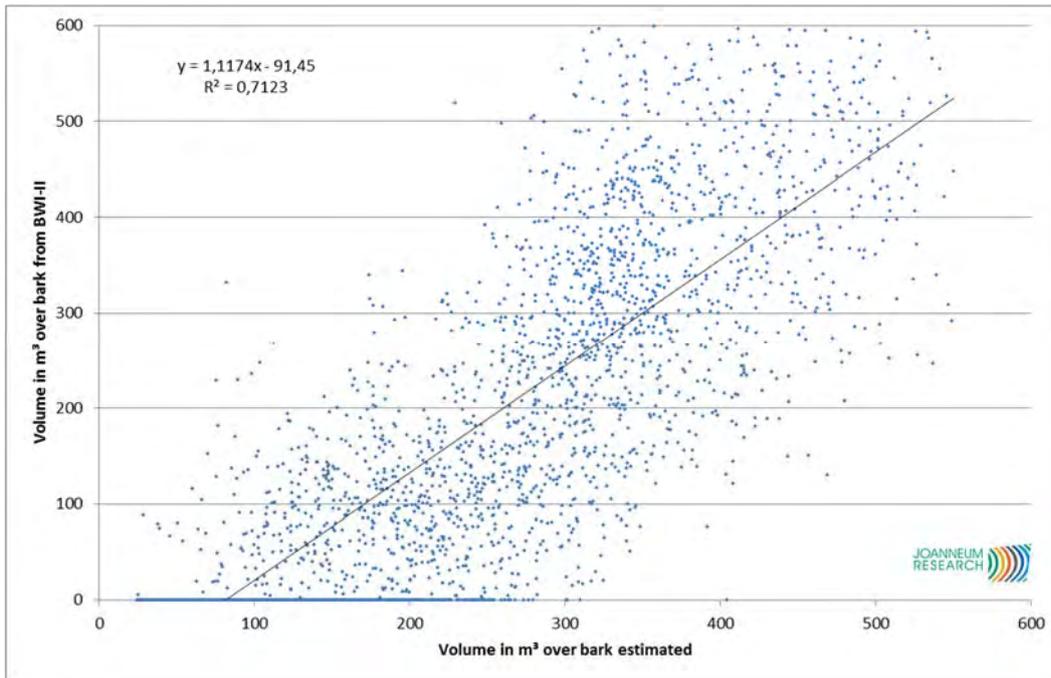


Figure 18 Stem volume - Scattergram and linear trendline for un-calibrated estimates based on n=20.688 NFI-plots

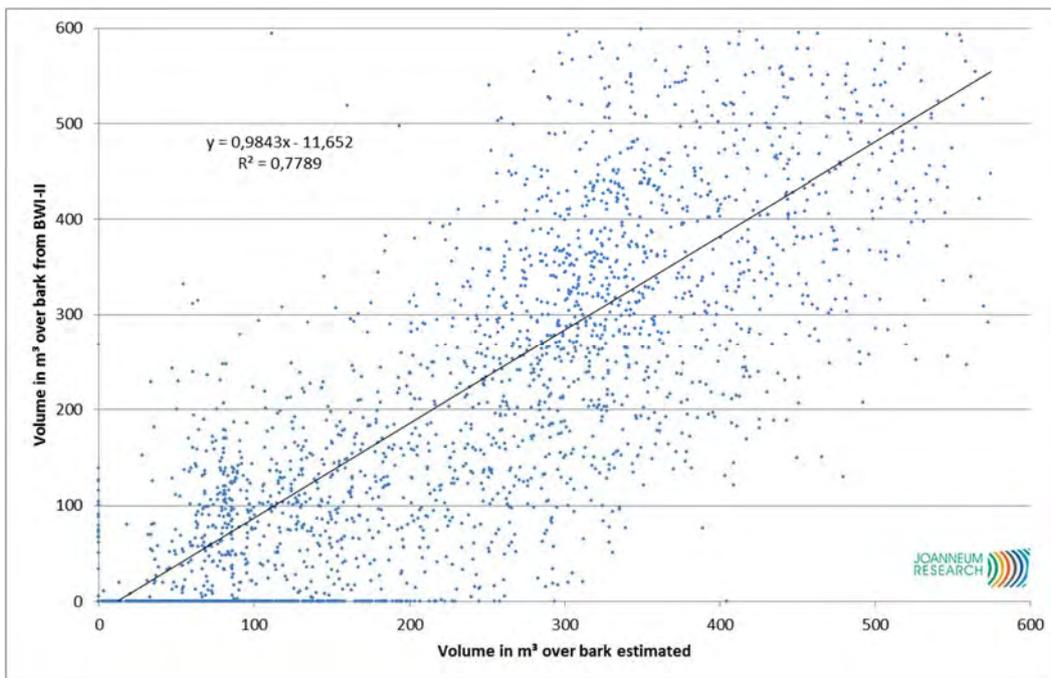


Figure 19 Stem volume - Scattergram and linear trendline for calibrated estimates based on n=20.688 NFI-plots

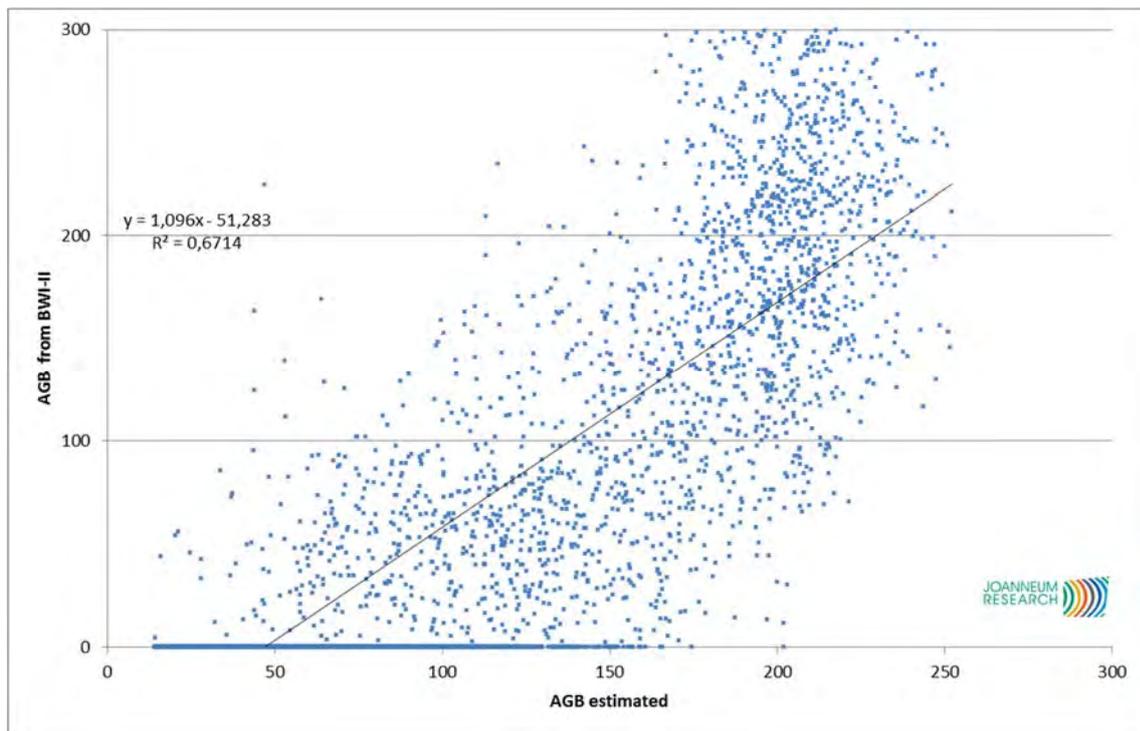


Figure 20 Above ground woody biomass - Scattergram and linear trendline for un-calibrated estimates based on n=20.688 NFI-plots

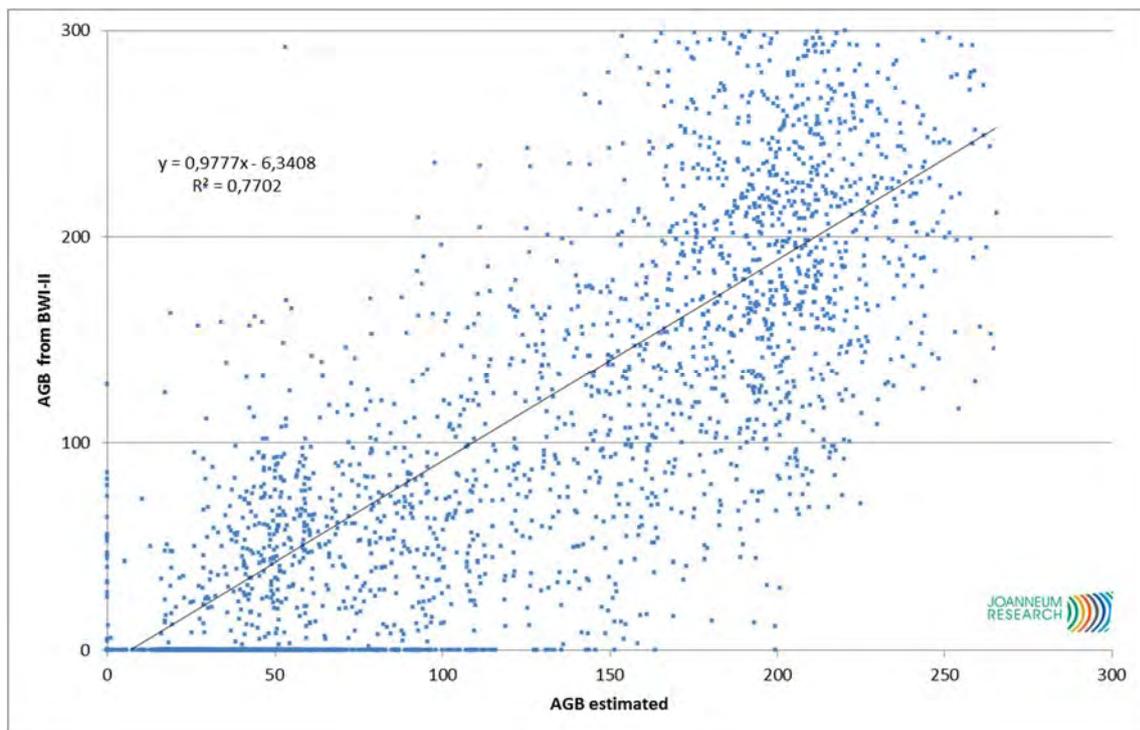


Figure 21 Above ground woody biomass - Scattergram and linear trendline for calibrated estimates based on n=20.688 NFI-plots

As above figures and regression analysis show, calibrating significantly increases the estimation accuracy. A small remaining bias after the calibration results from the fact,

that the forest-non forest mask includes a small fraction of agricultural fields. However, as for future operational applications, a manual editing of the forest-non-forest mask should be avoided because of time and cost reasons, only the fully automatically generated forest mask was used.

In the following, the discussion and illustration of the results focuses on the German test site and the years 2002 and 2012, as comprehensive reference data was available for these two years from the national forest inventory for this site, and also the accuracy assessment (next chapter) is performed based on these data sets.

Next figures show the estimation results of above ground woody biomass for parts of the German/France demonstration site. In addition to the estimates for the years 2002 and 2012 also the changes are illustrated, which show the effects of storm damages which occurred in 1999 and 2012. In areas damaged by Storm “Paula” in 1999 the green areas show ongoing regeneration processes between 2002 and 2012. The storm damages from 2012 are depicted in red colours.

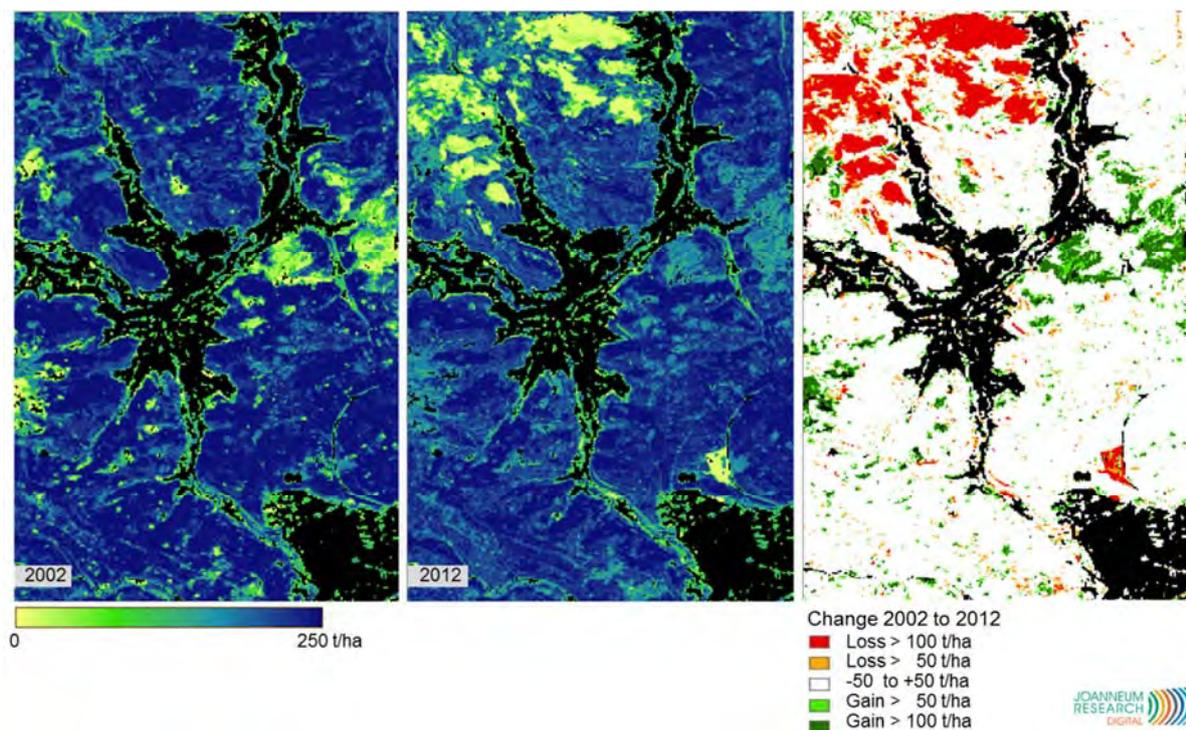


Figure 22 Above ground woody biomass estimates for the years 2002 (left), 2012 (center) and changes in woody biomass (right) for a sub-region which is also shown in Figure 15.

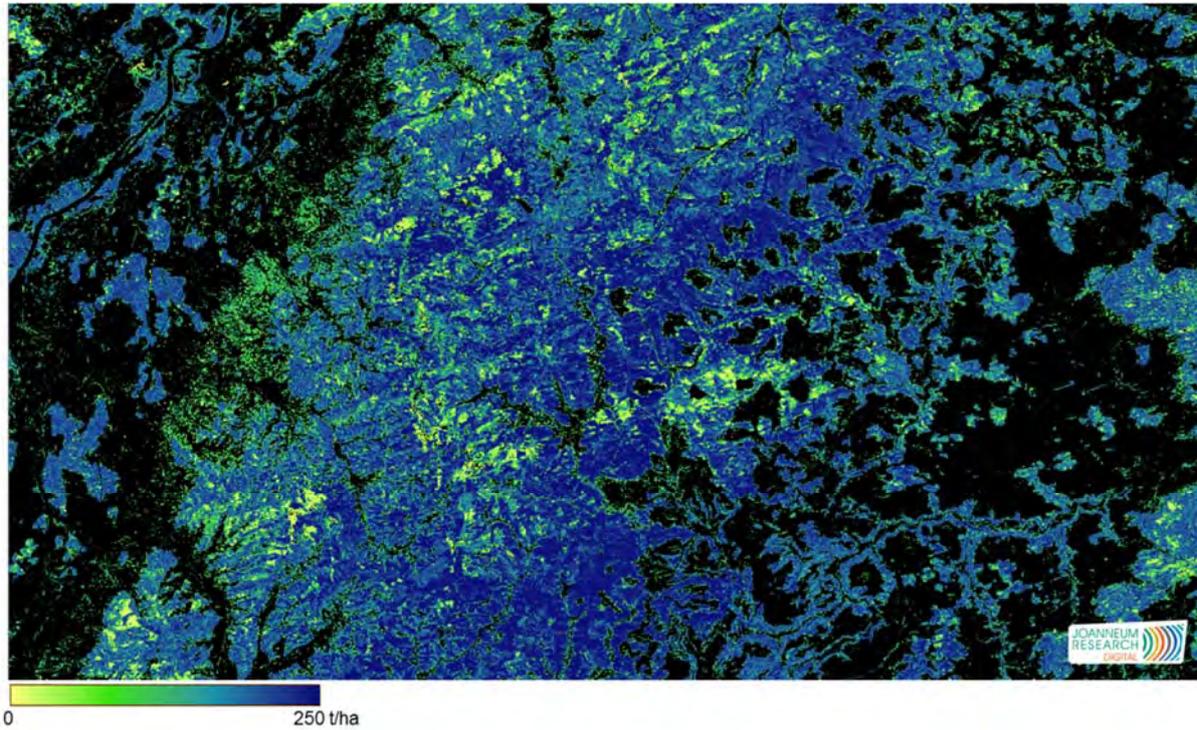


Figure 23 Above ground woody biomass estimates for the year 2002. Large areas which were damaged by the storm “Paula” in 1999 are characterised by low above ground woody biomass.

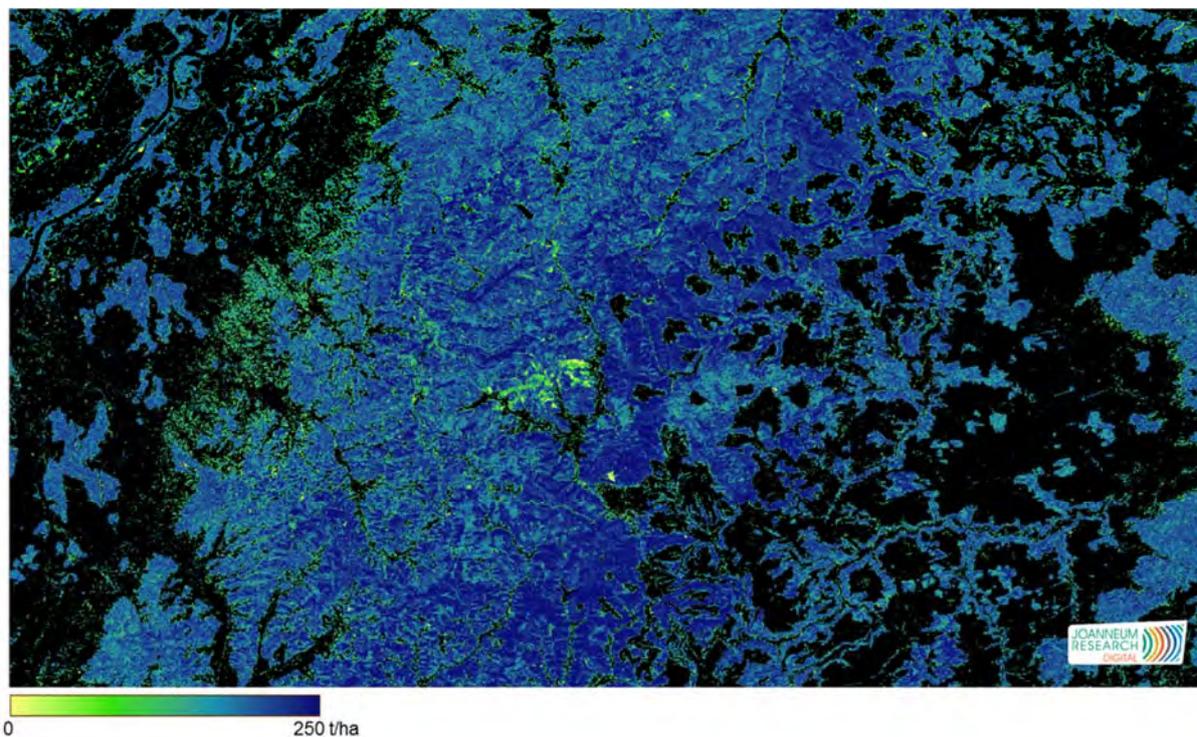


Figure 24 Above ground woody biomass estimates for the year 2012. In the center new damages are mapped, which were caused by a storm in 2012.

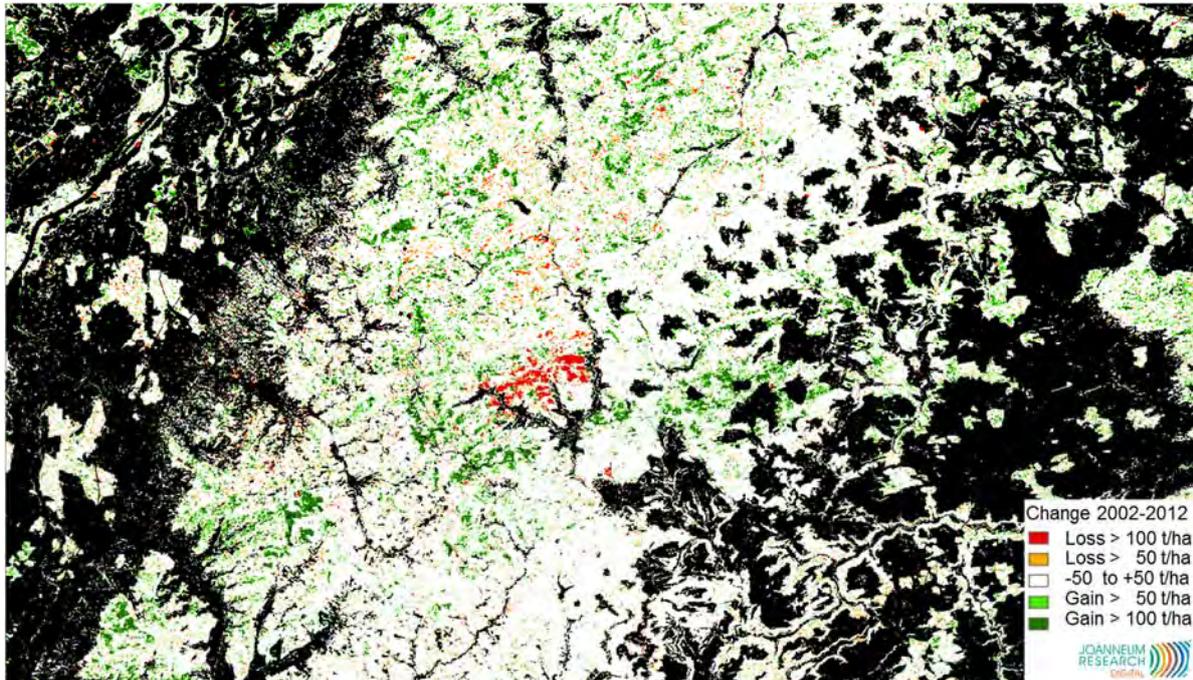


Figure 25 Changes in above ground woody biomass between 2002 and 2012. Whereas large areas which were damaged by the storm “Paula” in 1999 are in a regeneration process (compare also above figures), in the center new damages are mapped, which were caused by a storm in 2012.

Assessment of storm damages:

The estimation results can also be used for large area assessment of changes such as e.g. storm damages. In next figure an example is shown in the region of Freiburg in the German/France demonstration site where storm damages occurred at first and second July 2012.

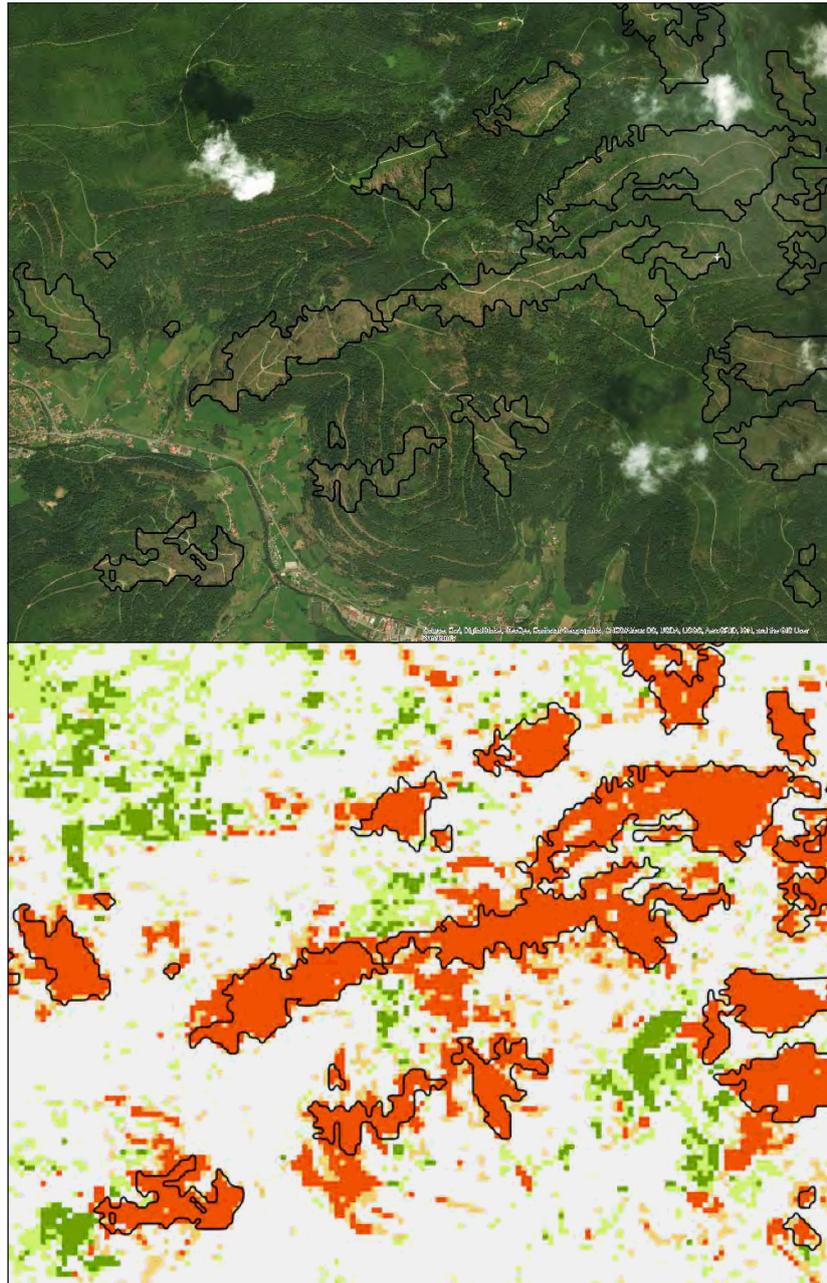


Figure 26 Assessment of storm damages in an area nearby Freiburg in Germany. Whereas large areas which were damaged by the storm “Paula” in 1999 are in a regeneration process (increase in stem volume drawn in green), damages caused by a storm on first and second July 2012 are clearly depicted (decrease in stem volume drawn in red). Visually interpreted outlines of storm damaged areas are drawn in black.

In next figure, results derived from the high resolution time series are compared with results derived from low resolution MODIS time series.

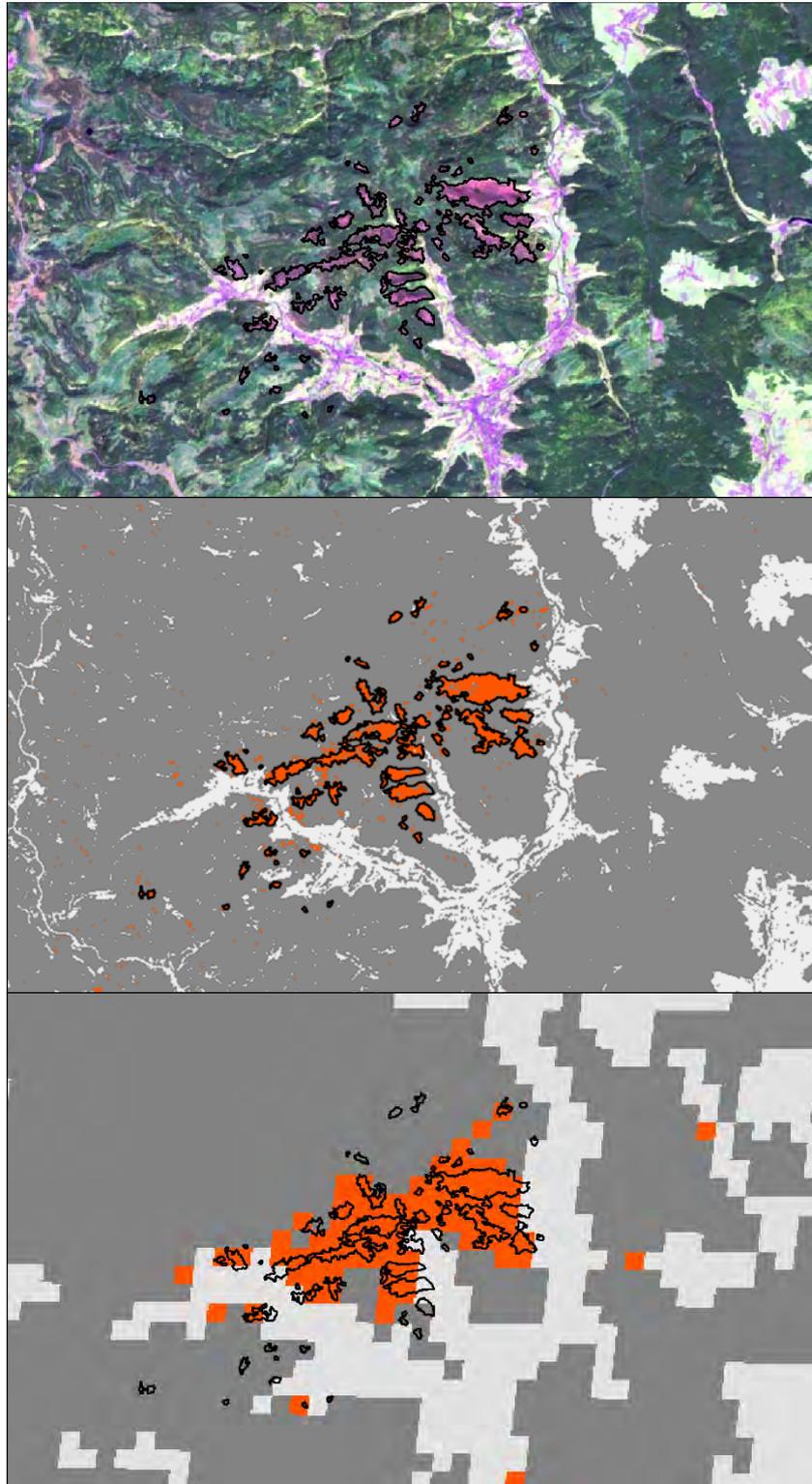


Figure 27 Assessment of storm damages in an area nearby Freiburg in Germany. Above, Landsat data with 30m spatial resolution overlaid with visually delineated storm damaged areas are shown. In the centre, a result of the landsat based assessment is drawn and below the results from low resolution MODIS assessment is shown.

Whereas large areas which were damaged by the storm “Paula” in 1999 are in a regeneration process (increase in stem volume drawn in green), damages caused by a storm on first and second July 2012 are clearly visible.

As shown above, the time series estimates allow large area assessment of storm damages, however, the estimates cannot replace field measurements in case that exact estimates of the damages are required.

### 1.1.1.7 Accuracy Assessment

#### Assessment of low spatial resolution change monitoring results:

In the first project phase, MODIS time series were used in the frame of the methodological developments. For quantitative evaluation of the monitoring method, a sampling based approach was applied, based on visual interpretation of the landsat time series as reference data.

Table 12 Evaluation results as contingency tables with reference category in columns and classified category in rows and overall accuracy given in percent.

	change	no change
change	20	0
no change	3	25
Overall accuracy:	94%	

Results derived from low resolution data such as MODIS are mainly relevant for monitoring at the global level, whereas for future operational applications at the pan-European level, assessments based on high resolution Sentinel-2 and Landsat 8 is recommended.

#### Assessment of high spatial resolution results:

For the high resolution assessments, a fully independent accuracy assessment has been performed, based on the field inventory data from the third national forest inventory of Germany. For clustering and calibration, only field inventory data from the second national forest inventory of Germany was used as described in the previous chapter, whereas for the independent accuracy assessment, only field inventory data from the third national forest inventory of Germany was used.

The assessments are based on a total number of 5172 sampling locations, each covered by four field inventory plots. As the assessment units of the field inventory plots (from the so-called “Winkelzählprobe” deviate from the satellite estimation assessment units (satellite image pixels), aggregation was performed to the sampling locations level by calculating the mean-values of the forest parameters for the estimations (e.g. mean of the four pixels corresponding to the four NFI plots). This aggregation reduces differences related to the different assessment units. Further,

this aggregation reduces impacts of remaining geo-location errors which are in the order below one pixel for the Landsat time series based estimates. However, both effects are still present in the accuracy assessments, which are therefore conservative estimates of the actually achieved accuracy. As aggregation is performed for two by two pixels, below accuracy assessments give the accuracy of aggregated forest parameter maps, e.g. maps with a spatial resolution of 60m by 60m per pixel. Further aggregation increases the estimation accuracy. For future operational estimations at the European level, an aggregation to 1ha by 1ha pixels is therefore recommended.

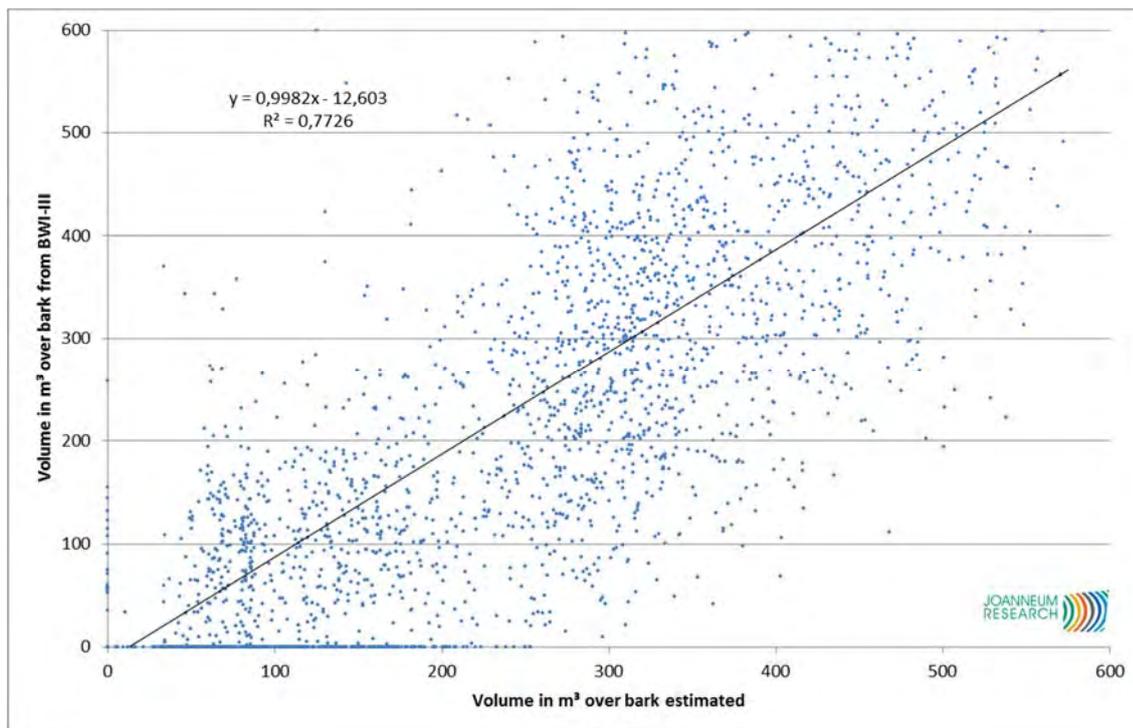


Figure 28 Independent accuracy assessment for estimation of stem volume. Scattergram and linear trendline based on n=5.167 sampling locations (each consisting of four NFI-plots) from the third national forest inventory of Germany.

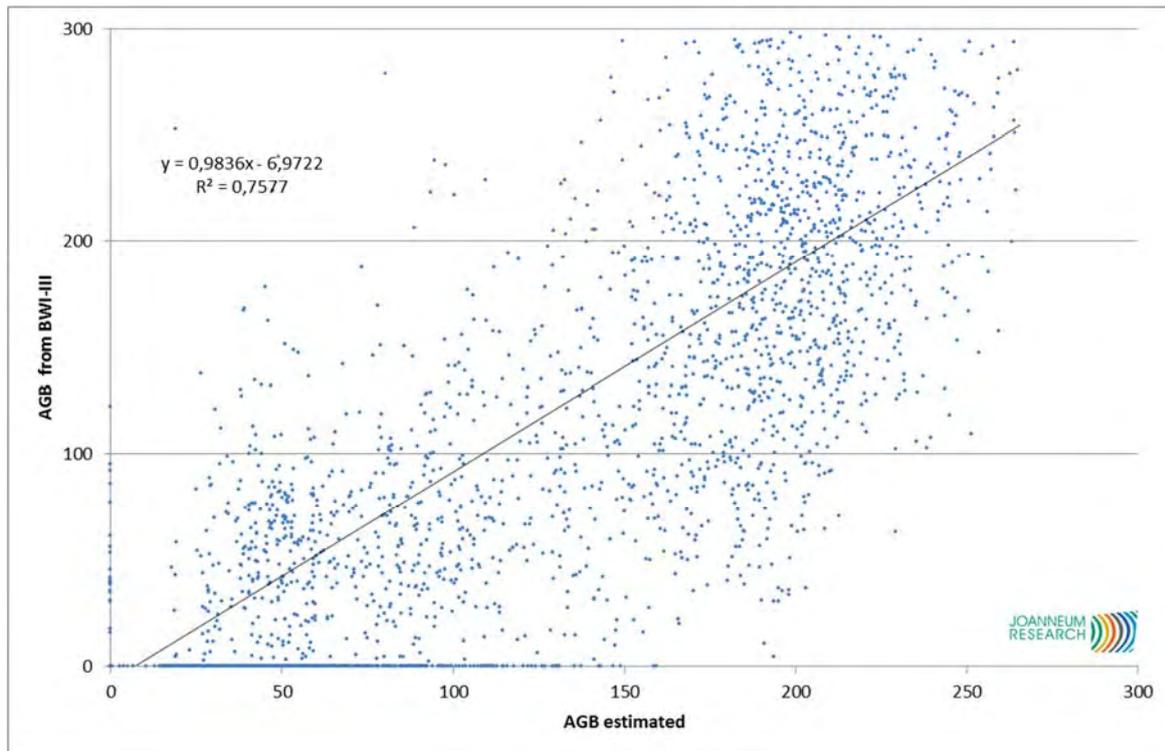


Figure 29 Independent accuracy assessment for estimation of above ground woody biomass. Scattergram and linear trendline based on n=5.167 sampling locations (each consisting of four NFI-plots) from the third national forest inventory of Germany.

#### 4.2.8 Conclusions

For a future estimation of above ground woody biomass at the national to continental level, following main recommendations are drawn from the achieved results:

- For monitoring periods starting in 2015, the main data source should be Sentinel2, complemented with Landsat 8 in regions with frequent cloud cover
- For monitoring periods before 2015, multi-spectral Landsat imagery can be employed, however at a reduced accuracy level compared to Sentinel2 based approaches because of the reduced spatial, temporal and spectral resolution.
- Fully automated, precise geometrical and radiometrical pre-processing is required which includes topographic normalisation in mountainous to hilly terrain.
- Filtering over time is recommended not only for noise reduction and gap-filling but also to “normalise” varying phenological conditions over time (and thereby allowing to work with one “normalised” signature library)
- Signature libraries at the level of bio-geographic regions which are based on field inventory data and absolutely calibrated time series should be used as basis for estimating
- Methods which directly relate the plot measurements to remote sensing data such as kNN based estimations should be avoided, because the assessment

units for the field measurements in general differ from the pixel measurement units

- To increase estimation accuracies, it is recommended to provide the final estimation results in aggregated form, e.g. with 1ha grid-cell resolution or for larger assessment units such as at NUTS level-3.

#### 4.2.9 References

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## 4.3 Integration of forest height estimation in timber volume and forest biomass mapping

### 4.3.1 Introduction

Above ground woody biomass and wood volume of a single tree are, besides the form of a tree, largely influenced by the tree height. Above ground woody biomass and wood volume of a forest stand are therefore largely influenced by the height of the trees and thus the forest height. It is therefore of high relevance for mapping of forest biomass and wood volume to integrate forest height estimates and maps.

This is generally possible by the estimation of the difference between the surface model and the terrain model resulting in an estimate of the vegetation height, in case of forests of the forest height.

The terrain model can in presence of dense high forest merely be determined with high accuracy by LIDAR that can penetrate the vegetation allowing the utilisation of reflectances from the ground. Provided such terrain model is available at high resolution from aerial LIDAR flight campaigns, it is sufficient to merely estimate the current vegetation surface in order to determine the vegetation height by the difference between the vegetation surface and the terrain model.

In many European countries such high quality terrain models are available. Both space born and airborne sensors can be used to determine surface height models at differing accuracies and spatial resolutions.

For a large scale application with Tandem-X a SAR sensor constellation was selected for an application test, since based on this sensor recently a global surface model was produced and is currently available. It is thus of high interest to explore its integration into large scale mapping of forest biomass and wood volume.

For local to regional airborne LiDAR can provides most accurate vegetation height mapping and it could be recently demonstrated that this enables wood volume maps of high accuracy in an application for the federal state of Baden-Württemberg (Maack et al. 2016<sup>16</sup>). Still airborne LiDAR campaigns are not yet regularly updated by national survey agencies, whereas for digital aerial photography this is the case in the majority of European countries and thus digital surface models from digital aerial photography offer, in combination with existing digital terrain models an approach with the potential for future for regional to even large scale applicability if access to such vegetation height maps is given at affordable cost.

16 Maack J, Lingenfelder M, Weinacker H, Koch B (2016): Modelling the standing timber volume of Baden-Württemberg—A large-scale approach using a fusion of Landsat, airborne LiDAR and National Forest Inventory data *Int J Appl Earth Obs*; 49: 107-116:

## 4.3.2 Mapping based on field inventory data, TanDEM-X, terrain information and Landsat – Test region federal state of Baden-Württemberg, Germany

### 1.1.1.8 Introduction

The use of remote sensing for the quantification of forest resources, viz. above ground biomass and growing stock volume has been a topic of research as well as has been in practice for forest monitoring to support decision making. There have been continuous efforts to apply improved methodologies and tools to improve the quality of estimations. While single sensor approaches are also in practice, multi-sensor approaches have been applied with increasing level of success for forestry applications, especially for biomass and volume estimation. The combined use of multispectral information and of the information on vegetation height is promising and with TanDEM-X a new option is now available on global scale.

TanDEM-X is a two satellite mission of German Aerospace Center (DLR) primarily aimed at producing a high resolution global DEM product based on X-band interferometric SAR data. The elevations are defined with respect to the reflective surface of X-Band Interferometric SAR returns, and since over forests the X-band scattering is centered towards the upper part of the vegetation volume, this creates a potential for forest height retrieval provided the information on the terrain height is available from another source.

The objective of this study is to test the suitability of TanDEM-X intermediate product (IDEM) for forest biomass and growing stock mapping in a multi-sensor approach for regional to large scale *applications*.

### 1.1.1.9 The test region

The study was conducted in federal state of Baden Württemberg (BW) which is located in the south west of Germany. With a total land area of 35,751 km<sup>2</sup> Baden Württemberg is the third largest state in Germany. According to the National Forest Inventory (BWI3) figures collected for the year 2012 the total forest area in the state is around 13719 km<sup>2</sup> corresponding to 39.4 percent of the total area.



Figure 30 Study area - federal state of Baden-Württemberg in Germany with footprints of the IDEM acquisitions overlaid (in red)

The ownership structure of the forest areas in the state have been shown in Figure 31.

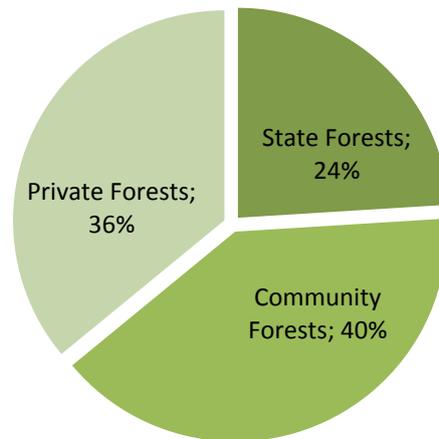


Figure 31 Forest ownership in Baden-Württemberg (percentage of total forest area) Source: (Kändler and Cullmann 2016 Fehler! Textmarke nicht definiert.)

The species composition of the forests in BW as shown by the results of the BWI3 (Kändler and Cullmann 2016<sup>17</sup>) are shown in Figure.

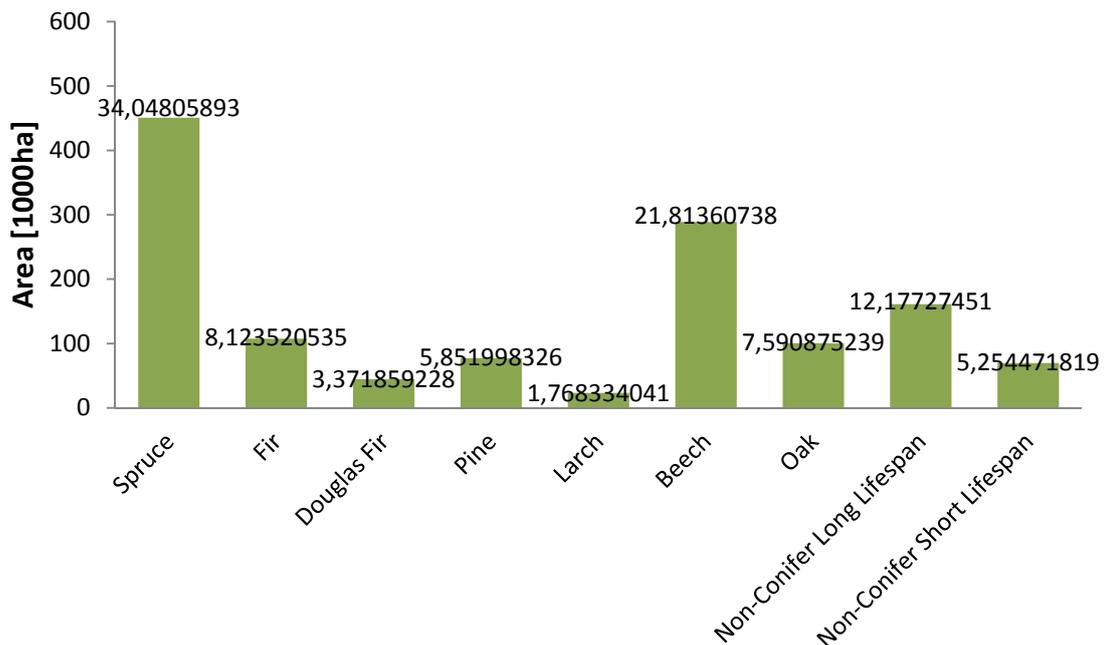


Figure 32 Forest tree species composition for Baden-Württemberg in 2012

While the flat Upper Rhine Valley to the west is rich in fertile soils which support agricultural, horticulture and viticulture, Black Forest (also known as Schwarzwald) is

17 Kändler G, Cullmann D. (2016): Regionale Auswertung der Bundeswaldinventur 3, Land Baden-Württemberg. Bericht. Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg.

[http://www.fva-bw.de/monitoring/bui/bwi/bwi3/pdf\\_download/Land\\_Baden-W%FCrttemberg.pdf](http://www.fva-bw.de/monitoring/bui/bwi/bwi3/pdf_download/Land_Baden-W%FCrttemberg.pdf)

the largest continuous forest area in Germany. The highest elevation of 1493m above sea level is at Feldberg in the Black Forest while the lowest elevation is 85m. The climate is diverse with influences from both western maritime and eastern continental climates. The average annual temperature ranges from 9 °C in the Rhine Valley and 5 °C in the mountains.

#### 1.1.1.10 *Remote Sensing datasets:*

##### **TanDEM-X**

TanDEM-X is a dual satellite interferometric synthetic aperture radar (SAR) mission of the German Aerospace Centre (DLR), and the primary goal of the mission is to generate a high-precision global Digital Elevation Model (DEM) with a 12m pixel resolution. Two types of datasets were used for the current study, viz. Coregistered Single look Slant range Complex (CoSSC) data and Intermediate digital elevation model (IDEM) data. The COSSC data was used to test the vegetation height accuracies of the TanDEM-X mission while the IDEM was acquired for the entire state of Baden Württemberg and was used as the primary dataset for forest AGB estimation.

The CoSSC data is a product where the TanDEM-X acquisitions from the operational modes are processed by the Integrated TanDEM Processor (ITP) using the processing blocks for bistatic calculations and synchronization, SAR data focusing, Coarse azimuth coregistration, spectral filtering and finally co-registration and resampling. For further detailed technical information about the CoSSC product please refer to Balss et al. (2012)<sup>18</sup>.

Each CoSSC consists of a co-registered image pair, one monostatic active image where the satellite transmits and receives the SAR signal (Master) and a bistatic passive image where the signal is only received and not transmitted (Slave). Four image pairs (hereinafter referred to as scenes 1-4) were selected based on their location, all covering large parts of the study area and overlapping each other in certain areas. The images were acquired acquisitions took place between July 2011 and September 2013.

All scenes were acquired in Stripmap mode with single, horizontal polarization (HH) covering an area of about 35 x 55 km or 1750 km<sup>2</sup>. The quality of all scenes was automatically approved during preprocessing and, according to their metadata, will be used for the global digital elevation model “WorldDEM”.

18 Balss, U., Breit, H., Duque, S., Fritz, T., Rossi, C., 2012. TanDEM-X Payload Ground Segment: CoSSC Generation and Interferometric Considerations German Aerospace Center (DLR), Remote Sensing Technology Institute, Oberpfaffenhofen. [https://tandemx-science.dlr.de/pdfs/TD-PGS-TN-3129\\_CoSSCGenerationInterferometricConsiderations\\_1.0.pdf](https://tandemx-science.dlr.de/pdfs/TD-PGS-TN-3129_CoSSCGenerationInterferometricConsiderations_1.0.pdf). (Accessed 14 July, 2015)

Three scenes were acquired in an ascending (flying northwards) and one in a descending (flying southwards) orbit. The three ascending scenes had incidence angles between 39.3° and 41.4° while the descending scene had a larger incidence angle of 46.2°. More technical information about acquisitions of Important information about the scenes is summarized in Table 13. It can be seen that scene 2 was acquired before foliation in spring which enables for a comparison between summer and winter data. Unfortunately the scene that was acquired in a descending orbit also has the highest incidence angle and the smallest baseline. Testing for the effect of flight direction, incidence angle and baseline on the quality of the derived height models was therefore not possible, because these different acquisition characteristics could not be tested separately and research on these aspects should be carried out with adequate data.

Table 13 Acquisition specifications of CoSSC data

Scene	Date of Acquisition	Baseline [m]	$2\pi$ Ambiguity height [m]	Polarization	Incidence Angle [°]	Orbit	Master Satellite
1	2011-07-27	-278.9	23.9	HH	40.6	Ascending	TanDEM-X
2	2013-04-03	-360.5	17.7	HH	39.3	Ascending	TanDEM-X
3	2012-08-15	-417	16.4	HH	41.4	Ascending	TanDEM-X
4	2013-09-02	-224	35.8	HH	46.2	Descending	TerraSAR-X

### IDEM (Intermediate DEM):

The Intermediate DEM (IDEM) is a DEM product derived from acquisitions of the first global coverage of TanDEM-X mission. This coverage uses one baseline configuration for acquiring each scene and does not have the advantages of the dual-baseline technique, or multiple incidence angles. This may lead to phase unwrapping errors and data gaps due to omitted scenes in rough terrain areas. IDEM is available at pixel spacings of 0.4 arcsecond, 1 arcsecond and 3 arcseconds (at equator). For this study, the IDEM scenes at 0.4 arcsecond at equator (approximately 12m) resolution were used. The overall absolute horizontal and vertical accuracies are presumed to be less than 10m but the vertical accuracies have not been specified. Although it is expected to have higher height errors compared to the final DEM (Wessel 2016<sup>19</sup>), it can be used as a precursor to the final DEM and to test the suitability of TanDEM-X DEM as a potential source of height information which can be used to estimate above ground forest biomass. For a detailed overview of the DEM generation process please refer to B.Wessel (2016)**Fehler! Textmarke nicht definiert..**

19 B. Wessel (2016): TanDEM-X Ground Segment – DEM Products Specification Document, EOC, DLR, Oberpfaffenhofen, Germany, Public Document TD-GS-PS-0021, Issue 3.1, 2016. [Online]. Available: <https://tandemx-science.dlr.de/>

The study area of Baden Württemberg is covered by 11 scenes which were acquired during the first acquisition period between 2011 and 2012 (Figure 30). The tiles georeferenced to the geographic latitude longitude grid were mosaicked using the Erdas Imagine mosaicing functionality, and reprojected to Gauss Krüger projected coordinate system. The mosaicked DEM which is a digital surface model (DSM) was resample to a 10 m pixel size for further analysis.

### **Airborne Laser Scanner:**

Using Airborne Light Detection and Ranging (LiDAR) technology in remote sensing has increased the amount and value of the information that can be collected relative to three-dimensional structure and geometry of objects on the earth surface (Pirotti 2010<sup>20</sup>).

Airborne LiDAR data for entire Baden Württemberg whad been collected in campaigns organized by the Landesamt für Geoinformationen und Landentwicklung (LGL) between 2000 and 2005. The point data was collected at a density of 0.8 per m<sup>2</sup> and this information was used to generate digital terrain model (DTM) and DSM at 1 m pixel resolution using TreesVis 0.86 (Weinacker et. al., 2004<sup>21</sup>). The ALS based DSM was used for comparison with TanDEM-X CoSSC derived DSMs over non-forest areas to identify systematic height offsets and as an input reference DEM during the interferometric processing of TanDEM-X DSMs. The ALS DTM was used as terrain input when extracting the forest height information from IDEM as well as input variable in the multisensor based AGB modelling approach.

### **Landsat 7 ETM+:**

The Landsat program has been providing continuous multispectral data since 1972 and this data is available without restrictions from USGS. In addition to the Landsat Level 1 standard data products, higher level science data products (e.g. land surface reflectance) can also be ordered through a number of data access sites (URLs: <https://earthexplorer.usgs.gov> last accessed 10.01.2017, <http://glovis.usgs.gov>, last accessed 10.01.2017; <http://landsatlook.usgs.gov>, last accessed 10.01.2017). The current operational satellite are Landsat 7 launched on April 15, 1999 and Landsat 8 which was launched on February 11, 2013.

A mosaic of spectral information from Landsat 7 ETM+ scenes from vegetation seasons from 2011 - 2013 was generated and and an NDVI product was computed using the NIR and Red bands of the mosaic. Furthermore a Principal Component

20 Pirotti. F (2010): ICESat/GLAS Waveform Signal Processing for Ground Cover Classification: State of the Art. Italian Journal of Remote Sensing, 42, pp. 13-26.

21 Weinacker H., Koch B., Weinacker R. (2004): TREESVIS: a software system for simultaneous 3D-real-time visualisation of DTM, DSM, laser raw data, multispectral data, simple tree and building models. International Archives of Photogrammetry. Remote Sens. Spatial Inf. Sci. 36, 90–95.

(PCA) Analysis was performed with all spectral bands to obtain the first three PCAs, which were further used in the subsequent classification process. Because maize and forest canopy have a similar reflectance these two classes are often mixed in the classification process. To address this, the spectral variance of the NDVI during the vegetation seasons was calculated. With a simple threshold based approach, the agricultural fields could be excluded from the final classification results.

Additionally, forest type map and forest/non-forest maps were produced using random forest classification and training datasets obtained from BWI 3 plots, and visual interpretation of VHR satellite imageries resp.

#### 1.1.1.11 *Field reference data:*

The Third National Forest Inventory of Germany (BWI) data is the primary reference dataset used in this study. The third BWI (BWI-3) is the most current large scale field reference data available at national scale with the data having been collected in the years 2011 and 2012. The inventory is conducted along permanently delineated sample points distributed in all forest types and ownerships. While the national inventory sampling intensity is conducted along a 4 x 4 kilometer sampling grid, in Baden Württemberg and some other federal states, the samples are collected on a denser 2 x 2 km grid. Each sample is called a tract and the data collection is done at each of the 4 corners of the tract (provided all the corners are inside forest) at a distance of 150 x 150 meter.

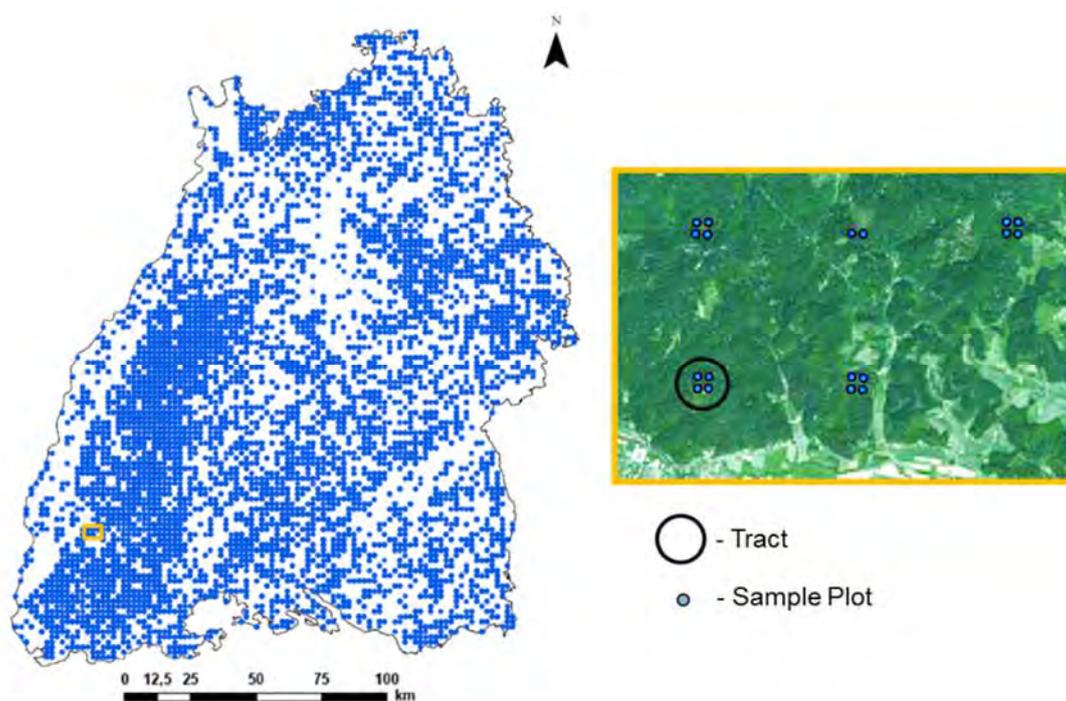


Figure 33 Location of plots of the third national forest inventory in the study area. Sampling locations in 2 x 2 km grid (main map area) with 4 plots (less if areas are not fully covered by forest) of 150 x 150m distance at each sampling location (inset)

The inventory comprises an extensive assessment of different forest parameters including but not restricted to species, age, height, diameter at breast height (DBH), etc. The trees to be measured are not selected inside a fixed plot but are selected by the angle count sampling method using a basal area factor of 4. Of all selected trees the height of two trees from the main tree species and one from every other tree species in the mid to high diameter class are measured to assess the main stand. In addition one tree from every tree species from the upper canopy layer and one coniferous and broadleaved tree from the lower canopy layer (if present) are measured in the secondary stand (Nebenbestand). The height and DBH are then used in allometric equations to calculate the AGB and volume for each of the inventoried plots. For details of the inventory methods and the measured parameters, please refer to Polley, 2011<sup>22</sup>.

In addition to the national forest inventory plot data, the stand level data from the public forest administration was also used for validation of the stand level AGB results. This data is collected periodically (every 10 years) for forest management planning activities. The volume data originate from the sample based inventory and a stratification by forest type that are assigned to the single stands considering that a stand can be composed of several forest types by story layers or small scale mixture. Data from forest enterprises are used where field data collection took place between 2010 to 2013.

22 Polley, H. (2011). Aufnahmeanweisung für die dritte Bundeswaldinventur. 2. geänderte Auflage, Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz (BMELV). Bonn.

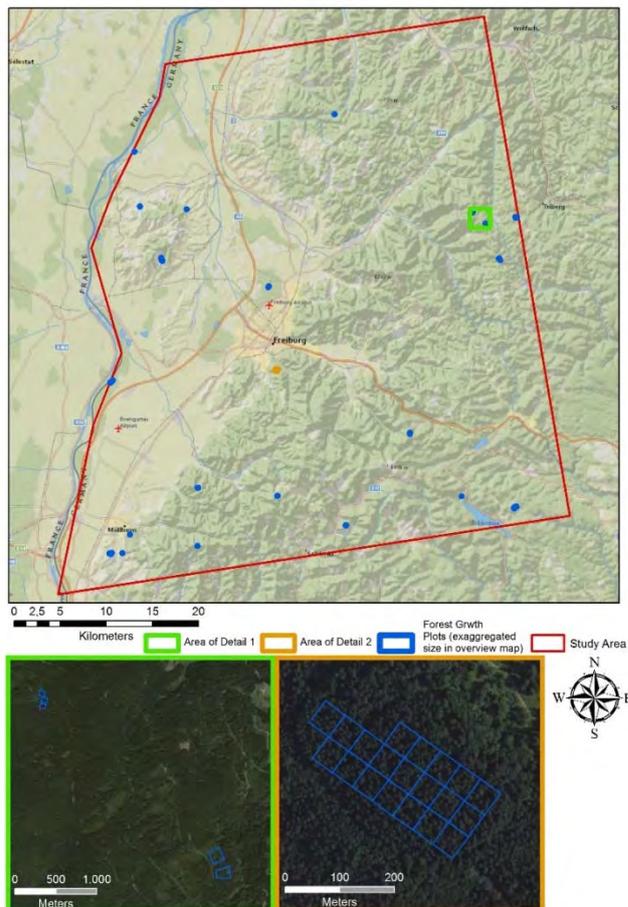


Figure 34 Overview of location of Forest Growth Plots in the sub-study area and detail maps exemplifying different plot designs

Finally, we used plot height data from several management inventories comprising of dense sampling grids in the range of 100m by 100m to 200m by 200 m from forest growth plots that varied in size (about 0.1 – 1 ha) and pattern (Figure 34). These plots were used to assess the overall and forest heights obtained from TanDEM-X CoSSC and TanDEM-X IDEM surface models.

#### 1.1.1.12 *TanDEM-X forest height evaluation*

In this chapter, the general accuracy of canopy heights retrieved from TanDEM-X CoSSC and IDEM datasets has been evaluated.

#### **SAR Data Processing:**

The SAR data was processed with the Envi Sarscape software version 5.1. The InSAR TanDEM-X bistatic DEM Workflow which is specifically designed to process TanDEM-X data was applied. The workflow consists of the following steps which are common in interferometric SAR Processing, also see Figure 35:

- Interferogram Generation and Flattening
- Adaptive Filter and Coherence Generation
- Phase Unwrapping

- Phase to Height Conversion and Geocoding

The single steps of the workflow are described in detail in Höhl, 2015<sup>23</sup>.

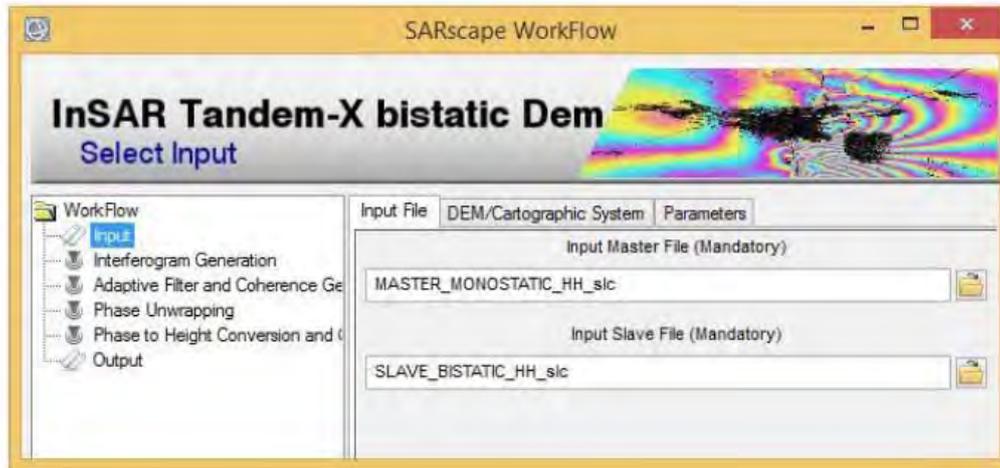


Figure 35 Sarscape TanDEM-X interferometry workflow and file inputs.

## Results

Initial tests on one scene showed that 2x2 looks provided best coherence results. Adaptive filters that were explored utilising the Sarscape software have been: Adaptive-, Boxcar- and Goldstein Filter that have been tested to identify the most suitable processing procedure for forest height retrieval. A detailed description of the filters and their application can be found in the Sarscape manual (SARMAP, 2014).

<sup>23</sup> Höhl Markus (2015). The Potentials of TanDEM-X Based Forest Height Modelling: A Case Study from the Upper Rhine Valley and Southern Black Forest. Master Thesis, Faculty of Environment and Natural Resources, University of Freiburg.

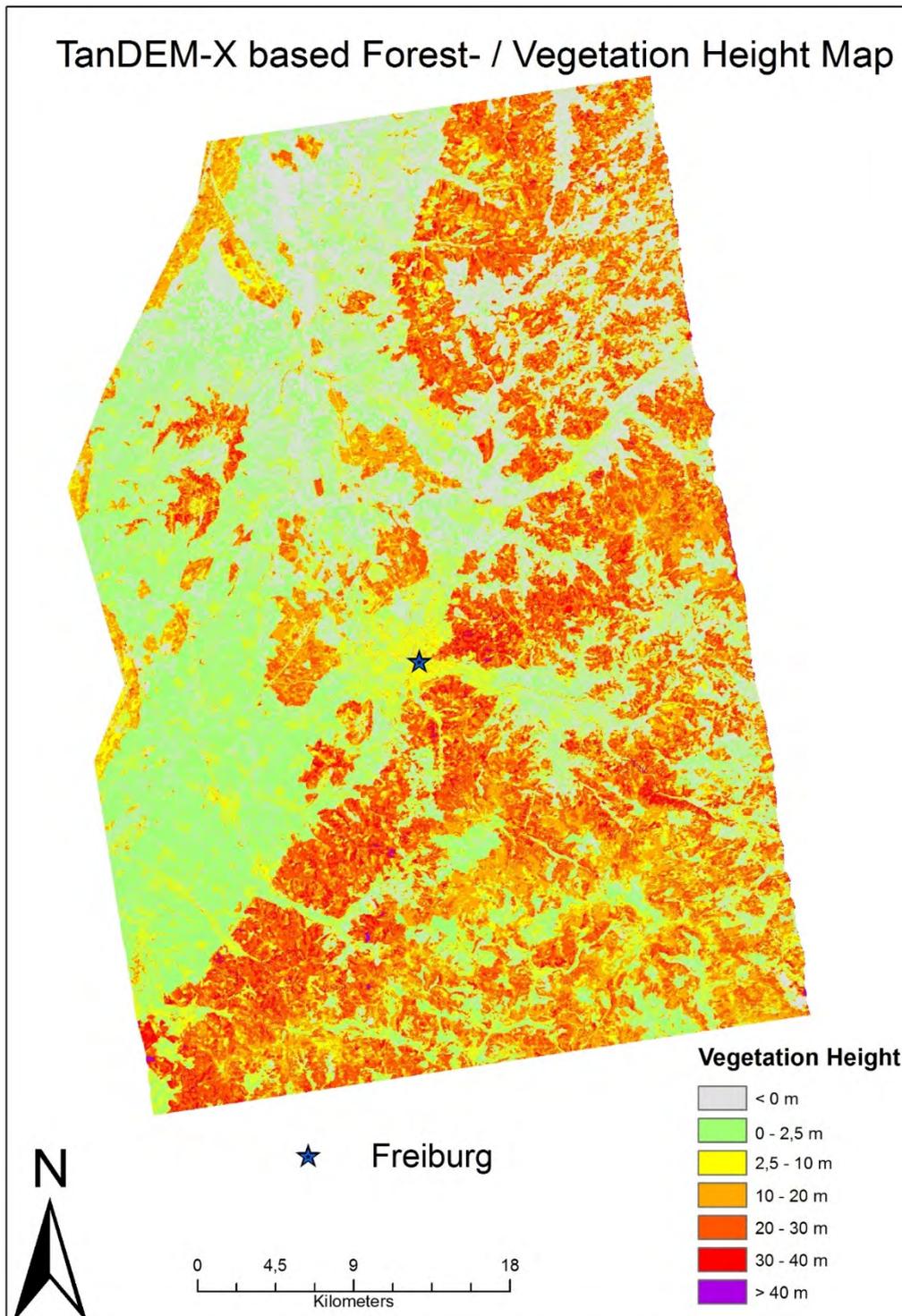


Figure 36 Forest / Vegetation Height Map, Scene 1, Adaptive Filter, Minimum Cost Flow Phase Unwrapping

Comparisons of the different processing options for the determination of the model height per plot based on the SAR based height model and the boxplots of the error distribution of different forest height models processed using different filters are shown in Figure 37 and Figure 38. The plots show that lesser numbers of plots were underestimated when the maximum model height was applied. The distribution of errors is similar for different processing options of the same scene with overlapping

notches of the boxplots indicating that the medians do not differ significantly. Figure 39 allows a direct comparison between the forest height models of different scenes. The plots indicate that the IDEM based forest height models show the biggest average underestimation of all assessed models with a significantly lower median compared to the remaining height models, as indicated by the notches. It can also be seen that the height models derived from different scenes differ from each other with significantly different medians for several datasets and a different spread of error with scene 2 based height models showing the biggest spread.

Summarizing it can be stated that the TanDEM-X based forest height models show a trend towards underestimation of forest mean height, especially when using the mean model values for the comparison to field heights. The IDEM based forest height model shows a significantly bigger average underestimation than the processed models that were selected for this comparison.

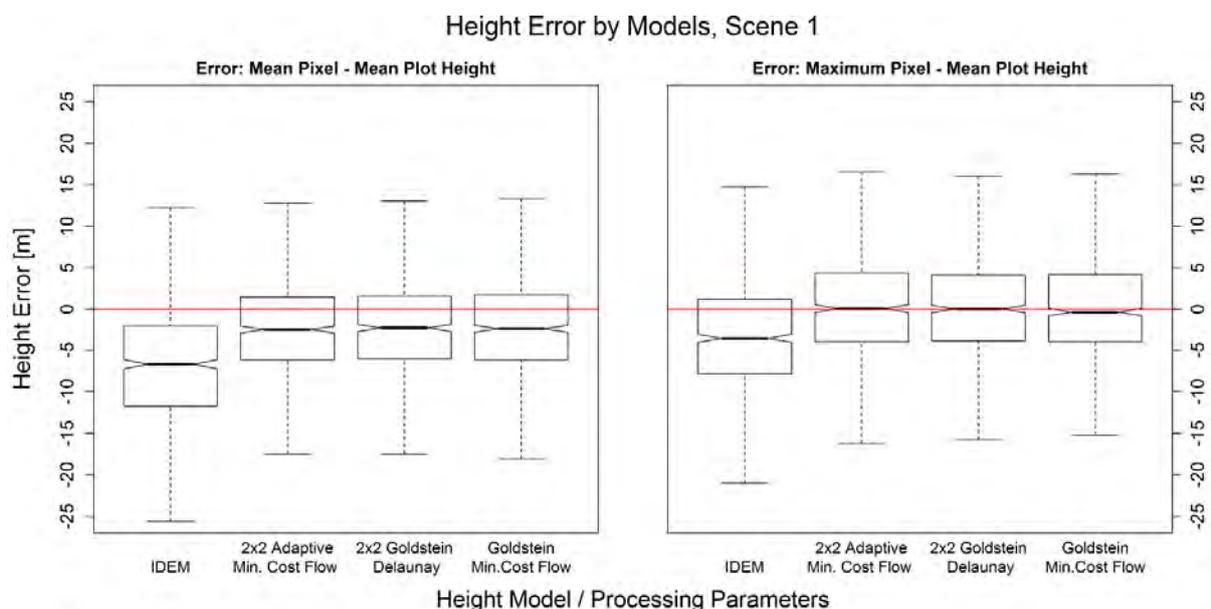


Figure 37 Scene 1 + IDEM: Height Error: mean / maximum model height – mean stand height  
 Comparison of well performing forest height models to each other and IDEM and comparison between the use of mean- and maximum model height values with regards to the errors.  
 Processing Parameters: Number of looks, applied noise filter and phase unwrapping of the particular forest height model used for the analysis. Red Line: Zero line.

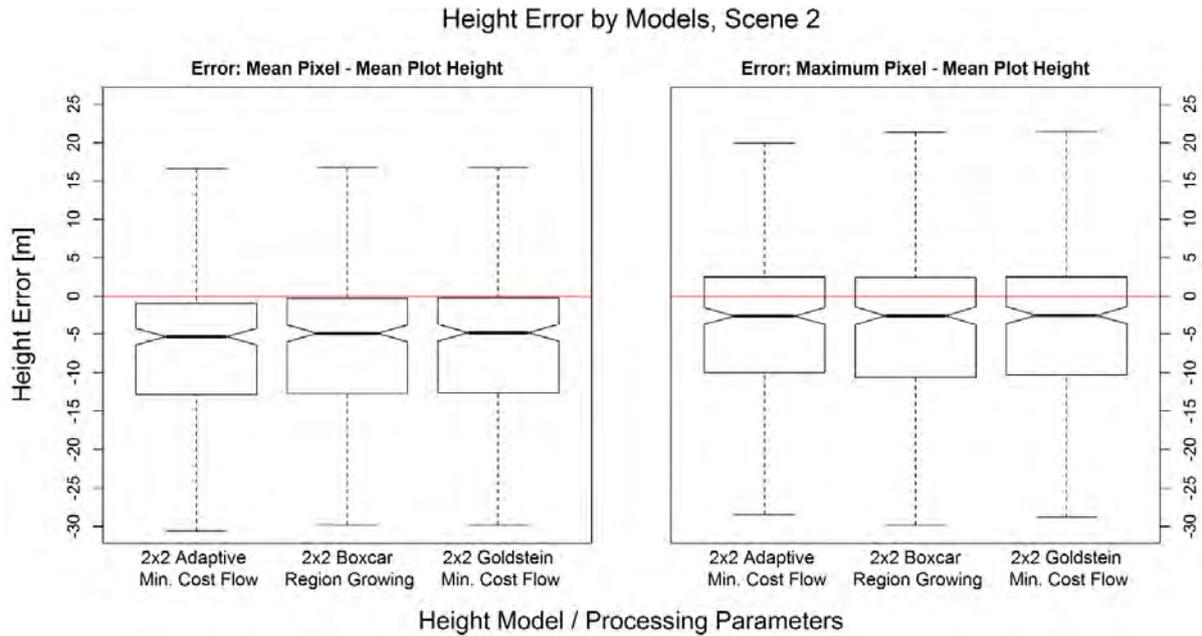


Figure 38 Scene 2: Height Error: mean / maximum model height – mean stand height. Comparison of well performing forest height models to each other and IDEM and comparison between the use of mean- and maximum model height values with regards to the errors. Processing Parameters: Number of looks, applied noise filter and phase unwrapping of the particular forest height model used for the analysis. Red Line: Zero line.

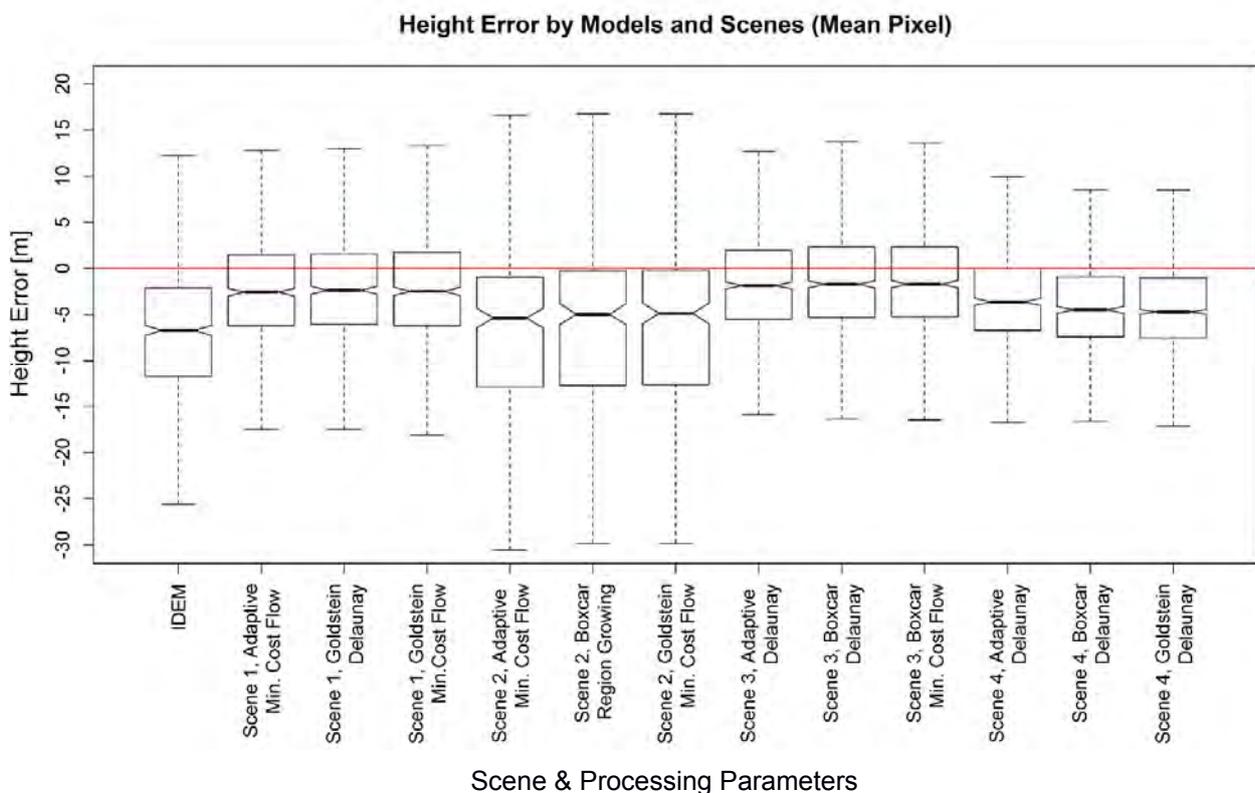


Figure 39 IDEM + Scene 1 – 4, Boxplots of height errors between MEAN model height and mean plot height for comparison between the scenes and models. Scene & Processing Parameters: Scene Number, applied noise filter and phase unwrapping of the particular forest height model used for the analysis. Red Line: Zero line.

## Magnitude of Forest Height Model Error

For a better overview and comparison of the error magnitude of the different scenes and height models the normalised root mean square error (NRMSE) of the nine height models processed for every scene were plotted for all sets of reference data (Figure 40).

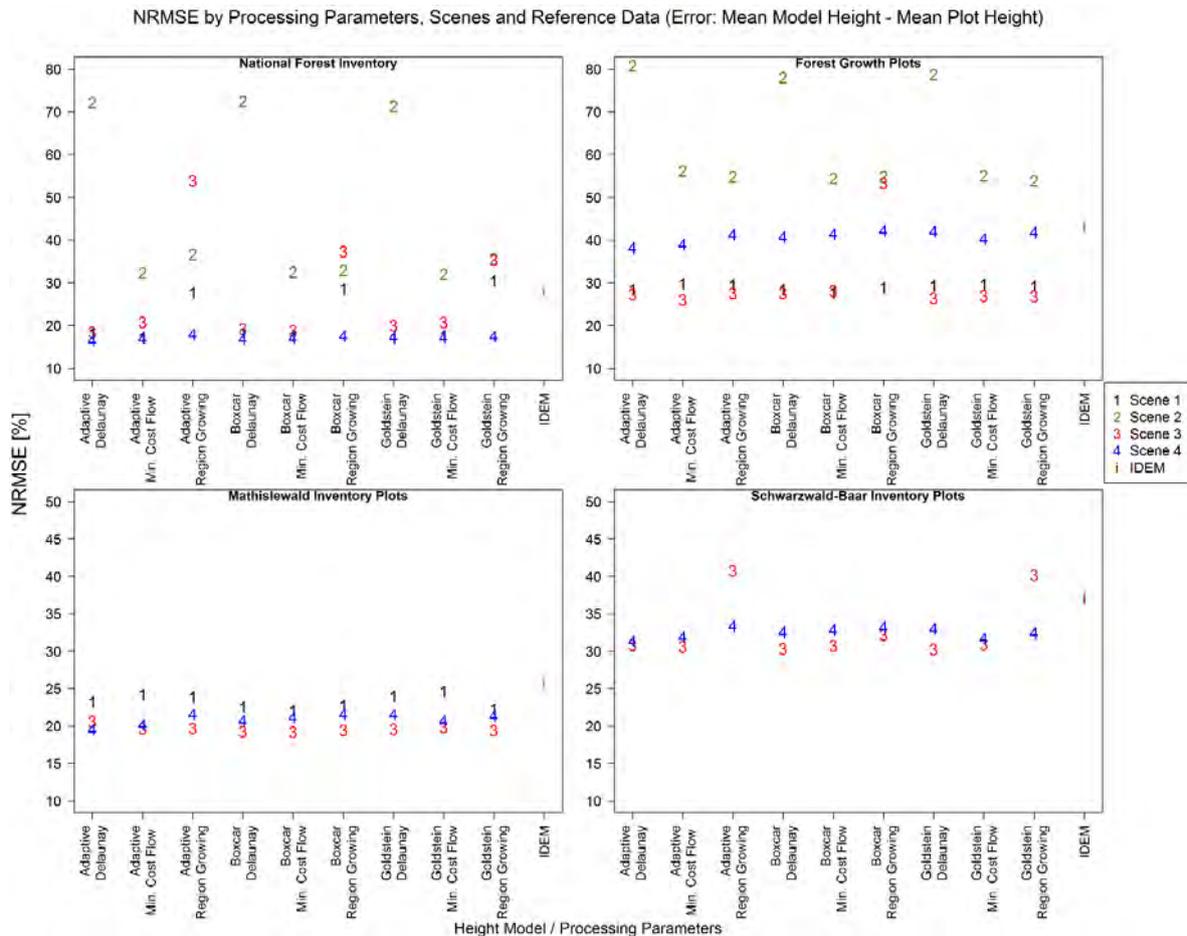


Figure 40 NRMSE of all forest height models by processing parameters, scenes and reference datasets for the mean model heights compared to the mean field heights. Height Model/ Processing Parameters: applied noise filter and phase unwrapping of the particular forest height model used for the analysis

Figure 40 Fehler! Verweisquelle konnte nicht gefunden werden. shows that magnitude of errors varies between the different acquisitions or scenes with scene 2 resulting in the biggest errors due to the fact that it has been acquired before foliation in spring. Not always the same processing procedures showed the same results for the different scenes and the same forest height model might show different errors for different reference datasets. In general better accuracies were found when the maximum, instead of the mean model height value per plot was compared to the mean tree height of the plot. IDEM based forest height models shows larger errors than most of the processed models. It further appears that most height models of the same scene show similar errors while only those processed with the Region Growing phase unwrapping algorithm (for scene 1 and 3) and the Delaunay Minimum Costflow

phase unwrapping (for scene 2) show bigger errors or outliers as compared to the remaining height models of the same scenes. Therefore, the Minimum Cost flow phase unwrapping algorithm is not showing such outliers appears to be most stable. Since all noise filters in combination with Minimum Cost Flow phase unwrapping produce comparably low errors and no outliers for a specific filter, all filters can also be considered to be stable.

### **Relation of Forest Height Models and Plot Parameters**

The non-parametric Spearman's rank correlation coefficient was applied to test the relationship between modeled forest heights and field height of the national forest inventory plots. Reduced major axis regression was then plotted to visualize the relationship and to further assess the potential to derive forest parameters from TanDEM-X data using the methods applied in this study (Figure 41). All correlations were highly significant ( $p$ -value  $< 0.001$ ) for all forest height models indicating a true relationship between forest heights derived from TanDEM-X data and field measures of forest height and volume. Correlation coefficients for the dependence between model heights and field heights bigger than 0.6 and as big as 0.72 were found for numerous height models. For the relationship between model heights and measured forest volume coefficients bigger than 0.5 and as big as 0.58 were observed. The highest correlations were observed for the height models derived from scene 4 and scene 1 while those of scene 2 showed only weak correlations. The correlations of IDEM are lower than for most of the processed height models except for the scene 2 models. The use of maximum model height per plot resulted in generally slightly higher correlations than the mean model height. These findings also corresponds to the findings presented before with regards to the error magnitude. Kruskal-Wallis one-way analysis of variance combined with the post-hoc test after Nemenyi was used to compare the mean and maximum height values of the different forest height models to test if the different correlation originates from true differences in model heights. The analysis showed highly significant differences ( $P$ -value  $< 0.001$ ) between forest heights derived from IDEM and all processed height models. The same was found for scene 1 and 3 height models processed with Region Growing phase unwrapping as compared to other forest height models of the same scenes indicating that the big errors or outliers originate from true differences in model heights associated with processing errors.

In addition reduced major axis regressions were fitted for selected datasets to visualize the relationship between modelled- and measured forest height and for the assessment of the potential to predict forest height using the models of this study (Figure 42). While most regression lines show a clear linear relationship between modelled forest height and plot height /volume. Figure 43 show that winter acquisitions (scene 2) appear to be not suitable for forest height or volume retrieval.

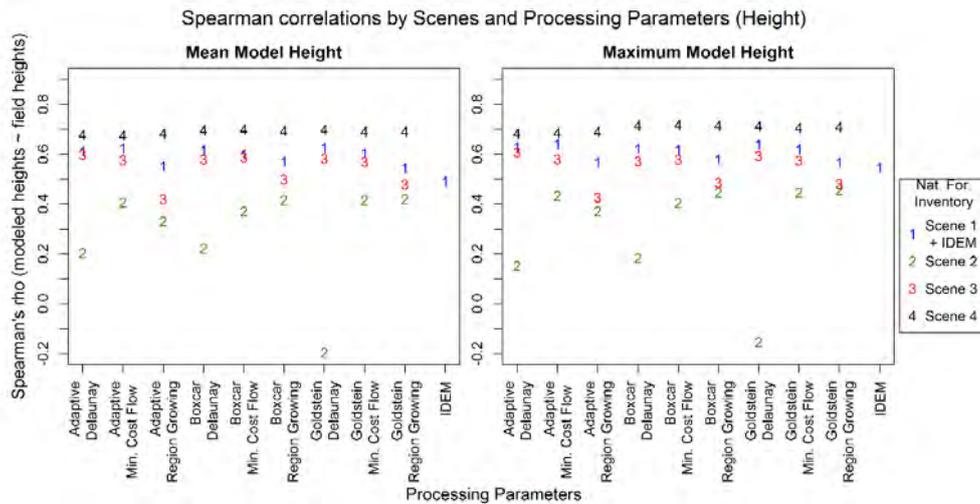


Figure 41 Spearman correlation coefficients for relationship between modelled forest heights and field heights by processing parameters, scenes and use of mean and maximum model height values. Processing Parameters: applied noise filter and phase unwrapping of the particular forest height model used for the analysis

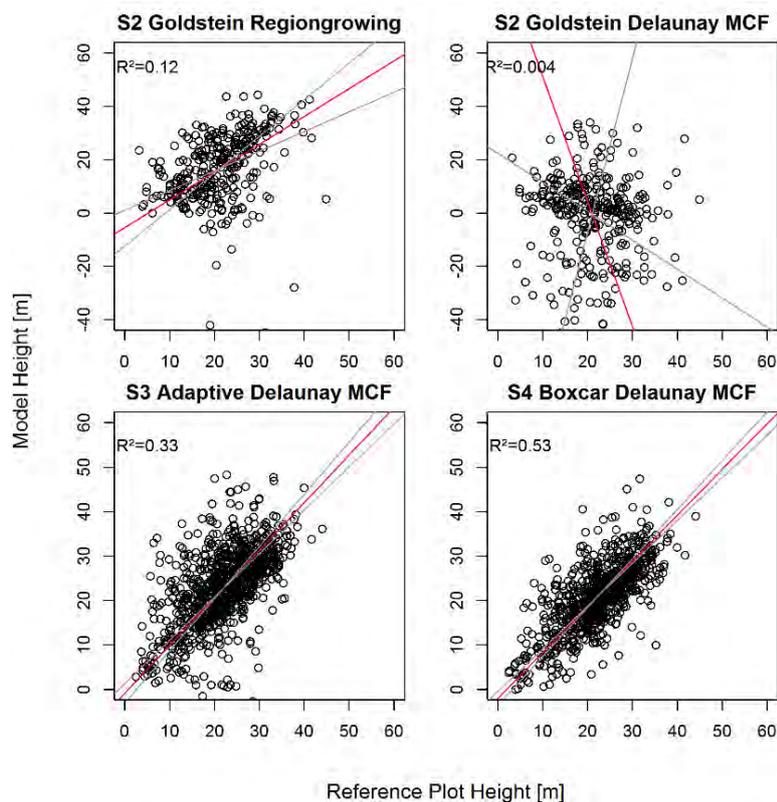


Figure 42 Reduced Major Axis Regression for different forest height models: model height (maximum model height) ~ reference plot height. Red line: Regression line, grey lines: Confidence interval around regression line visualizing 95% confidence interval of regression gradient.

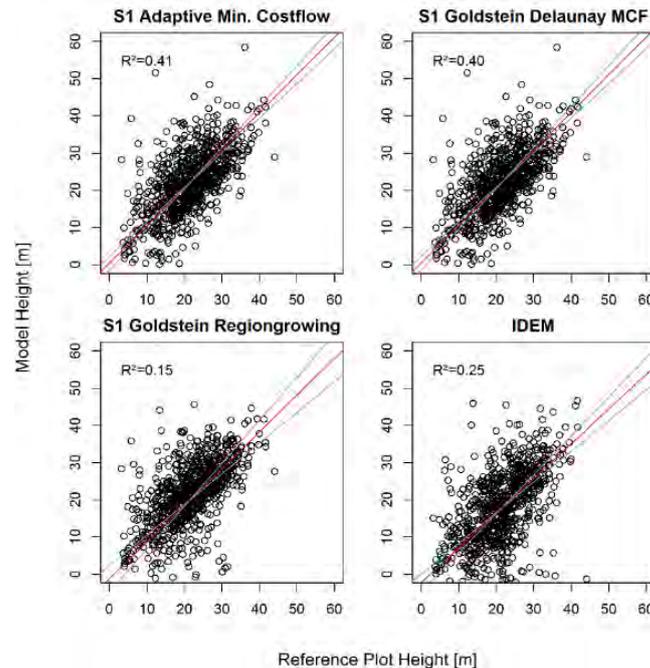


Figure 43 Reduced Major Axis Regression for different forest height models: model height (maximum model height) ~ reference plot height. Red line: Regression line, grey lines: Confidence interval around regression line visualizing 95% confidence interval of regression gradient.

### 1.1.1.13 Regional scale timber volume mapping using IDEM

The previous chapter shows that using TanDEM-X in general and TanDEM-X IDEM in particular it is possible to obtain forest heights at accuracy between 5-7 m or with less than 20% error. This chapter deals with using TanDEM-X IDEM to generate a regional scale high resolution forest volume map for Baden Württemberg.

#### Variable-set generation and modelling framework:

More than 13000 measured BWI-3 plots in the whole of Baden-Württemberg were scanned and only those plots were used in the modelling procedure which were well within the forest boundaries and not subjected to edge effects. For this all plots falling in a buffer distance of approximately 50 m from the forest boundaries were dropped. Additionally, outlier plots with volume higher than 1200 m<sup>3</sup>/ha and plots with no measured volume were excluded.

Table 14 List of final set of predictor variables used for above ground biomass modelling

Predictors	Source
DTM (mean heights)	LiDAR
nDSM (mean heights)	TanDEM-X (DSM) & LiDAR (DTM)
Slope	LiDAR
Aspect	LiDAR
Band1 (blue)	Landsat-7 ETM+
Band3 (red)	Landsat-7 ETM+
band5 (SWIR-1)	Landsat-7 ETM+
NDVI	Landsat-7 ETM+ (NIR and Red bands)

The remote sensing datasets which were considered for further processing include the nDSM (TanDEM-X IDEM surface model subtracted from LiDAR terrain model), DTM (pure LiDAR based), slope and aspect maps (derived from LiDAR DTM), Landsat (Landsat-7 ETM+ land surface reflectance for all bands except thermal infrared) and NDVI (derived from Landsat-7 ETM+ NIR and R bands). The remote sensing parameters were extracted for the BWI-3 plots using zonal statistical tools and circular buffers. Since during the forest inventory tree data collection was done using an angle-count methodology, extraction of remote sensing variables corresponding to the NFI plots was done using different sized circular buffers viz., 15m, 20m and 30m radius. The final results were generated using 20m radius circular buffers which performed significantly better compared to the other buffer sizes. The variables which were extracted from the remote sensing datasets included:

- nDSM: mean, standard deviation, minimum, maximum
- DTM: mean, standard deviation, minimum, maximum
- Landsat: mean reflectance Band1,2,3,4,5,7
- Slope: mean
- Aspect: majority
- NDVI: mean

The final variable set which was used for developing the standing volume estimation model was obtained by dropping the variables which showed strong correlation. The decision on dropping the variables was taken using different diagnostic tools including variation inflation factor (VIF) and by fitting different multiple linear regression models and then comparing their relative significance levels. In the end 8 predictor variables were selected (Table 14) and used as the model inputs.

Multiple linear regression (MLR) and random forest algorithms were used to develop the prediction models and the relative performance was compared to get the best performing model. While, multiple linear regression has been widely used tool for prediction modelling with fair accuracy, RandomForest (RF) ensemble learning method has emerged as one of the most precise prediction methods for classification

and regression modelling in recent years. Proposed by Leo Breiman (2001), RF algorithm presents several advantages including effectiveness to consider complex interactions among input variables, efficiency to run on large datasets, non-sensitivity to noise and over-fitting (Wang et al. 2016).

The MLR and RF modelling was performed using the “caret” (Kuhn 2015) and “raster” (Hijmans and Etten, 2015) packages in R (version 3.3.0, 64 bit) open source statistical software (R development Core Team, 2015). Please refer to Breiman 2011 and the statistical package descriptions for details of RF algorithm and its implementation in R.

### Results and Validation:

We fitted MLR and RF models simultaneously with the same sets of predictors and in all cases the performance of RF models was always found to be significantly higher in terms of  $R^2$  and root mean square error (RMSE) when compared to the MLR models. As the objective of this study was to test the suitability of TanDEM-X IDEM derived forest height information for forest growing stock mapping, we compared models without and with IDEM mean heights as predictors, all other input variables remaining the same in both the models. The  $R^2$  and RMSE in the goodness-of-fit plots (Figure 44) clearly show that the TanDEM-X based canopy height is the most significant of all other predictor variables, explaining more than double the variances when compared to the model which includes all other variables except the canopy height.

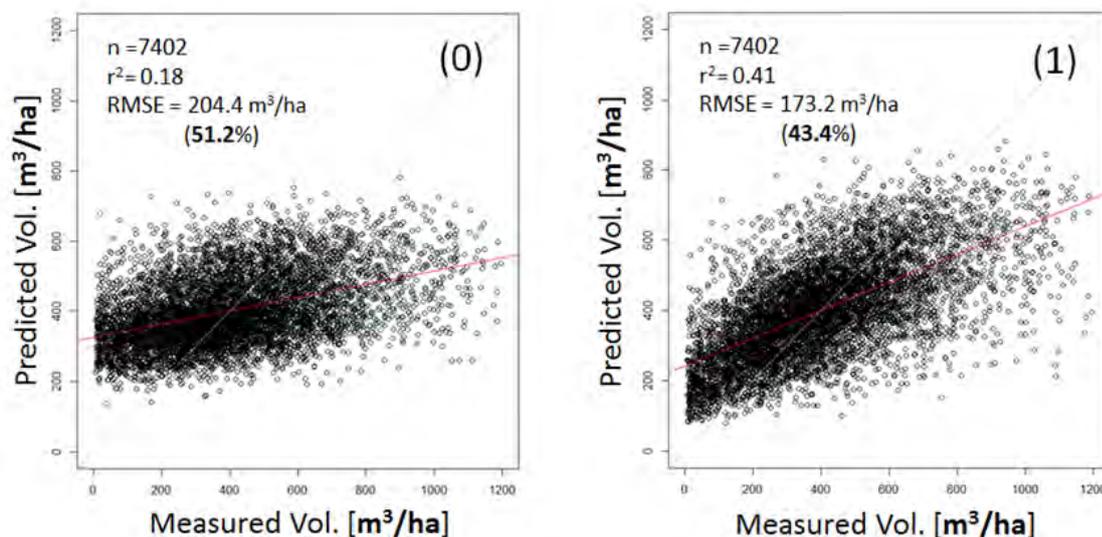


Figure 44 Goodness-of-fit plots where measured values are plotted against RF model predicted forest volume for model without (0) and with (1) TanDEM-X IDEM based canopy height information. The other input variables in both 0 and 1 remain the same.

When we look at the relative performance of the final RF model for the two main forest types, viz., conifers and non-conifers, we see that the model predicts conifer forests with significantly higher precision than the non-conifer forests. The plots in Figure 45 show the goodness-of-fit by plotting measured volume per hectare against

the predicted volume per hectare for BWI-3 forest inventory classified as conifers and non-conifers separately. Of interest also would have been using forest type as one of the predictors and/or fitting the models separately for broadleaf and for conifers forests. This however was not done in the current study. Additionally of interest would be testing the effect of ownership type on prediction accuracy as reported by Maack et al. 2016 **Fehler! Textmarke nicht definiert.** who observed, for forest volume estimation models using BWI-2, LiDAR and Landsat data, variable performance across different forest ownership classes. This could be done in the future when access to forest ownership datasets is made possible and could further improve the prediction efficiency of the developed models.

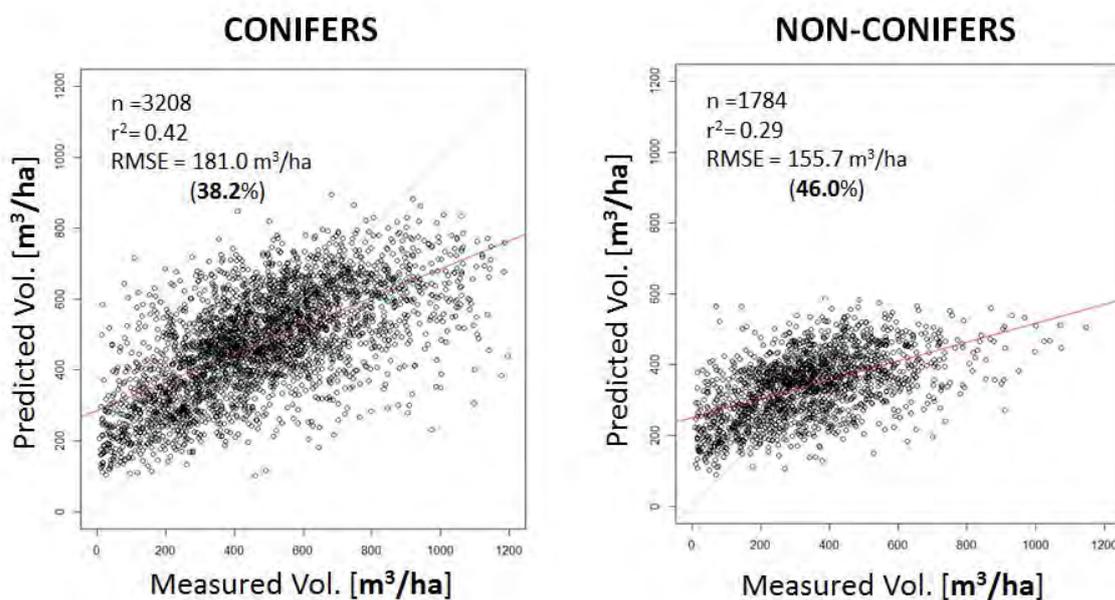


Figure 45 The performance of the final model for conifers and non-conifers

The validation of the volume per hectare and total volume predicted by RF model was done on forest stand level using independently collected forest management planning datasets for the state forests in Baden Württemberg. Since independent reference data could not be obtained for community and private forests these were included in the validation exercise. On one hand, overall mean volume in m<sup>3</sup> per hectare was calculated from all the measured state forest stands located in each Landkreis (NUTS3 region). Similarly the modelled volume per hectare for the same areas was calculated and both were plotted against one another (Figure 46). Also, the total standing volume per NUTS3 region, both measured as well as modelled, were compared in Figure 47. The agreements in both the scatterplots show that TanDEM-X IDEM along with Landsat and LiDAR terrain characteristics was able to provide regional scale forest biomass estimates satisfactorily using a RF based regression modelling approach. In Table 15 only those NUTS3 regions are used where the field data collection was performed during 2011 – 2013 which is the time period during which the remote sensing data (except for the terrain data) was also

collected. These validations further show that in majority of cases the mean predicted volume was within 35% RMSE of the estimated stand volume which is a reasonably good performance when compared to other studies using area based approaches for estimation of forest biomass using other remote sensing data (for example Kankare et al. 2013, Maack et al. 2016Fehler! Textmarke nicht definiert.).

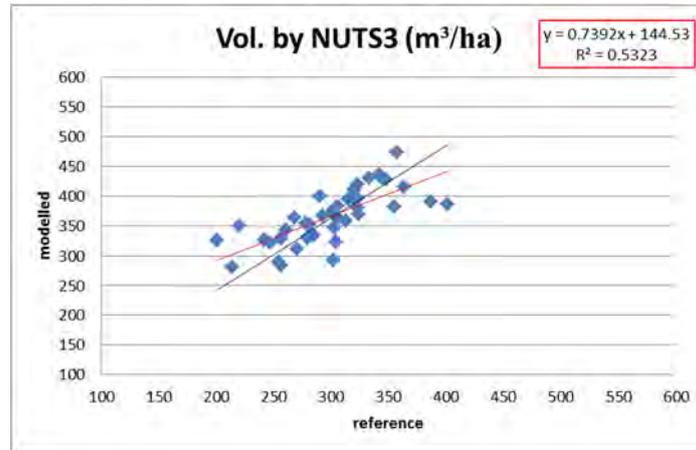


Figure 46 Scatterplots showing measured vs modelled volume in m<sup>3</sup> per hectare for different NUTS3 (German name of the administrative unit: Landkreis) regions in Baden Württemberg

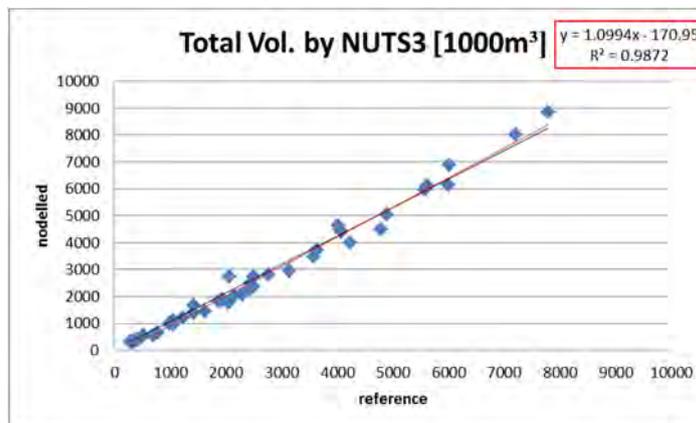


Figure 47 Scatterplots showing Total measured vs modelled volume in 1000m<sup>3</sup> for different NUTS3 (German name of the administrative unit: Landkreis) regions in Baden Württemberg

Table 15: Comparison of mean volume per stand (modelled) with the volume per stand (measured) in the forest management planning dataset for national forests. Only data collected between 2011 and 2013 have been included.

	Year	No. of Stands	R Sq.	rmse [m <sup>3</sup> ha <sup>-1</sup> ]	rmse%
Overall	2011-2013	9686	0.42	108.96	29.49
Alb-Donau-Kreis	2011	772	0.42	96.22	27.37
Calw	2013	2404	0.44	110.76	30.06
Enzkreis	2011	723	0.36	107.55	28.45
Esslingen	2012	677	0.35	103.12	27.64
Freiburg	2011	115	0.28	160.19	35.43
Heilbronn	2012	705	0.31	102.04	27.67
Neckar-Odenwald-Kreis	2011	455	0.48	112.97	36.15
Ortenau	2011	264	0.22	108.37	31.27
Reutlingen	2013	877	0.48	94.22	27.64
Schwarzwald-Baar-Kreis	2013	443	0.35	139.48	34.03
Stuttgart	2013	229	0.18	95.33	28.80

The spatially distributed growing stock volume estimated for the entire federal state of Baden-Württemberg is shown in in Figure 48 and Figure 49.

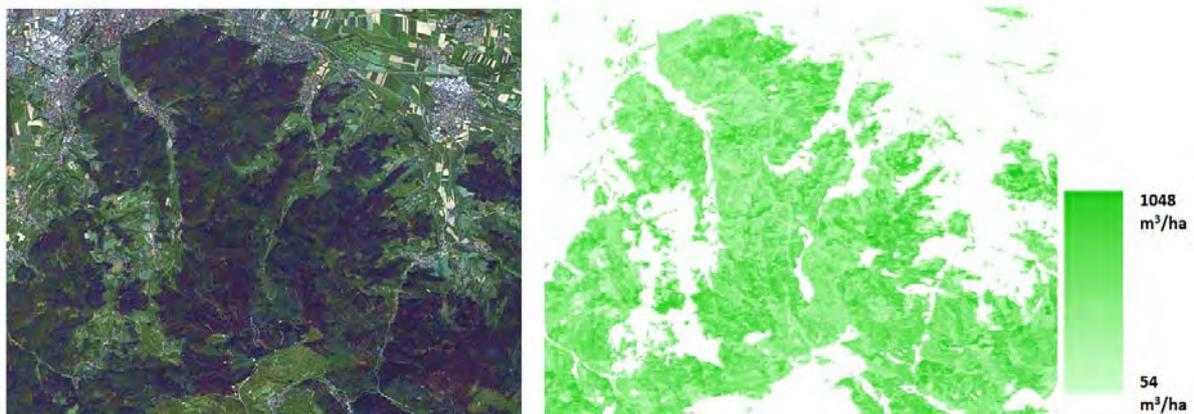


Figure 48 A subset of the estimated volume (right) and a high resolution image (left) of the same area (white colour refer to non-forest areas which are masked out from processing)

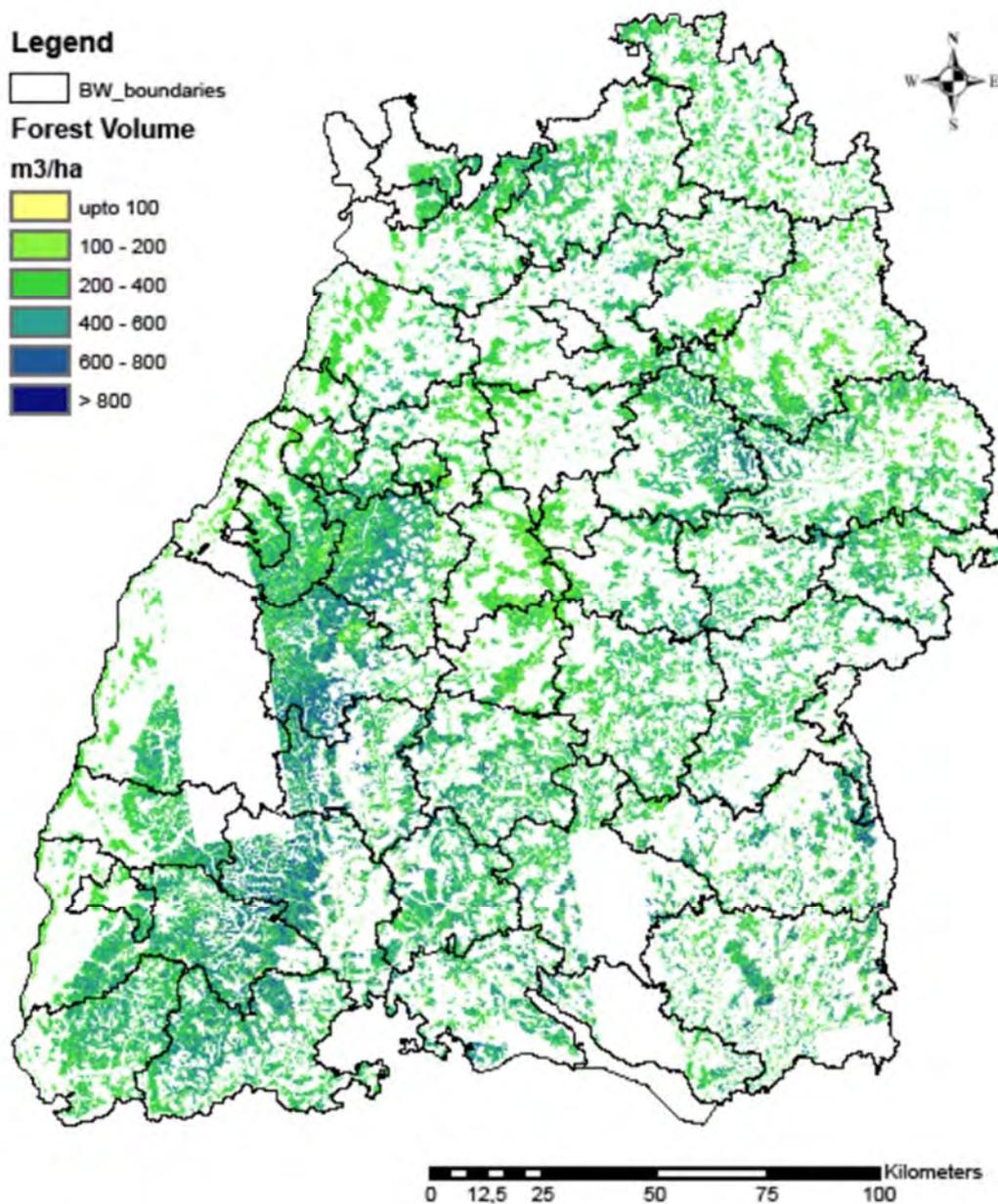


Figure 49 Volume map for the federal state of Baden Württemberg (non-forest and missing data appear in white)

#### 1.1.1.14 Conclusions

##### TanDEM-X based forest height assessment:

Processing options that show a potential to substantially improve forest height models processing vs. the standard IDEM processing were identified. Although IDEM showed the highest underestimations when compared to the results obtained by processing individual scenes, the magnitude of underestimations remained with acceptable limits of height variability. Thus when applying processing that is

optimised for forest height retrieval results for timber volume and biomass mapping achievable with IDEM can be expected to be improved.

It could be shown that the overall underestimation of forest heights in the range of 4m or relative 10% and that positive correlations in the dimension of 0.5 can be achieved. These findings show the examined vegetation models show properties with a good potential for the utilisation for timber volume and biomass mapping of forests.

### **Regional scale timber volume mapping using IDEM:**

Utilizing TanDEM-X IDEM in combination with Landsat and DTM data for large scale mapping of forest volume in a multi-sensor approach increases the accuracy of volume maps substantially. Such maps are not suitable for local applications such as forest management or operational planning, but the accuracy achieved allows strategic planning and provides a large scale overview on forest resources covering all ownership classes.

To conclude, we can say that the Tandem-X mission and the final Tandem-X based DEM product (with gaps filled and errors removed vs the intermediate product we tested here) will make it possible to provide wall to wall forest volume and above ground biomass maps where high quality DTMs and plot data from national forest inventories are available.

#### **1.1.1.15 References**

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### 4.3.3 Vegetation height assessment using airborne laser scanning, digital stereo aerial photographs, stereo WorldView-2 and TanDEM-X - test region located in the federal state of Baden-Württemberg, Germany

#### 1.1.1.16 Introduction

Forest canopy height model (CHMs) and its derived metrics can be used for a variety of valuable applications in the forest domain. For instance, CHM can be used for change detection, canopy gap dynamic, and single tree detection, etc. (Koch et al. 2006; Pitkänen et al. 2004; Yu et al. 2004; Zielewska-Büttner et al. 2016). Height and density metrics derived from CHMs at plot level can be used for the assessment of forest height, forest timber volume, biomass, basal area and mean diameter-at-breast-height point (DBH) using area-based approach (Bohlin et al. 2012; Næsset 2004; Ota et al. 2015; Rahlf et al. 2014; Straub et al. 2013a; White et al. 2013). The same parameters at single tree level can also be derived directly (i.e. tree height and crown area) or indirectly (i.e. volume, basal area and mean DBH) from CHM by separation of individual crown using individual tree detection approach. (Brandtberg 1999; Hyyppä and Inkinen 1999; Koch et al. 2006).

CHM as well as height metrics derived from Airborne Laser Scanning (ALS) also called Light detection and ranging (LiDAR) data were successfully demonstrated in many case studies for the assessment of forest structure information, as ALS has the capability for extraction of both the digital terrain model (DTM) which represent the forest floor as well as the digital elevation model (DEM) which represent the entire canopy of forest (Hyyppä et al. 2008; Nelson et al. 1984; Nilsson 1996; Packalén et al. 2008; Tesfamichael et al. 2010; White et al. 2015a; Yamamoto et al. 2011). Over the last decade, ALS has revolutionized the process of forest mapping and has been used operationally for forest inventory in many Nordic countries like Norway, Finland, and Sweden (Maltamo and Packalen 2014; Næsset 2007, 2014). However in many countries, ALS acquisitions are often not as frequently updated by the survey administrations and therefore cannot be used for the regular measurement as needed for forest management planning due to high cost. It is also unclear in most federal states in Germany, that in which time frequencies ALS data will be acquired (Dees et al. 2012).

In Contrast to ALS, stereo aerial photographs (AP) are updated on a routine basis at regular time intervals by the survey agencies/administration (Stepper et al. 2014; Straub et al. 2013a; White et al. 2015c). As an example in the Baden-Württemberg state of Germany, stereo APs are regularly updated after every three years by the “Landesamt für Geoinformation und Landentwicklung” (LGL) and can be used for the regular update of forest structure information. There are several software packages and image matching algorithms for the generation of 3D point clouds, and we have selected two widely used programs that are based on different methodological approaches for our study. One is enhanced Automatic Terrain Extraction (eATE): an ERDAS LPS module, that is a correlation technique based on search windows for the

identification of corresponding pixels using spatial correlation metrics. The search range along the epipolar line is constrained by estimated minimum and maximum elevation values (Straub et al. 2013b). The other one is Semi-Global Matching (SGM) developed by Hirschmüller (Hirschmuller 2005; Hirschmüller 2008). It uses a pixel wise approach, utilizing the radiometric robust mutual information and a smoothness constraint to generate dense surface point clouds. The method first identifies a pixel on the base image and then searches for the similar pixel along the epipolar line in the pair image. The minimum aggregated cost leads to a disparity map. Several studies showed that SGM is the superior methodology (Gehrke et al. 2010; Hirschmuller 2005; Rothermel and Haala 2011). The comparative studies between the point clouds image matching algorithms so far have not focused over forest terrain, and this forms one of the main research gap for our study.

Stereo AP has to be captured by, and airplane involves planning the flight and acquiring the permits for data acquisition. But stereo very high-resolution satellite imagery (VHRS) like Worldview-2, Ikonos, SPOT, Kartoset and Quick birds etc. are a cost-efficient alternative to stereo AP and can be obtained regardless of various national over-flight restrictions (Hobi and Ginzler 2012). Also, the temporal resolution, wide regional coverage and sub-metric ground resolution are the great advantages of VHRS compared with stereo AP (Straub et al. 2013b). One problem of using VHRS is the clouds coverage, which creates a problem for image matching algorithms for identification of similarly matched point between the base image and the overlapping image. To cover the problem of cloud coverage we are evaluating an option of TanDEM-X which is active space born sensor and has day and night acquisition. Moreover, it has worldwide coverage and can be obtained in all types of weather condition regardless of environmental constraint.

Digital Surface Model (DSM) can be produced from stereo AP, stereo WorldView-2 using image-matching algorithms and TanDEM-X using interferometry, but the generation of highly accurate DTM in a dense forest environment where forest floor is not visible is not possible with the mentioned sensors. Thus to it is necessary that in the application area a highly accurate DTM originating from ALS is available. This is for the majority of the European countries the case. Subtracting pre-existing ALS-derived DTM from DSM derived from stereo AP, stereo WorldView-2 and TanDEM-X can be a solution for the generation of CHM (Bohlin et al. 2012; Jan 2005; Rönnholm et al. 2004; St-Onge et al. 2004; Véga and St-Onge 2008).

The main aim of the study is to evaluate different active and passive airborne and spaceborne sensors for estimating vegetation height for small and potential large area applications. The more specific objectives are the following

- (1) How does the image-based point clouds derived from AP perform in comparison with ALS for estimating vegetation heights? Additionally two widely used image matching algorithms, viz. SGM and eATE for forest height retrieval have been compared in terms of their performance.

- (2) Secondly stereo WorldView-2 and TanDEM-X have been evaluated in comparison with stereo AP for estimating vegetation heights.

The study area is located in a relatively flat area north of Karlsruhe in the Federal State of Baden-Württemberg, Germany (Figure 50). The total area covers 12 km<sup>2</sup> and the dominant forest tree species are Scots pine (*Pinus sylvestris* L.), European/Common beech (*Fagus sylvatica* L.), Sessile oak (*Quercus petraea* leibel.) and Red oak (*Quercus rubra* L.). Further tree species including Douglas fir (*Pseudotsuga menziesii*), Norway spruces (*Picea abies*) and European larch (*Larix decidua*) can also occur occasionally.

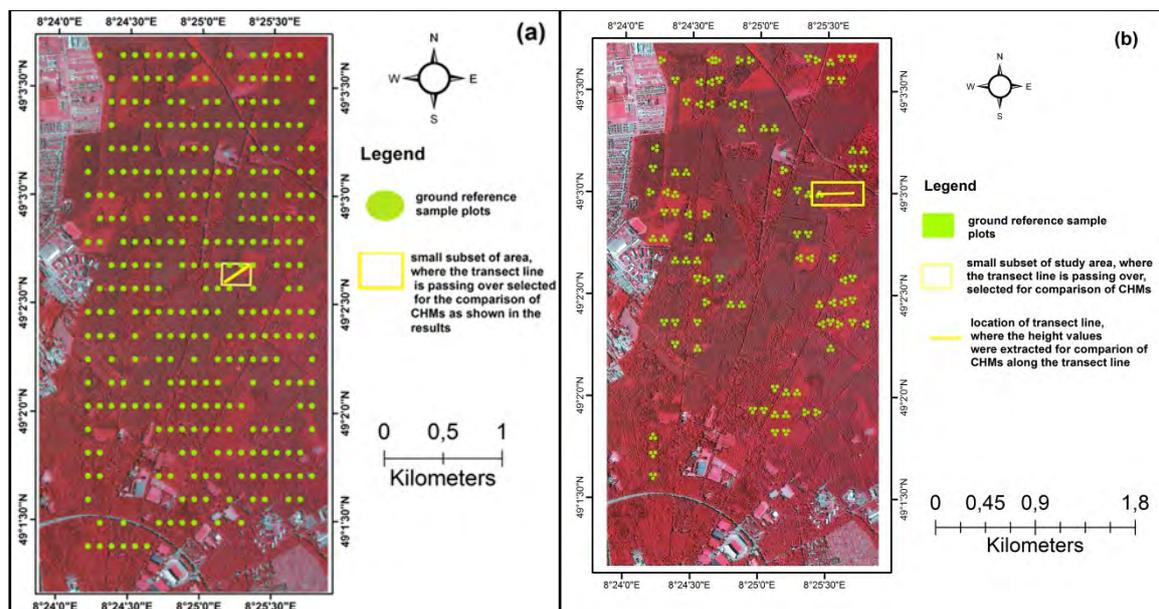


Figure 50 Geographical location of study test site based on false colour images, the circular artic lime colour represents the location of ground sample plots (a) used in objective 1 and (b) used in objective 2 and the yellow smallest rectangular block show the small subset area, where the yellow colour transect line is passing over selected for visual interpretation of the CHMs along the transect line © Orthophoto and Aerial Photos: Landesamt für Geoinformation und Landentwicklung für Baden-Württemberg ([www.lgl-bw.de](http://www.lgl-bw.de)) Az.: 2851.9-1/3

The state forest service of Baden-Württemberg set up a total of 296 permanent circular concentric plots during the summers of 2006 and 2007 over the entire study area, and these have been used for the collection of ground reference data for objective 1 (Figure 50, left side). The sample plots were distributed systematically over the study area in a 100 x 200 m sample grid.

Similarly for the objective (2) as shown in Figure 50 (right side), a total of 279 numbers of 12 m radius sample plots were taken representing all major forest types and age classes during mid of August and September 2013.

On each plot, trees with diameter-at-breast-height (DBH) <10 cm, between 10 and <15 cm, between 15 and <30 and >30 cm were measured, if they were at the distance of 2, 3, 6 and 12 m exactly from the plot center. Two dominant heights of each main tree species and one dominant height of other mixed species were

measured. The remaining tree heights were predicted by species-specific stand height curved developed by the Forest Research Institute, Baden-Wurttemberg (FVA), Germany (Kublin 2003b). Finally, ground Lorey's mean height (LMH) was calculated by multiplying the tree height (h) by its basal area (g), and then the sum of the multiplication of individual heights and basal areas are divided by the sum of the plot basal area (Lorey 1878). We selected LMH since it a standard forest measure to characterized forest canopy height giving higher weights to trees with a larger basal area.

### 1.1.1.17 *Methods*

Full-waveform ALS data was acquired in 2009 by Milan Geoservice Gmbh using the IGL Litemapper 5600 system with a Riegl LMS-Q560 (240 kHz) scanner. For the summer 2009 acquisitions during leaf-on conditions, the study area was flown over twice to obtain high point density. The first flight was conducted in north-south and the second in the east-west direction. The details of the flight and system parameters of ALS are shown in Table 16.

Table 16 Details of flight and system parameters of Airborne Laser Scanning (ALS)

Parameters	Airborne laser scanning (ALS)
<b>Flying height</b>	600 [m] above ground level
<b>Field of view (full scan angle)</b>	60 [°]
<b>Strip width [m]</b>	520 [m]
<b>Measurement rate</b>	240 [kHz]
<b>Point density</b>	~ 22 [points/m <sup>2</sup> ]
<b>Flying velocity</b>	46 [m/s]

Similarly, we used a block of 28 stereo APs with four spectral bands (blue, green, red and near-infrared). The stereo APs were acquired in summer, 2009 (used objective 1) and 2012 (used in objective 2) during the leaf-on canopy conditions. The aero-triangulation was done by Landesamt für Geoinformation und Landentwicklung with ground control points and based on initial measurement by Global Navigation Satellite System (GNSS) and inertial measurement unit . For the projection of the generated datasets, DHDN/3 Gauss-Krüger coordinate system was used throughout the process. The more details about the technical parameter are given in Table 17.

Table 17 Details of flight and technical characteristics of Digital Stereo Aerial Images

Parameters	Stereo aerial photographs /images (AP)
<b>Camera</b>	UltraCamXP
<b>Flying height</b>	2950 m
<b>Image overlap</b>	60% & 30%
<b>Swat width [m]</b>	520 [m]
<b>Acquisition date</b>	Summer, 2009 and 2012
<b>No. of images used in a block</b>	28
<b>Spectral bands</b>	blue, green, red and near-infrared

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<b>Resolution (GSD)</b>	0.2 m (20 cm)
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Image-based point clouds were generated from stereo AP using eATE manager (integrated module in LPS ERDAS IMAGINE 2015) by choosing a point sampling density of 1, whereby every other pixel is match. A point sampling density of 0 might be useful in term of accuracy, but it takes a considerable longer period to process (ERDAS\_IMAGINE 2012) and hence was not used. Pixel block size of 100 was selected where eATE engine divides the images into blocks of pixels and processes each block separately. Thread 2 indicates the number of distributed processing threads for this eATE process and each thread is assigned to a separate core in the machine. Radiometry threshold defines the measurement (percentage) of contrast around the central pixel in the master image. The default is 2.5, and it is recommended to use larger (than 2.5) threshold for high contrast images thereby ensuring a higher possibility of getting good correlated points. For low-contrast images, it is recommended to use a smaller threshold so that eATE correlates more points regardless of the contrast. If the threshold is set to zero then all points will be matched (ERDAS\_IMAGINE 2012). For segmentation, we used the infrared band because of its higher sensitivity to vegetation compared to the other bands. During correlation process, we optimized the matching by used all available spectral bands. For window size, which is representative of the pixel area used for computing the correlation coefficient between left and right images, we chose a larger (15\*15) value. While the default value is 9\*9, it is recommended to use a larger window size for areas with minimal variation (right in our case) and a smaller window (e.g., 5\*5) for areas with greater topographic relief. Coefficient start and end indicates the correlation coefficient used for each pyramid level. Higher coefficients range (0.7-0.8) produces higher accuracies, but fewer points may be matched while a lower range increases the number of correlated points. The Search window is the maximum search size in pixels surrounding the point to be interpolated and is a square. The default value is 50, and a higher number is suitable for low contrast areas, and a lower number is recommended for areas with higher contrast. We use a higher value because it gives better points despite increasing the processing time. A low value may give more uniformly distributed points, but the points may not be good. Standard deviation tolerance indicated the tolerance (in meters) for determining the standard deviation of the planar fit (default = 3) and LSQ refinement indicated the pyramid level to apply a least squares refinement. Edge contrast represents the number of pyramid levels to apply edge constraint and tolerance means the measure in pixel used to accept or reject the point during reverse matching. Smoothing looks for spikes in elevation, and low smoothing option ensures a minimal smoothing for data with few anomalies (ERDAS\_IMAGINE 2012).

Similarly, image-based point clouds were generated from stereo AP using SGM XPro (integrated in LPS ERDAS IMAGINE 2015) by setting urban situation to zero and can be utilized for urban areas applications. We selected Keep vertical which retains point clouds on the vertical surfaces like trees tops.

The stereo WorldView-2 scenes were acquired on 8th and 23rd of June 2013 with a spatial resolution of the panchromatic band (46 cm) and multispectral band (185 cm). For the generation of point clouds using eATE, we used panchromatic band (46 cm) and all the above parameter settings as we adopted for stereo AP except by using a point sample density of 0, where every pixel is matched. For the processing of 2012 stereo AP we also used a point sample density of 0 using eATE.

The TanDEM-X data were acquired in summer 2011 with HH polarization mode and was processed with Envi Sarscape software version 5.1 using the InSAR TanDEM-X bistatic DEM Workflow, which is specifically designed for the processing of TanDEM-X data. The workflow consists of the following steps:

- Interferogram Generation and Flattening
- Adaptive Filter and Coherence Generation
- Phase Unwrapping
- Phase to Height Conversion and Geocoding

### **Generation of Digital Surface Model (DSM), Digital Terrain Model (DTM) and Canopy height model (CHM)**

DSMs with a spatial resolution of 1 m were calculated from the image-based point clouds using eATE ( $DSM_{eATE}$ ) and SGM ( $DSM_{SGM}$ ) and from 3D point clouds of WorldView-2 using eATE. Similarly,  $DSM_{ALS}$  and  $DTM_{ALS}$  were generated from ALS data. For the generation of DSM and DTM the active filtering and interpolation techniques was adopted as implemented in the TreesVis software (Weinacker et al. 2004b). Finally the following CHM were generated:

A total of six kinds of canopy height models (CHM) were generated.

- (1) **CHM<sub>SGM</sub>** =  $DSM_{SGM} - DTM_{ALS}$  (Objective 1)
- (2) **CHM<sub>eATE</sub>** =  $DSM_{eATE} - DTM_{ALS}$  (Objective 1)
- (3) **CHM<sub>ALS</sub>** =  $DSM_{ALS} - DTM_{ALS}$  (Objective 1)
- (4) **CHM<sub>eATE</sub>** =  $DSM_{eATE} - DTM_{ALS}$  (Objective 2)
- (5) **WorldView-2 CHM** = WorldView-2 DSM -  $DTM_{ALS}$  (Objective 2)
- (6) **TanDEM-X CHM** = TanDEM-X DSM -  $DTM_{ALS}$  (Objective 2)

### **Computation of explanatory variables (metrics)**

The most commonly derived metrics from CHMs or point cloud in forest inventory are the percentiles (Næsset 2004). A total of 15 height metrics were calculated from the CHMs i.e. maximum, minimum, mean and the height percentiles (h99, h95, h90, h80.....,h10). For variation and heterogeneity of forest canopy height, we calculated the coefficient of variation (CV) and standard deviation (SD) from the CHMs. The metrics as mentioned above were derived from the vertical distribution of CHMs using a 12-meter radius circle corresponds to the size of ground sample plots. Besides, we calculated the canopy cover density parameters and canopy volume

( $C_{vol}$ ) which takes into account the horizontal distribution of the canopy structure. We calculated forest canopy density (cd) by dividing the number of pixels with heights above 2 m by the total number of pixels within an area of 12 m radius circular sample plots. Besides, we derived ten types of forest cover density metrics (i.e. cd1, cd2, cd3,...cd10) at sample plots location followed by the methodology adopted by Næsset (2004), Rahlf et al. (2014) and Straub et al. (2013a). The range between the lower canopy height (>2m) and maximum height was divided into ten fractions of equal length. Each fraction was considered a threshold and dividing all 1m x 1m cells covered by height above a certain threshold was defined as a potential crown region. The ratio of the crown region area above the pre-specified threshold to the total area of the sample plot was used as an estimate for the canopy cover. The canopy volume ( $C_{vol}$ ) was calculated from the CHM, which is the sum of all the heights of 1 x 1 m pixels size covering the total circular 12-meter radius sample plot area. The importance of all the above height metrics for the prediction of forest variables was already explained in details by (Bohlin et al. 2012), Næsset (2002), Rahlf et al. (2014) and Straub et al. (2013a).

### **Modelling for predicting ground Lorey's mean height (LMH)**

For predicted LMH, we fitted multiple linear regression models between all explanatory variables (extracted above) derived from  $CHM_{SGM}$ ;  $CHM_{eATE}$  and  $CHM_{ALS}$  and the response which are the LMH of the ground inventory sample plots (Objective 1). The explanatory variables which showed high collinearity and those which were the least significant were dropping out one by one starting with highest p-values (lower than 95% confident level) until a stage was reached, where removal of explanatory variables has significant impact on the coefficient of determination ( $R^2$ ), Root Mean Square Error (RMSE) and relative RMSE (RMSE %). For reporting the  $R^2$ , RMSE, and relative RMSE %, we used 3-fold cross-validation (repeated 3-times). The data were randomly split into 3-sets. At the first stage, the first set was knocked out as a test set and the remaining two were used as training sets. At the second stage, the middle set was knocked out as a test set and first and last were used as training sets. Similarly, at the third stage, the last set was knocked out as a test set and first and second sets were used as training sets. The  $R^2$ , RMSE, and RMSE% reported here were the mean of all 3-fold cross validation.

Similarly for objective 2, we fitted multiple linear regression models between all explanatory variable derived from  $CHM_{eATE}$ , WordView-2 and TanDEM-X CHM and the response which are the LMH of the ground inventory sample plots. For selection of final explanatory variables the above methods was adopted as we used in objective 1. For reporting RMSE and RMSE%, we used leave-out-once cross validation, where each single observation was held out as a testing set and the remaining data were used a training set. All the calculations were carried out using the caret package in R-statistics software (Kuhn 2008).

**Comparison of image-based CHM (CHM<sub>SGM</sub> and CHM<sub>eATE</sub>) with pure ALS CHM<sub>ALS</sub> and comparison of CHM<sub>eATE</sub> with WorldView-2 and TanDEM-X CHM**

In addition to above, we calculated difference maps by subtraction of image-based CHMs (CHM<sub>SGM</sub> and CHM<sub>eATE</sub>) of the entire study area from pure ALS (CHM<sub>ALS</sub>). The difference maps were calculated only for forested areas and all non-forested areas were mask out using forest and non-forest mask (Objective 1).

Similarly, we calculated difference map by subtracting CHM<sub>eATE</sub> from WorldView-2 and TanDEM-X CHM (Objective 2).

For normality test of error distribution, we used Q-Q plots (Figure 51 and Figure 52) and Anderson-Darling method integrated into ‘nortest’ package of R-statistical software (Gross and Ligges 2012). Since the distribution of errors was found to be non-normal (Figure 51 and Figure 52), we derived the accuracy assessment using sample quantiles of the error distribution based on the methodology for DEM accuracy assessment proposed by Höhle and Höhle (2009) and Hobi and Ginzler (2012). Using this approach, median (50% quantile), normalized median absolute deviation (NMAD) and the 68.3% and 95% sample quantiles were calculated from the difference maps using the open source R statistical software (Team 2014). The NMAD was calculated according to Höhle and Höhle (2009).

$$NMAD = 1.4826 \times \text{median} (|\Delta h_j - m_{\Delta h}|) \tag{4}$$

Where,  $\Delta h_j$  denotes the individual error,  $j = 1, \dots, n$  and  $m_{\Delta h}$  is the median of the errors. NMAD is thus proportional to the median of the absolute difference between errors and the median errors.

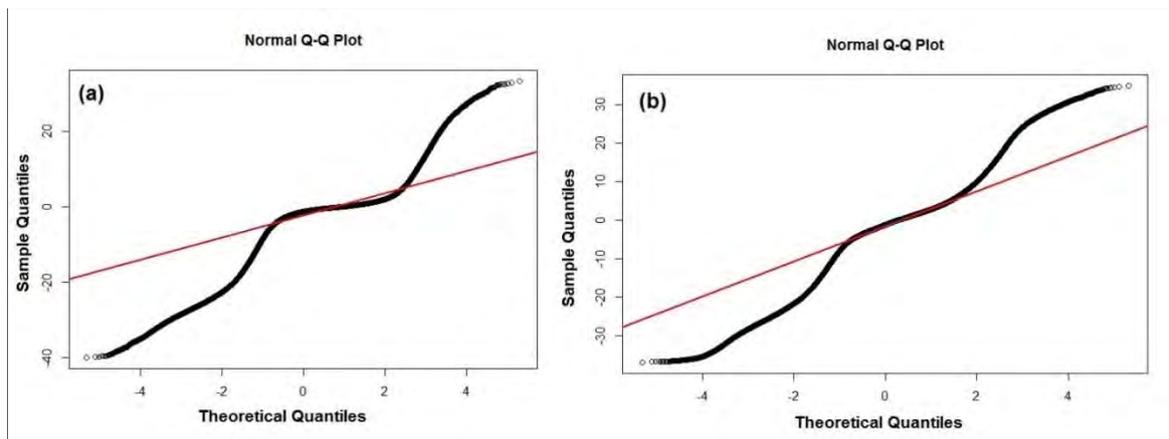


Figure 51 Non-normal Q-Q plots derived from non-normal error distribution for forested areas with superimposed normal distribution (a) CHM<sub>SGM</sub>-CHM<sub>ALS</sub> (b) CHM<sub>eATE</sub>-CHM<sub>ALS</sub> (Objective 1)

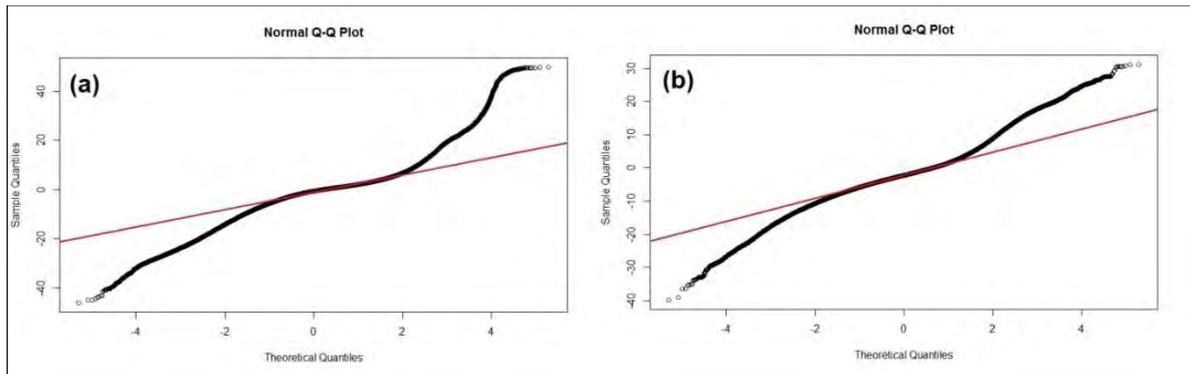


Figure 52 Non-normal Q-Q plots derived from non-normal error distribution for forested areas with superimposed normal distribution (a) CHM<sub>eATE</sub> - WorldView-2 CHM (b) CHM<sub>eATE</sub> - TanDEM-X CHM (Objective 2)

We also selected a transect line of 1.71 km as shown in Figure 50 and Figure 55 for visual interpretation of the trend of image-based CHM using eATE and SGM with ALS CHM (Objective 1).

Similarly, we selected a transect line of 350 m as shown in Figure 50 and Figure 58 for the visual interpretation of the trend of correlation between image-based point clouds using eATE and WorldView-2 and TanDEM-X CHM (Objective 2).

The height values of the CHMs falling along the transect line were extracted and plotted as a line graphs in order to see visually the trend of correlation between the CHMs.

### 1.1.1.18 Results

#### Predictions of ground Lorey's mean height (LMH) using image-based point clouds and ALS data at plot level (Objective 1)

The final most explanatory variables derived from CHM<sub>ALS</sub> were the height at 99<sup>th</sup> percentile and the canopy density (cd), and we achieved  $R^2 = 0.83$  and RMSE = 1.93 m against LMH (Table 18). Similarly, we achieved  $R^2 = 0.82$  and RMSE = 2.09 m by using height at 95th percentiles and canopy density (cd) as explanatory variables derived from CHM<sub>SGM</sub> against LMH. However, for the CHM<sub>eATE</sub>, we achieved  $R^2 = 0.55$  and RMSE = 3.22 m by using height at 90th percentiles, standard deviation (SD) and canopy density 2 (cd<sub>2</sub>) metrics as an explanatory variable (Table 18).

Table 18 Comparison of final predicted canopy height versus ground LMH based on 3-fold cross validation (n=296 plots)

Canopy height model (CHM)	Selected variables	Coefficients	R <sup>2</sup>	RMSE	RMSE%
CHM <sub>ALS</sub>	intercept**	4.59	0.83	1.93	7.92
	h99***	0.93			
	cd**	-4.45			
CHM <sub>SGM</sub>	intercept***	24.46	0.82	2.09	8.54
	h95***	0.96			
	cd***	-23.88			
CHM <sub>eATE</sub>	intercept***	35.02	0.55	3.22	13.23
	h90***	0.55			
	std***	0.7			
	cd <sub>2</sub> ***	-24.19			

**Note:** R<sup>2</sup> = coefficients of determination, Adj.R<sup>2</sup> = adjusted R<sup>2</sup> and (\*\*p < 0.001, \*\*p < 0.01, \*p < 0.05 and ·p < 0.1) indicated level of significant of t-test

Overall there are no strong differences between the predictive power of the explanatory variables derived from CHM<sub>ALS</sub> and CHM<sub>SGM</sub> for estimating LMH. However, the predictive power of explanatory variables derived from CHM<sub>eATE</sub> is not that accurate as CHM<sub>ALS</sub> and CHM<sub>SGM</sub> for estimating LMH.

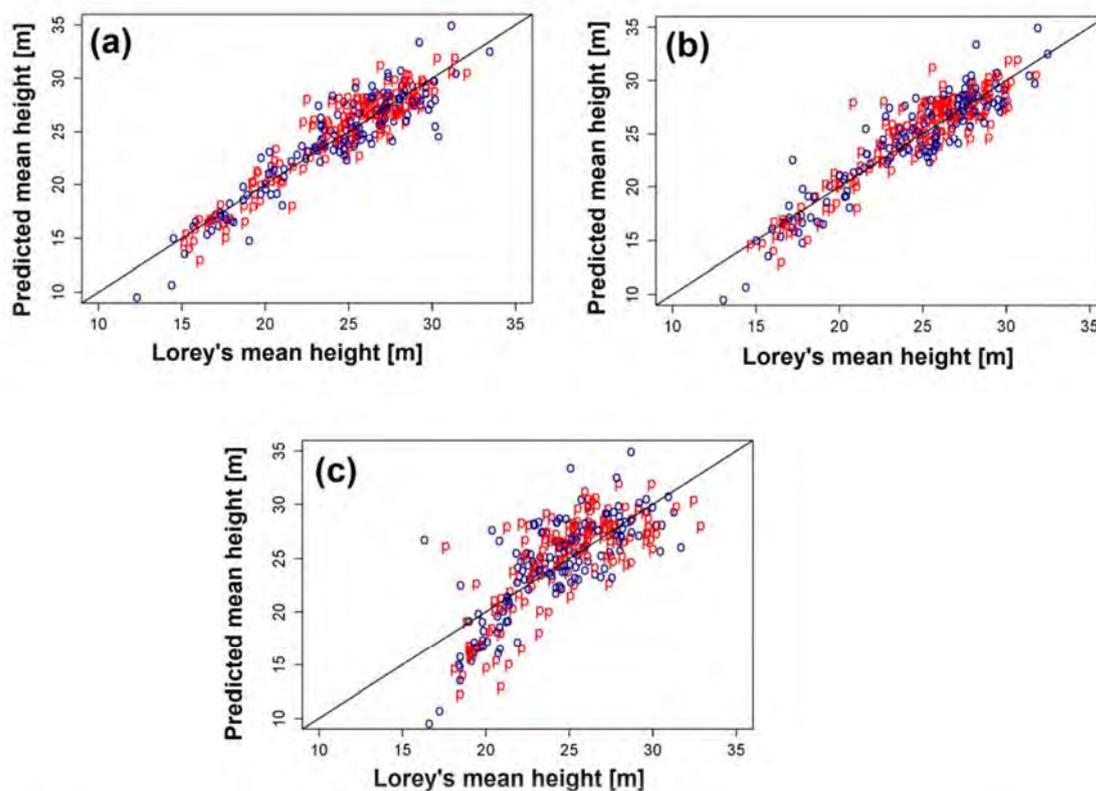


Figure 53 Lorey's mean height (LMH) (x-axis) plotted against predicted mean height (y-axis) (a) CHM<sub>ALS</sub> (b) CHM<sub>SGM</sub> and (c) CHM<sub>eATE</sub>

## Comparison of image-based CHM ( $CHM_{SGM}$ and $CHM_{eATE}$ ) with pure ALS ( $CHM_{ALS}$ )

A summary of the statistics for the error distribution derived by subtracting  $CHM_{SGM}$ ,  $CHM_{eATE}$  from  $CHM_{ALS}$  is shown in Table 19. We achieved a median error of -1.30 m and NMAD = 0.68 m from the difference maps derived by subtracting  $CHM_{SGM}$  from  $CHM_{ALS}$ . However, we achieved a median error of -1.18 m and NMAD = 1.11 m from the difference map obtained by subtracting  $CHM_{eATE}$  from  $CHM_{ALS}$ . In this case also  $CHM_{SGM}$  shows more closeness to  $CHM_{ALS}$  as compared to  $CHM_{eATE}$  (Table 19).

Table 19 Comparison of vertical agreement measures of image based CHM ( $CHM_{SGM}$  and  $CHM_{eATE}$ ) with pure ALS ( $CHM_{ALS}$ )

Forested areas	$CHM_{SGM} - CHM_{ALS}$	$CHM_{eATE} - CHM_{ALS}$
Sample size	Summary of the statistics of the error distribution derived from the differences maps	
50% (median) [m]	-1.30	-1.18
NMAD [m]	0.68	1.1
68.3%	-0.57	0.74
95% quantile [m]	0.99	6.64

Figure 54 shows final output maps of the CHMs for a small subset of area where the transect line was placed over for comparison of CHMs.

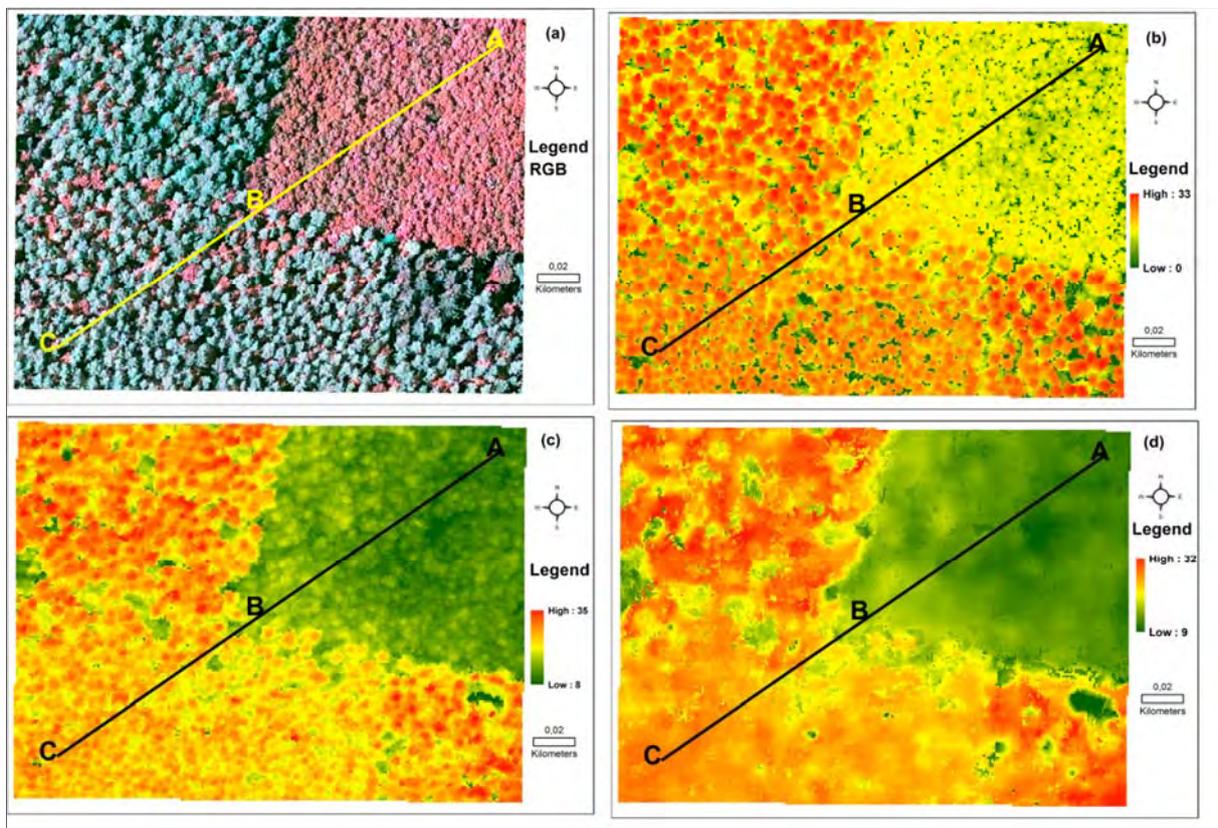


Figure 54 Final output maps of the CHMs, where the transect line was placed over (a) RGB (small subset of study area) (b)  $CHM_{ALS}$  (c)  $CHM_{SGM}$  and (d)  $CHM_{eATE}$

An example of the vertical profile of the four CHMs, where height values were extracted along the transect line (Figure 54) are plotted in the form of line graphs is shown in Figure 55. In general, all the three CHMs show a good degree of trends of correlation in the outer envelopes of the surface of forest structure. However, CHM<sub>ALS</sub> seems to be penetrated more downward through the small opening of the forest canopy stands. This shows that image-based CHMs could be limited to the outer envelope of the forest structure and cannot describe the details of the middle layer and forest ground forest floor.

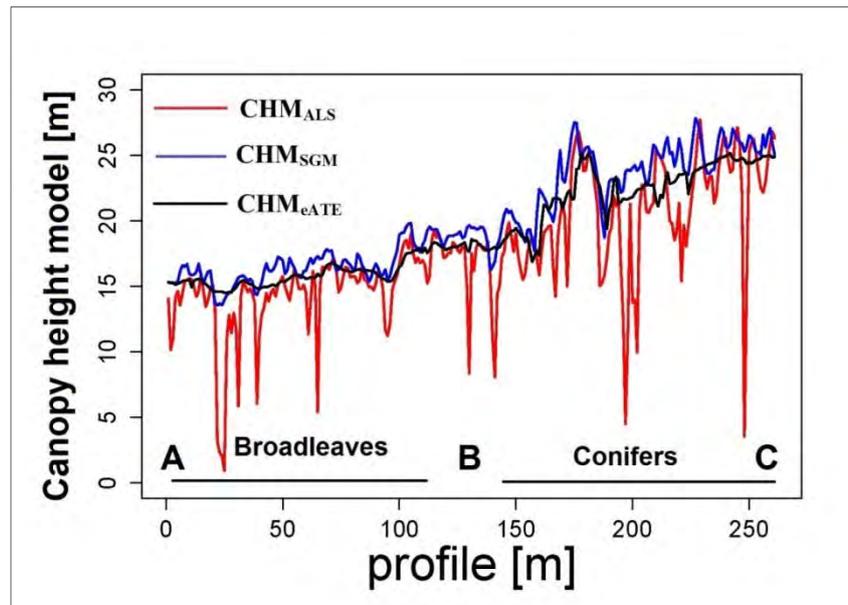


Figure 55 Vertical profile showing comparison of CHMs along the selected transect line

### Predictions of ground Lorey's mean height (LMH) using image-based point clouds, WorldView-2 and TanDEM-X at plot level (Objective 2)

The final most explanatory variables derived from CHM<sub>eATE</sub> were the height at 85<sup>th</sup> percentile and the canopy density (cd6), and we achieved  $R^2 = 0.74$  and RMSE = 1.71 m against forest height (Table 20). Similarly, we achieved  $R^2 = 0.46$  and RMSE = 2.04 m by using only maximum height derived from WorldView-2 CHM against LMH. For TanDEM-X CHM, we achieved  $R^2 = 0.45$  and RMSE = 2.13 m by using maximum height and range as explanatory variables against LMH (Table 20).

Table 20 Comparison of final predicted canopy height versus ground LMH using leave-out-once cross validation (n=279 plots)

Canopy height model	Selected variables	Coefficients	R <sup>2</sup>	RMSE	RMSE%
CHM <sub>eATE</sub>	intercept***	14.46	0.74	1.71	7.18
	h85***	0.79			
	cd6***	-8.4			
WorldView-2	intercept***	11.02	0.46	2.04	8.54
	max***	0.5			
TanDEM-X	intercept***	11.13	0.45	2.13	8.92
	max***	0.56			
	range***	0.55			

**Note:** R<sup>2</sup> = coefficients of determination, Adj.R<sup>2</sup> = adjusted R<sup>2</sup> and (\*\*p < 0.001, \*\*p < 0.01, \*p < 0.05 and ·p < 0.1) indicated level of significant of t-test

Our results illustrated that CHM derived from AP (CHM<sub>eATE</sub>) shows highest accuracy in terms of R<sup>2</sup> and RMSE followed by WorldView-2 and TanDEM-X CHM for predicting LMH.

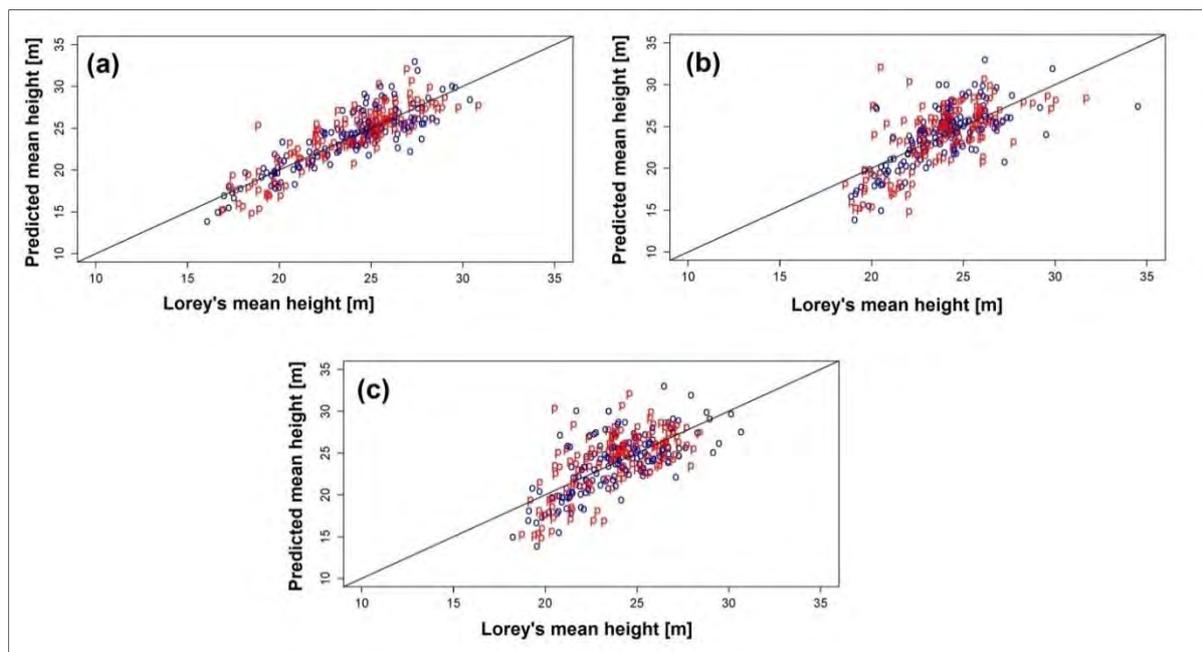


Figure 56 Lorey's mean height (LMH) (x-axis) plotted against predicted mean height (y-axis) (a) CHM<sub>eATE</sub> (b) WorldView-2 CHM and (c) TanDEM-X CHM

### Comparison of image-based CHM (CHM<sub>eATE</sub>) with WorldView-2 and TanDEM-X CHM (Objective 2)

A summary of the statistics of the error distribution derived by subtracting CHM<sub>eATE</sub>, from WorldView-2 and TanDEM-X is shown in Table 21. We achieved a median error of -0.62 m and NMAD 2.6 m from the difference map derived by subtracting WorldView-2 CHM from AP CHM. Similarly, from the difference map derived by

subtracting TanDEM-X CHM from AP CHM, we achieved a median error of -2.23 m and NMAD = 2.75 m (Table 21).

Table 21 Comparison of vertical agreement measures of image-based CHM ( $CHM_{eATE}$ ) with WorldView-2 and TanDEM-X CHM

Forested Areas	WorldView-2 CHM - AP CHM	TanDEM-X CHM-AP CHM
entire forested study area		
Mean diff [m]	-1,71	-2,18
Median diff [m]	-0.62	-2.23
NMAD [m]	2.6	2.75
68.30% quantile diff [m]	0.66	-0.65
95% quantile diff [m]	4.57	5.61

Figure 57 shows final output maps of the CHMs derived from AP, stereo WorldView-2 and TanDEM-X for a small subset of area where the transect line was placed over for the comparison of CHMs.

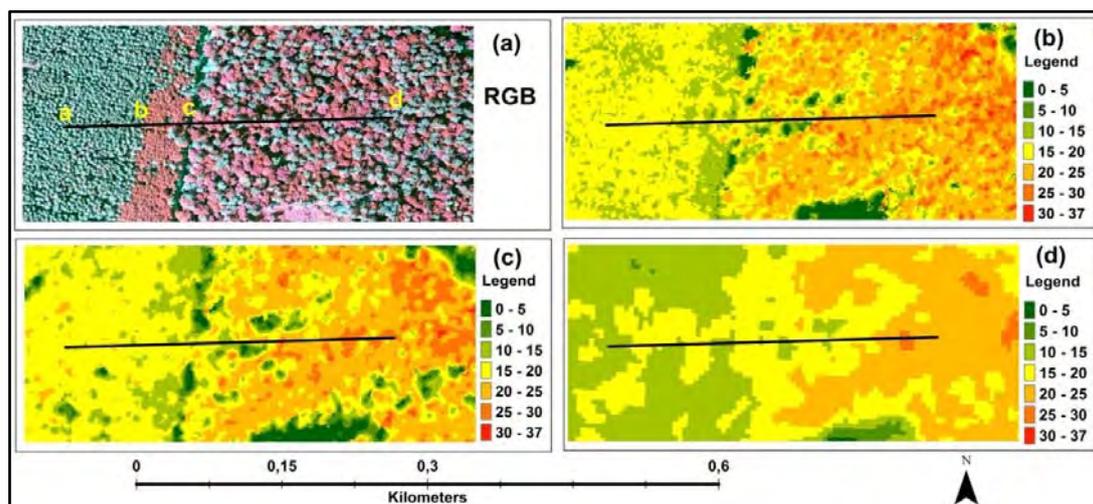


Figure 57 Final output maps of the CHMs, where the transect line was placed over (a) RGB (small subset of study area) (b)  $CHM_{eATE}$  (c) WorldView-2 and (d) TanDEM-X CHM

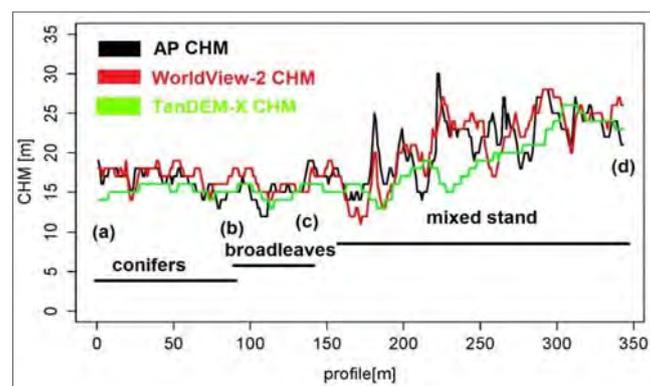


Figure 58 Vertical profile showing comparison of CHMs along the selected transect line

An example of the vertical profile of the four CHMs, where height values were extracted along the transect line Figure 58 are plotted in the form of line graphs is shown in Figure 57. In general, all the three CHMs show a good degree of trends of correlation in the outer envelopes of the surface of forest structure. However, TanDEM-X CHM shows slightly underestimation of vegetation height compared to AP CHM and WorldView-2 CHM.

#### **1.1.1.19 Conclusions**

Accurate and updated knowledge about forest height is fundamental in the context of forest management; however, measuring forest height using traditional forest inventory techniques is laborious, time-consuming and excessively expensive for large forest areas.

In this study, the potential of image-based point clouds produced from stereo AP by using different image matching algorithms i.e. SGM and eATE in comparison with ALS were tested for estimating forest heights (Objective 1). Our study indicated that image-based point clouds using SGM in the presence of pre-existing ALS derived DTM shows almost comparable results with ALS, however the performance of image-based point clouds using eATE is lower than ALS for estimating vegetation heights.

The comparisons of stereo WorldView-2 and TanDEM-X data with AP for estimating forest height (Objective 2) showed that stereo AP provide the most accurate option for estimation forest height followed by stereo VHRS and TanDEM-X.

The overall findings indicated that ALS data is the most suitable and accurate option because it penetrates down through the forest canopy and thus by gives information about canopy top, middle layer and forest ground floor. However, in the presence of pre-existing highly accurate ALS derived DTM, stereo AP can also offer a viable option for all those countries where stereo AP are regularly updated. The option of stereo WorldView-2 is also promising and could be more cost-efficient compared (with focus on direct costs) to stereo AP and can be obtained regardless of various national over-flight restrictions. The TanDEM-X also offers a viable option for large area forest applications.

Summarizing the findings of study, we evaluated different airborne and space borne as well as active and passive sensors for estimating forest vegetation heights and could contribute to cost-benefit comparisons for the different application scales a basis for the decision on considering accuracy and cost.

### 1.1.1.20 References

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#### 4.3.4 Assessment and mapping of forest timber volume based on field inventory data, digital aerial photography (in comparison to ALS) and terrain information - test region located in the federal state of Baden-Württemberg, Germany

##### 1.1.1.21 Introduction

Due to current advancement in the field of remote sensing (RS), it is now possible to assess and generate forest timber volume maps of high quality using the following approach. Field inventory observations collected at sample plots locations are combined with RS data sets to formulate prediction models, which are then interpolated and extrapolated over the entire forest area. (Hill et al. 2014). Such model has also an application potential in nearby areas where terrestrial measurements are not available, and where forest types and structure are comparable.

Among RS datasets, Airborne Laser Scanning (ALS), also known as Light Detection and Ranging (LiDAR) data have been effectively and efficiently used for the assessment and mapping of forest timber volume (Hollaus et al. 2007; Kankare et al. 2013; Latifi et al. 2010; Maack et al. 2016; Sheridan et al. 2014). ALS is an active RS technology that can be used to derive precise and accurate information characterizing forest structure (Næsset 2002; White et al. 2015a). Due to comparatively high acquisition cost of ALS data, the forest sector often took advantage of ALS data, which are primarily acquired for other applications as for instance for terrain mapping. For terrain mapping, the ALS data are usually acquired during leaf-off condition, where the ground is more visible from above, and hence the LiDAR signals penetrated more downward through the forest canopy to get precise information about the ground. However, operational guidelines usually recommend the acquisition of ALS data during leaf-on condition to support area based approach (ABA) (White et al. 2015a). Hence, it is important to evaluate the performance of ALS leaf-off in comparison with ALS leaf-on for the assessment of forest structure variables. But still, ALS data is the most costly option and e.g. Germany but as well in most countries no regular updated cycle is established by survey agencies (Dees et al. 2012). Stereo aerial photographs (AP) are updated on a routine basis at regular time intervals in the range of 3 years by survey agencies/administration in many parts of the Germany (Ullah et al. 2015) and many other European countries as well.

Due to recent advancement in the field of digital photogrammetry, image-based point clouds can be generated from AP using different image matching algorithms from which several information with high similarities to ALS can be produced (White et al. 2013). This allows the modeling of vertical vegetation structures and the calculation of the terrain models (DTMs). However DTMs with sufficient spatial resolutions and vertical accuracies in forested areas are only available from ALS data (White et al. 2013). Therefore, the application of image-based point clouds could be limited to those forest areas that already have a historical ALS-derived DTM. In Germany, highly accurate DTMs from pre-existing ALS campaigns are available for forested areas. Thus the idea of combining Digital surface model (DSM) or point clouds generated from recently acquired AP with previously available ALS DTM offers a promising solution for the assessment and mapping of forest timber (Bohlin et al. 2012; St-Onge et al. 2008).

Over the last few years, different image matching point clouds generating algorithms have been developed and tested for a variety of applications in forest science. For instance, Bohlin et al. (2012) used Match-T DSM software to generate point clouds for forest variables estimation. Similarly, White et al. (2015b) used Semi-global matching (SGM) algorithm as implemented in the Remote Sensing Software Package Graz (Joannuem\_Research) to generate point clouds for estimating plot level Lorey's height, basal area and forest timber volume. Järnstedt et al. (2012) used Next-Generation Automatic Terrain Extraction (NGATE) module of the software SOCET SET and Straub et al. (2013) used enhance automatics terrain extraction (eATE) of the IMAGINE Photogrammetry software of the ERDAS IMAGINE for the estimation of forest structure variables. The above mentioned studies so far have not focused on the comparison of image matching point clouds algorithms for the assessment of forest timber volume and this form the main research gap, which we are trying to answer.

The Relationship between forest timber volume and remote sensing datasets can be statistically modelled using parametric (regression) and non-parametric modelling approached. For example, Latifi et al. (2010) used non-parametric method for estimating forest timber volume and biomass in a temperate forest using LiDAR data. Similarly, Rahlf et al. (2014) adopted parametric method (multiple linear regression) for estimating forest timber volume. In this study, we are comparing the performance of both parametric (multiple linear regression) and the most often used non-parametric k-nearest neighbour (k-NN) and support vector machine (SVM) for the assessment and mapping of forest timber volume. The more specific objectives of the study are the following.

- a) To evaluate the potential of ALS leaf-off versus ALS leaf-on for the assessment and mapping of forest timber volume.
- b) To compare the potential of ALS and photogrammetric image-based point clouds for the estimation and mapping of forest timber volume.
- c) To compare parametric and non-parametric methods for estimating and mapping of forest timber volume.

## The test regions

The study site and description is the same as shown in Figure 13 in study 7. A total of 375 permanent sample plots of 12-meter radius in the study site were collected in summer 2006 and 2007 by the state forest service of Baden-Württemberg following the standard inventory concept providing information for forest management. The sample plots were distributed systematically over the study area in a 100 x 200 m sample grid. On each plot, trees with diameter-at-breast-height (DBH) <10 cm, <15 cm, <30 cm, and ≥30 cm were measured, if they were at the distance of 2, 3, 6 and 12 m exactly from the plot center. Two dominant heights of each main tree species and one dominant height of other mixed species were measured. The remaining height tree heights were predicted by species-specific stand height curved developed by the Forest Research Institute, Baden-Wurttemberg (FVA), Germany. The single tree timber volume was calculated using the taper functions of Kublin (2003). After the calculation of single tree timber volume, the total volume at plot level in cubic meters per hectare was derived by

summing up the individual tree volumes weighted by the inverse of the corresponding sample plot area. More detail about the methodology can also be found in Latifi et al. (2010). An overview on the volume distribution is provided in Table 22.

Table 22 Summary of the ground forest timber volume collected at sample plots location

summary of the ground forest timber volume [ $\text{m}^3 \text{ha}^{-1}$ ] collected at sample plots location						
Minimum	25 % percentile	median	mean	75 % percentile	Maximum	SD
0.00	168.7	245.5	251.7	342.1	609.9	118.11

## Remote sensing data

We used the same ALS (leaf-on) and stereo aerial photographs as we presented in the section 7.1.1.3. In addition to that we used ALS (leaf-off) data with following description (Table 23).

Table 23 Details of flight and system parameters of Airborne Laser Scanning (leaf-on/leaf-off)

Parameters	ALS (leaf-off)
<b>Flying height</b>	800 [m]
<b>Field of view (full scan angle)</b>	36 [°]
<b>Strip width [m]</b>	690 [m]
<b>Measurement rate</b>	100 [kHz]
<b>Point density</b>	~ 20 [points/m <sup>2</sup> ]
<b>Flying velocity</b>	46 [m/s]

The processing of AP using SGM and eATE for the generation of image-based point clouds were already explained in section 7.1.1.3.

### 1.1.1.22 Methods

The image-based point clouds derived from AP using SGM and eATE and the ALS (leaf-on/leaf-off) 3D point clouds were normalized in the presence of pre-existing ALS (leaf-off) DTM. A total of 15 height metrics were derived from normalized point clouds at same plot location i.e. maximum, minimum, mean, quadratic mean and the height percentiles (h10, h20, ..., h90, h95, h99). For variation and heterogeneity of forest canopy height we calculated coefficient of variation (CV) and standard deviation (SD) from the normalized point clouds. The above mentioned metrics are generally derived from the vertical distribution of ALS and Image-based point clouds. In addition, to that we calculated the canopy cover density metrics and canopy volume ( $C_{Vol}$ ) which take into account the horizontal distribution of the canopy structure.

For density metrics we generated canopy height models (CHMs) with spatial resolution of 1 m using the DSM derived from point clouds of AP using SGM and eATE and ALS (leaf-on/off) 3D point clouds and DTM derived from ALS (leaf-off) data. For the generation of DSM and DTM; the exact method as implemented at TreesVis software (Weinacker et al. 2004b) was used, which take highest point for DSM and lowest point for DTM within pre-specified pixels resolution. For interpolation the algorithm employs the general technique of matching a deformable surface to the point clouds by means of energy minimization. The detail of method can be found in Weinacker et al. (2004a).

We calculated forest canopy density (cd) by dividing the number of pixels containing height above 2 m by the total number of pixels with in an area of 12 m radius circular sample plots. In addition, we derived 10 types of others forest cover density metrics (i.e. cd1, cd2....cd10) at sample plots location followed by the methodology adopted by Næsset (2004),\_Rahlf et al. (2014) and Straub et al. (2013). The range between the lower canopy height (>2m) and maximum height was divided by 10 fraction of equal length. Each fraction was considered a threshold and dividing all 1m x 1m cells covered by height above a certain threshold was defined as potential crown region. The ratio of the crown region area above the pre-specified threshold to the total area of the sample plot was used as an estimate for the canopy cover.

In addition to above, forest canopy volume ( $C_{Vol}$ ) was calculated from the CHM, which is the sum of all the heights of 1 m x 1 m pixel size covering the total circular 12 meter radius sample plot area.

We used multiple linear regression models between the all explanatory variables derived from remote sensing datasets and the response which is the volume of the ground inventory sample plots. After multiple linear regression models, step method was applied and the explanatory variables were removed based on minimizing Akaike information criterion (AIC). Subsequently, the importance of the selected variables were analysed in a backward elimination based on the goodness-of-fit (i.e. the coefficients of determination ( $R^2$ ) and adjusted  $R^2$ ), if the removal of variables decrease the  $R^2$  and adjusted  $R^2$ .

After selection of the final explanatory variables, linear model (LM), k-nearest neighbor (k-NN) and support vector machine (SVM) were employed for the assessment and prediction of forest timber volume at plot level.

To determine the prediction accuracy, the absolute and relative root mean square (RMSE) (equations 1 and 2) were computed based on leave-out-on cross validation, where each single observation was held out as a testing set and the remaining data were used a training sets. The entire calculations were carried out in R-statistical software (Team 2014).

$$\frac{y_i - \hat{y}_i}{\sqrt{1 - R^2}} \quad (1)$$

$$RMSE[\%] = \frac{RMSE_{(LOOCV)}}{\bar{y}_i} * 100 \quad (2)$$

Where  $y_i$  is the observed values,  $\hat{y}_i$  is the predicted value of LOOCV,  $\bar{y}_i$  is the mean of the observed values and  $n$  is the total number of ground sample plots.

The final most explanatory variables selected for volume prediction were generated for a grid area of 20 m x 20 m and were used for the prediction of final volume maps using wall-to-wall mapping based on area based approach (ABA).

### 1.1.1.23 Results

The details of final selected variables based on stepwise multiple linear regression models for the estimation of forest timber volume using all the four datasets (1 - 4) are given in ALS (leaf-on) slightly outperformed in term of the coefficient of determination ( $R^2$ ) then the results obtained from ALS (leaf-off) and AP using SGM and eATE. Overall there is not a significant difference between the results achieved from ALS (leaf-on/off) versus AP using SGM in term of  $R^2$  and adjusted  $R^2$  for the estimation of forest timber volume (Table 24). However, the results of final model selection for estimating forest timber volume obtained from image-based point clouds using eATE are slightly poorer than SGM and LiDAR (leaf-off/on).

The root mean square (RMSE) and relative root mean square (RMSE%) derived from the predicted model based on leave-out-one cross-validation are given in Table 25. There is not a significant difference between the results obtained from ALS (leaf-on/off) and image-based point clouds using SGM for the estimation of forest timber volume. However, the accuracy of the results achieved from image-based point clouds using eATE is slightly lower as compared to the others three datasets.

Table 24 Results of the final selected variables based on stepwise linear regression model for the estimation of forest timber volume at plot level for variable set (1-4) derived from normalized point clouds (nPCs) and Canopy height model (CHMs)

Remote sensing datasets	Selected variables	Coefficients	R <sup>2</sup>	Adj. R <sup>2</sup>
1. ALS (leaf-on)	intercept	284.26***	0.56	0.55
	cd	-241.01***		
	cd1	-261.31***		
	cd6	-73.35**		
	h <sub>(sum)</sub>	0.07***		
2. ALS (leaf-off)	intercept	9.62	0.54	0.54
	h <sub>(sum)</sub>	0.06***		
	cd	-221.12***		
	sd	12.09***		
1. AP using SGM	intercept	-206.60***	0.54	0.53
	h <sub>10</sub>	7.39***		
	cv	169.10***		
	h <sub>80</sub>	15.16***		
2. AP using eATE	Intercept	153.72	0.43	0.43
	h <sub>95</sub>	15.69***		
	cd	-225.15		
	sd	-6.16*		

Note: R<sup>2</sup> = coefficients of determination, Adj.R<sup>2</sup> = adjusted R<sup>2</sup> and (\*\*\*)p < 0.001, \*\*p < 0.01, \*p < 0.05 and ·p < 0.1) indicated level of significant of t-test

Table 25 Comparison of RMSE and RMSE % derived from predicted models Vs observed using leave out one cross validation (LOOCV)

<b>Remote sensing datasets</b>	<b>RMSE</b>	<b>RMSE %</b>
<b>Linear regression model (LM)</b>		
ALS (leaf-on)	70.9	29.0
ALS (leaf-off)	70.4	28.0
AP using SGM	70.8	28.1
AP using eATE	75.6	30.0
<b>k-nearest neighbor (k-NN)</b>		
ALS (leaf-on)	73.6	29.2
ALS (leaf-off)	72.9	29.0
AP using SGM	74.3	29.5
AP using eATE	78.5	31.2
<b>Support vector machine (SVM)</b>		
ALS (leaf-on)	74.8	29.7
ALS (leaf-off)	70.4	28.0
AP using SGM	72.5	28.8
AP using eATE	77	30.6

Multiple linear models (LM) show slightly higher accuracy in term of RMSE and RMSE% for the prediction of forest timber volume at the plot level. However, LM did not outperform the others two non-parametric prediction method (i.e. k-NN and SVM).

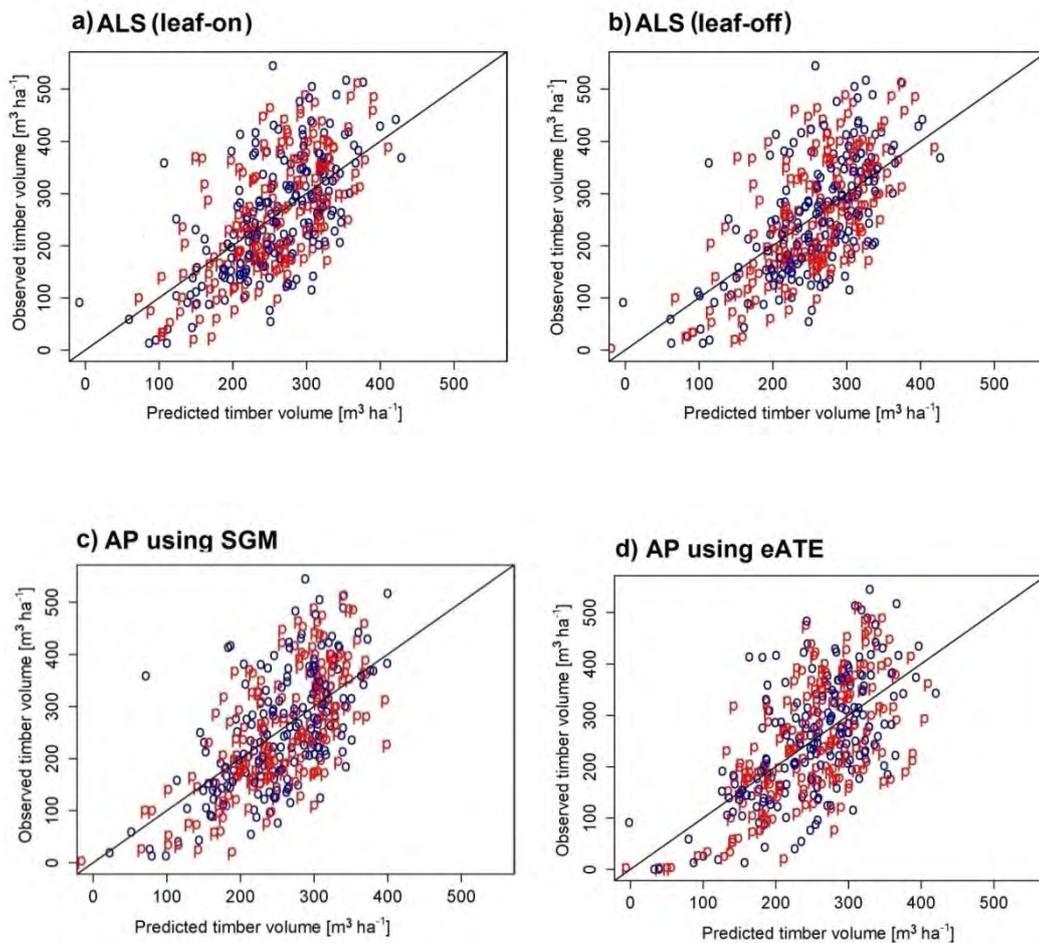


Figure 59 Predicted versus observed volume for all the four datasets based on multiple linear regression model (a) ALS (leaf-on), (b) ALS (leaf-off), (c) AP using SGM and (d) AP using eATE

The final output maps of volume [m<sup>3</sup>/ha<sup>-1</sup>] developed from multiple linear regression models extracted for a small subset area are given in Figure 60.

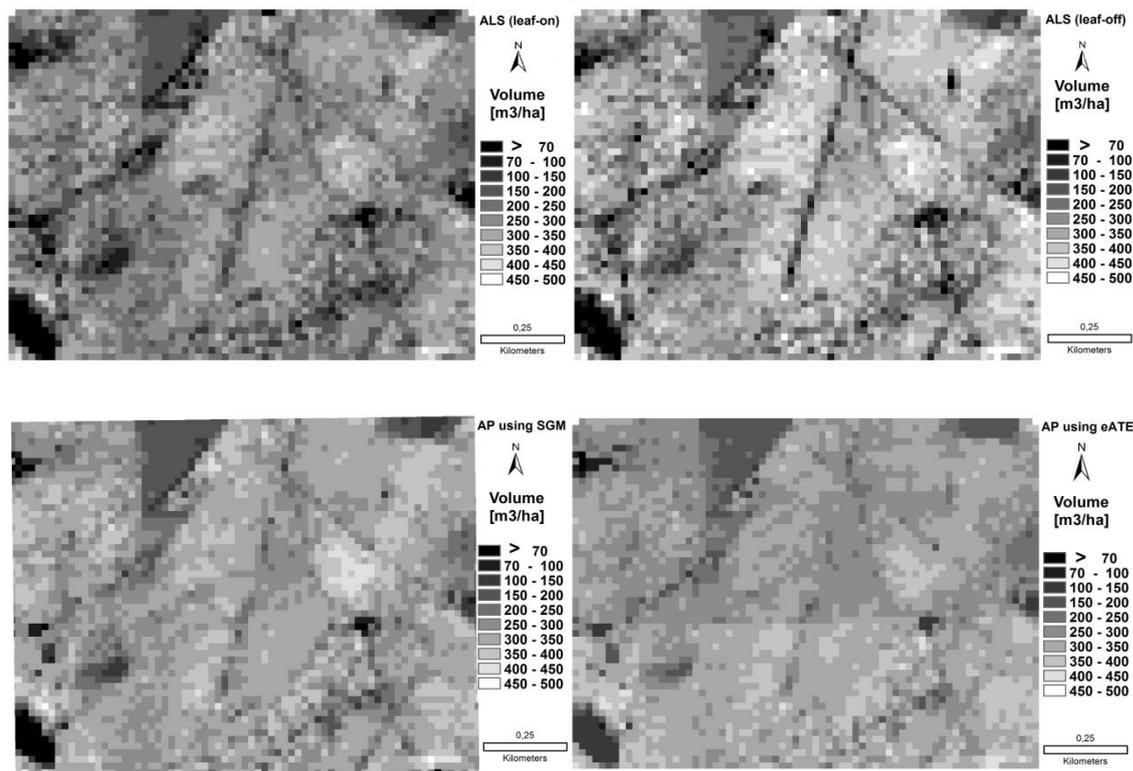


Figure 60 Timber volume prediction maps (m<sup>3</sup> ha<sup>-1</sup>) derived from (a) ALS (leaf-on), (b) ALS (leaf-off) (c) AP using SGM and (d) AP using eATE using multiple linear regression models

### 1.1.1.24 Conclusions

Assessment and mapping of forest timber volume is crucial for forest manager in the context of timber oriented forest management. In this study the potential of airborne laser scanning (ALS) during leaf-on/off versus image-based point clouds based on different image matching algorithms i.e. Semi-Global Matching (SGM) and enhance Automatic Terrain Extraction (eATE) were tested for estimating forest timber volume. In addition, the performance of parametric (multiple linear regression) and non-parametric prediction method i.e. k-nearest neighbor (k-NN) and support vector machine (SVM) were also evaluated. We used forest height and density metrics derived from remote sensing datasets as explanatory variables and ground volume collected at sample plots location as a response variables. ALS leaf-off shows almost similar results with a RMSE = 27.97% versus ALS leaf-on (28.97%) using linear regression model followed by SVM and k-NN. Similarly, image-based point clouds using SGM also shows similar results with a RMSE = 28.13% with ALS (leaf-off/on) using multiple linear regression model followed by SVM and k-NN respectively. The performance of image-based point clouds using SGM in comparison with eATE was slightly more accurate for the assessment of forest timber. In general, we did not found any significant difference between the performance of parametric and non-parametric prediction methods. The finding of the study will be useful for the assessment and mapping of forest timber volume using ALS (leaf-off/on) and image-based point clouds using SGM and eATE.

### 1.1.1.24.1 References

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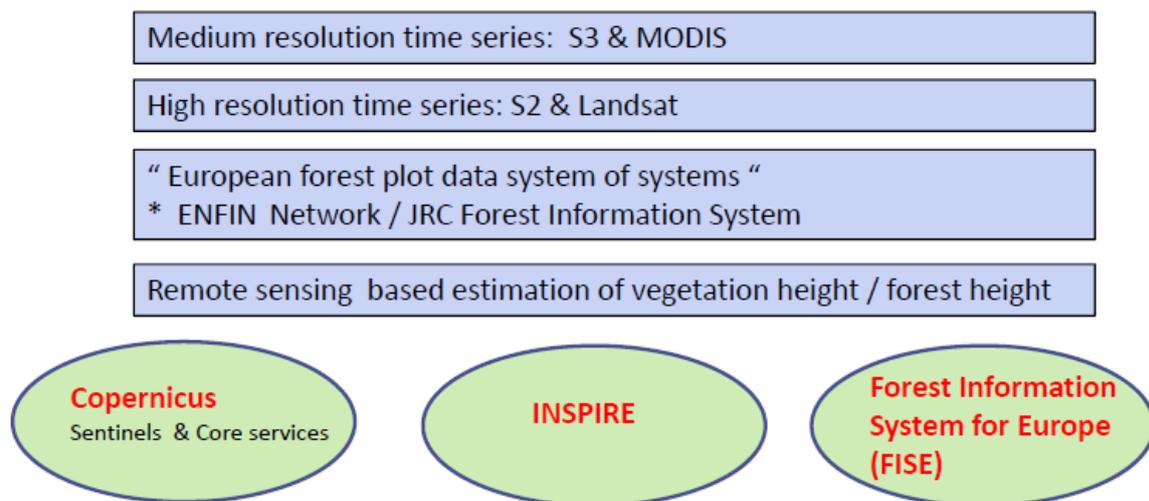
#### 4.3.5 Conclusions

The accuracy of surface models from the different sensor options show high quality resulting in a high potential for modelling and mapping forest height, timber volume, and forest biomass. For applications resulting from these options it is necessary to evaluate availability, cost and resulting accuracy for the region under study considering the scale of the application and the user requirements.

#### 4.4 Concept using remote sensing for forest biomass supply potential information for Europe

The concept for mapping and updating of information on Forest Biomass, Forest Volume, Forest Increment, Harvesting potentials including Disturbance Assessments is illustrated in Figure 61.

### Concept using remote sensing for forest biomass supply potential information for Europe



*Implementation of these three systems is progressing and this will support the potential implementation of the proposed concepts.*

Figure 61 Concept using remote sensing for forest biomass supply potential information for Europe

The concept is based on the following synergetic elements:

- Medium resolution time series: S3 & MODIS
- High resolution time series: S2 & Landsat
- "European forest plot data system of systems" – the ENFIN<sup>24</sup> Network in cooperation with the JRC Forest Information System
- Remote sensing based estimation of vegetation height/ forest height

In the following project experiences and the role of the single element of the concept are described.

## Medium resolution time series: S3 & MODIS

- Experiences from S2BIOM
  - o Assessment of large storm damages and large forest fires was successfully evaluated within S2BIOM. Further developments are required in regard of a Near Real Time (NRT) capability
  - o NFI data integration allows fully automated monitoring
- Future role
  - o Utilisation for Near Real Time assessment after large scale changes
  - o Utilisation for calibration of S2 Data to achieve more accurate estimates of forest status and changes
  - o Estimation of above ground woody biomass and stem volume from national to European level
  - o Synergy with high resolution time series// S2 & Landsat element

## High resolution time series: S2 & Landsat

- Experiences from S2BIOM
  - o Assessment of disturbances was successfully evaluated within S2BIOM. Further developments are required in regard of a Near Real Time (NRT) capability NFI data integration allows fully automated monitoring
- Future role
  - o Annual estimation of above ground woody biomass and stem volume from regional to European level
  - o Near Real Time disturbance assessments at regional, national to continental level
  - o Annual disturbance assessments including mapping of disturbance types
  - o Linkage with the ENFIN<sup>24</sup> Network / JRC Forest Information System
  - o Utilising developments of the H2020 project DIABOLO<sup>25</sup>
    - Integration of advances from DIABOLO (WP5) in harvesting potential projections
    - Integration of advances from DIABOLO (WP4) on disturbance monitoring in forests
    - Integration of advances from DIABOLO (WP2) on plot level based updates and projections

<sup>24</sup> ENFIN European National Forest Inventories Network.

<sup>25</sup> *DIABOLO - Distributed, Integrated and Harmonised Forest Information for Bioeconomy Outlooks. This project is receiving funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 633464. Project duration: 1.3.2015–28.2.2019.*

## Remote sensing based estimation of vegetation height / forest height

- Experiences from S2BIOM
  - o Provides very high estimation quality on NUTS 3 level
  - o Explored options: InSAR (TandemX based); Lidar; optical satellite & aerial photo stereo based surface model determination
  - o NFI or other types of forest plot data integration are fundamental
  - o Availability and accessibility of surface models and terrain models will boost through INSPIRE
  - o Many competing EO & aerial remote sensing based options
- Future role
  - o Highly relevant element
  - o Alternative options to determine forest height need to be evaluated for European scale applications
  - o Linkage with the ENFIN<sup>26</sup> Network / JRC Forest Information System
  - o Utilising developments of the H2020 project DIABOLO<sup>27</sup>
    - Integration of advances from DIABOLO (WP5) in harvesting potential projections
    - Integration of advances from DIABOLO (WP4) on disturbance monitoring in forests
    - Integration of advances from DIABOLO (WP2) on plot level based updates and projections

The future ESA BIOMASS mission (ESA 2012) was not subject of the S2BIOM study. It has the potential to be integrated once the sensor is available. Restrictions that may result from P-band signal distortions over parts of Europe will have to be taken into account (Dees et al. 2014, Figure 62).

<sup>26</sup> ENFIN European National Forest Inventories Network.

<sup>27</sup> DIABOLO - Distributed, Integrated and Harmonised Forest Information for Bioeconomy Outlooks. This project is receiving funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 633464. Project duration: 1.3.2015–28.2.2019.



Figure 62 Restriction of forest mapping capability of BIOMASS due to Space Object Tracking Radar (ESA 2012, page 172)

Further EO based advancements will be possible in the agricultural sector. The near future availability of the high temporal and spatial resolution of the Sentinel 2a & 2b in combination with Landsat 8 and the Sentinel 1 satellites will allow to work on the establishment of an EO based system for the agricultural supply potential assessment. Especially the, compared to the past and the presence in future much higher temporal resolution of EO based imaging is of high, and more fundamental relevance compared to the forest sector. This, since it is very important that the temporal dynamics that occur on agricultural areas during the year can be assessed as good as possible. Especially the potential capacity for a European wide mapping of different agricultural cropping types and of temporarily unused agricultural land is of high importance.

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Dees M., Gallaun H., Schardt M., Datta P., Enssle F., Ermert J. and Koch B. (2014) Large scale forest biomass & harvesting potential & biomass supply potential maps - methods, examples and novel future options with a focus on Sentinel 2. First "Sentinel-2 for science workshop", ESA-ESRIN, Frascati, Italy, 20 to 23 May 2014. 4p.

## Annex

### A1 GLOBIOM model

#### What is GLOBIOM?

The Global Biosphere Management Model (GLOBIOM)<sup>28</sup> (Havlík et al., 2014) is a global recursive dynamic partial equilibrium model of the forest and agricultural sectors, where economic optimization is based on the spatial equilibrium modelling approach (Takayama and Judge, 1971). The model is based on a bottom-up approach where the supply side of the model is built-up from the bottom (land cover, land use, management systems) to the top (production/markets) (see Figure 63 for an overview of the model framework). The agricultural and forest productivity is modeled at the level of gridcells of 5 x 5 to 30 x 30 minutes of arc<sup>29</sup>, using biophysical models, while the demand and international trade occur at regional level (30 to 53 regions covering the world, depending on the model version and research question). Besides primary products, the model has several final and by-products, for which the processing activities are defined.

The model computes market equilibrium for agricultural and forest products by allocating land use among production activities to maximize the sum of producer and consumer surplus, subject to resource, technological and policy constraints. The level of production in a given area is determined by the agricultural or forestry productivity in that area (dependent on suitability and management), by market prices (reflecting the level of demand), and by the conditions and cost associated to conversion of the land, to expansion of the production and, when relevant, to international market access. Trade is modelled following the spatial equilibrium approach, which means that the trade flows are balanced out between different specific geographical regions. Trade is furthermore based purely on cost competitiveness as goods are assumed to be homogenous. This allows tracing of bilateral trade flows between individual regions.

By including not only the bioenergy sector but also forestry, cropland and grazing land management, and livestock management, the model allows for a full account of all agriculture and forestry GHG sources. GLOBIOM accounts for ten sources of GHG emissions, including crop cultivation N<sub>2</sub>O emissions from fertilizer use, CH<sub>4</sub> from rice cultivation, livestock CH<sub>4</sub> emissions, CH<sub>4</sub> and N<sub>2</sub>O emissions from manure management, N<sub>2</sub>O from manure applied on pasture, above and below ground biomass CO<sub>2</sub> emissions from biomass removal after converting forest and natural land to cropland, CO<sub>2</sub> emissions from soil carbon included cultivated organic soil

<sup>28</sup> See also:

<sup>29</sup> The supply-side resolution is based on the concept of Simulation Units, which are aggregates of 5 to 30 arc-minute pixels belonging to the same country, altitude, slope, and soil class. (Van Vuuren et al 2010)

(drained peatland, at country level). These emissions inventories are based on IPCC accounting guidelines.

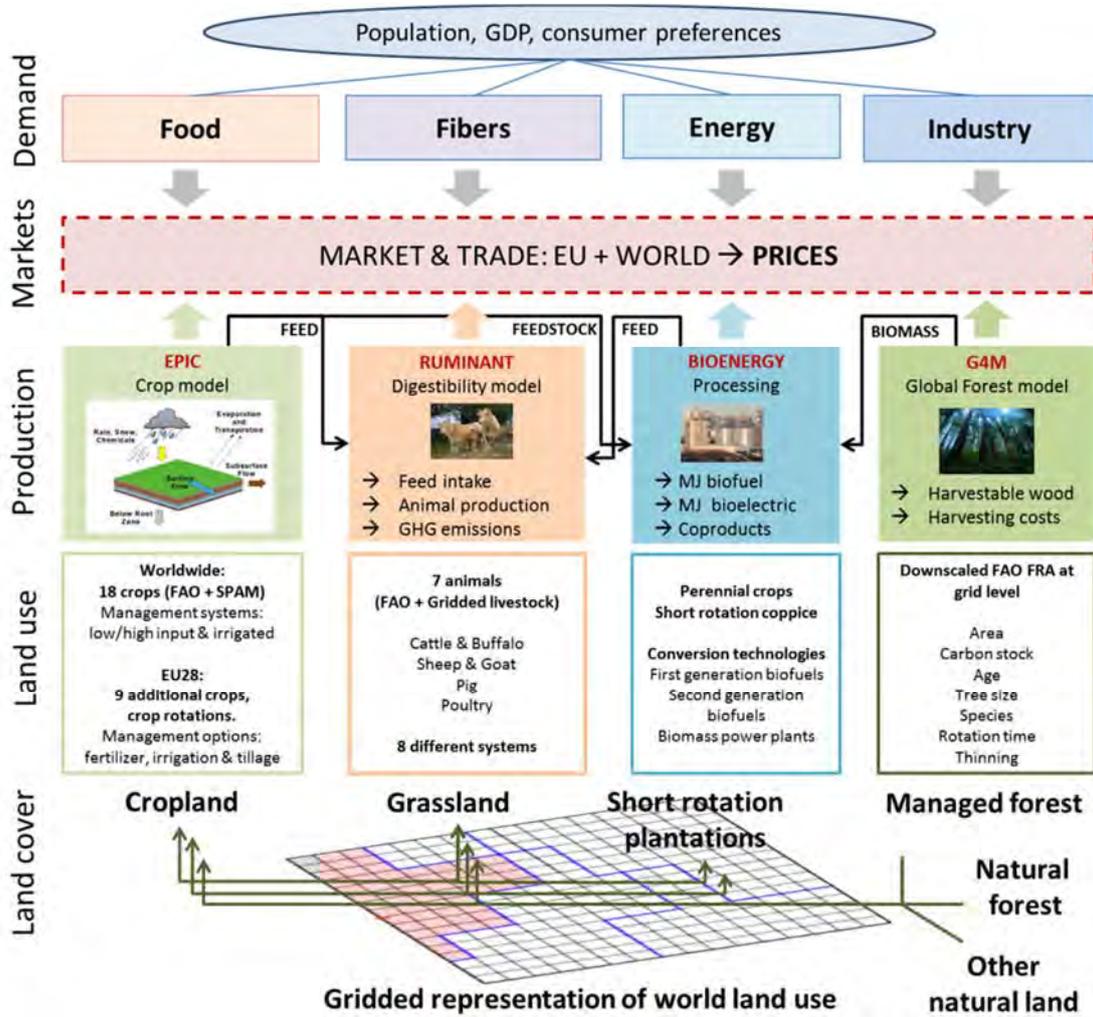


Figure 63. Illustration of the GLOBIOM model.

## Representation of land use change

The model includes six land cover types: cropland, grassland, other natural vegetation land, used forests, unused forests, and plantations<sup>30</sup>. Economic activities are associated with the first four land cover types. Depending on the relative profitability of primary, by-, and final products production activities, the model can switch from one land cover type to another. Land conversion over the simulation period is endogenously determined for each gridcell within the available land resources. Such conversion implies a conversion cost – increasing with the area of land converted - that is taken into account in the producer optimization behavior. Land conversion possibilities are further restricted through biophysical land suitability and production potentials, and through a matrix of potential land cover transitions (see Figure 64).

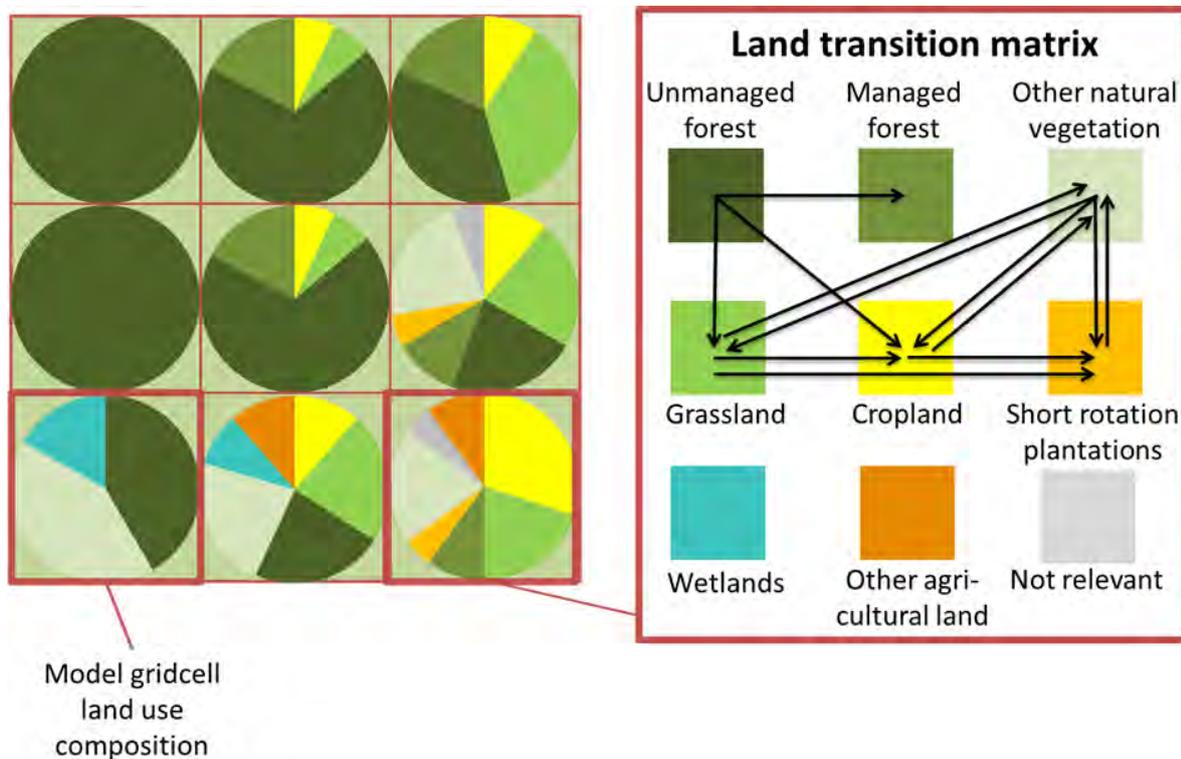


Figure 64. Land cover representation in GLOBIOM and the matrix of endogenous land cover change possibilities

## Land use change emissions

<sup>30</sup> The term "used forests" refers to all forest areas where harvesting operations take place, while "unused forests" refers to undisturbed or primary forests. There are other three land cover types represented in the model to cover the total land area: other agricultural land, wetlands, and not relevant (bare areas, water bodies, snow and ice, and artificial surfaces). These three categories are currently kept constant at their initial level.

Land use change emissions are computed based on the difference between initial and final land cover equilibrium carbon stock. For forest, above and below-ground living biomass carbon data are sourced from G4M which supplies geographically explicit allocation of the carbon stocks. The carbon stocks are consistent with the 2010 Forest Assessment Report (FRA 2010), providing emission factors for deforestation in line with that of FAOSTAT. Carbon stock from grazing land and other natural vegetation is also taken into account using the above and below ground carbon from the biomass as of Ruesch et al. (2008). When forest or natural vegetation is converted into agricultural use, the GLOBIOM approach consider that all below and above ground biomass is released in the atmosphere.

### **Categories of biomass and biomass conversion are included in GLOBIOM**

GLOBIOM represents a number of conventional and advanced biofuels feedstocks:

- 27 different crops including 4 vegetable oil types<sup>31</sup>;
- Co-products: 3 oilseed meal types, wheat and corn DDGS;
- Perennials and short rotation plantations: Miscanthus, switchgrass, short rotation coppice;
- Used forest: 4 types of stem wood, primary forestry residues from wood harvest;
- Wood processing residues: bark, black liquor, sawdust, sawchips;
- Recovered wood products;
- Crop residues (e.g. straw).

Various energy **conversion processes** are modelled in GLOBIOM and implemented with specific technological costs, conversion efficiencies and co-products:

- Wood (forestry): sawnwood, plywood, fiberboard, pulp and paper production, combustion, fermentation, gasification;
- Lignocellulose (energy crop plantations): combustion, fermentation, gasification;
- Conventional ethanol: corn, sugar cane, sugar beet and wheat ethanol processing;
- Conventional biodiesel: rapeseed oil, soybean oil, soya oil and palm oil to FAME processing;
- Oilseed crushing activities: rapeseed, soybeans, and sunflower crushing activities.

This allows ethanol, methanol, biodiesel, heat, electricity and gas to be distinguished and traced according to their feedstocks. Furthermore, competition for biomass resources as considered is also taken into account between the various sectors in term of the demand for food, feed, timber, and energy.

### **Agricultural production within GLOBIOM**

GLOBIOM explicitly covers production of each of the 18 world major crops representing more than 70% of the total harvested area and 85% of the vegetal

31 *Palm oil, rapeseed oil, soy oil and sunflower oil*

calorie supply as reported by FAOSTAT. Each crop can be produced under different management systems depending on their relative profitability: subsistence, low input rainfed, high input rainfed, and high input irrigated, when water resources are available. Crop yields are generated at the grid cell level on the basis of soil, slope, altitude and climate information, using the EPIC model. Within each management system, input structure is fixed following a Leontief production function. However, crop yields can change in reaction to external socio-economic drivers through switch to another management system or reallocation of the production to a more or less productive gridcell. Besides the endogenous mechanisms, an exogenous component representing long-term technological change is also considered.

### **Livestock sector within GLOBIOM**

The GLOBIOM model also incorporates a particularly detailed representation of the global livestock sector. With respect to animal species, distinction is made between dairy and other bovines, dairy and other sheep and goats, laying hens and broilers, and pigs. Livestock production activities are defined in several alternative production systems adapted from Seré and Steinfeld (1996): for ruminants, grass based (arid, humid, temperate/highlands), mixed crop-livestock (arid, humid, temperate/highlands), and other; for monogastrics, smallholders and industrial. For each species, production system, and region, a set of input-output parameters is calculated based on the approach in Herrero et al. (2008).

Feed rations in GLOBIOM are defined with a digestion model (RUMINANT, see (Havlík et al., 2014)) consisting of grass, stovers, feed crops aggregates, and other feedstuffs. Outputs include four meat types, milk, and eggs, and environmental factors (manure production, N-excretion, and GHG emissions). The initial distribution of the production systems is based on Robinson et al. (2011). Switches between production systems allow for feedstuff substitution and for intensification or extensification of livestock production. The representation of the grass feed intake is an important component of the system representation as grazing land productivity is explicitly represented in the model. Therefore, the model can represent a full interdependency between grazing land and livestock [k](#).

### **Available supply of wood biomass and types of wood**

Total forest area in GLOBIOM is calibrated according to FAO Global Forest Resources Assessments (FRA) and divided into used and unused forest utilizing a downscaling routine based on human activity impact on the forest areas (Kindermann et al., 2008b). The available woody biomass resources are provided by G4M for each forest area unit, and are presented by mean annual increments. Mean annual increments for forests are then in GLOBIOM divided into commercial roundwood, non-commercial roundwood and harvest losses, thereby covering the main sources

of woody biomass supply.<sup>32</sup> The amount of harvest losses is based on G4M estimates while the share of non-commercial species is based on the Forest Resource Assessment (FRA) (FAO 2010) data on commercial and non-commercial growing stocks. In addition to stemwood, available woody biomass resources also include branches and stumps; however, environmental and sustainability considerations constraint their availability and use for energy purposes.

### **Available woody biomass resources from plantations**

Plantations are covered in GLOBIOM in the form of energy crop plantations, dedicated to produce wood for energy purposes. Plantation yields are based on NPP maps and model's own calculations, as described in Havlík et al. (2011). Plantation area expansion depends on the land-use change constraints and economic trade-offs between alternative land-use options. Land-use change constraints define which land areas are allowed to be changed to plantations and how much of these areas can be changed within each period and region (so-called inertia conditions). Permitted land-cover types for plantations expansion include cropland, grazing land, and other natural vegetation areas, and they exclude forest areas. Within each land-cover type the plantation expansion is additionally limited by land suitability criteria based on aridity, temperature, elevation, population, and land-cover data, as described in Havlík et al. (2011).

Plantation expansion to cropland and grazing land depends on the economic trade-off between food and wood production. Hence, the competition between alternative uses of land is modeled explicitly instead of using the "food/fiber first principle," which gives priority to food and fiber production and allows plantation to be expanded only to abandoned agricultural land and wasteland (Beringer et al., 2011; Hoogwijk et al., 2009; Smeets et al., 2007).

### **Woody biomass production costs**

Woody biomass production costs in GLOBIOM cover both harvest and transportation costs. Harvest costs for forests are based on the G4M model by the use of spatially explicit constant unit costs that include planting, logging, and chipping in the case of logging residues. Harvest costs also vary depending on geographical considerations such as the region and the steepness of terrain. Transport costs are on the other hand not spatially explicit but are modelled by using regional level constant elasticity transport cost functions, which approximate the short run availability of woody biomass in each region. These transport costs functions are then shifted over time in

32 Commercial roundwood is stemwood that is suitable for industrial roundwood (sawlogs, pulplogs and other industrial roundwood). Harvest losses and non-commercial roundwood are stemwood that is unsuitable for industrial roundwood. The difference between harvest losses and non-commercial roundwood is that the former has unwanted stemwood sizes, while the latter has unwanted wood characteristics.

response to the changes in the harvested volumes and related investments in infrastructures.

### **Woody biomass demand and forest industry technologies**

The forest sector is modeled to have seven final products (chemical pulp, mechanical pulp, sawnwood, plywood, fiberboard, other industrial roundwood, and household fuelwood). Demand for the various final products is modeled using regional level constant elasticity demand functions. Forest industrial products (chemical pulp, mechanical pulp, sawnwood, plywood and fiberboard) are produced by Leontief production technologies, which input-output coefficients are based on the engineering literature (e.g. FAO 2010). By-products of these technologies (bark, black liquor, sawdust, and sawchips) can be used for energy production or as raw material for pulp and fiberboard. Production capacities for the base year 2000 of forest industry final products are based on production quantities from FAOSTAT (FAO 2012). After the base year the capacities evolve according to investment dynamics, which depend on depreciation rate and investment costs. This implies that further investments can be done to increase production capacities or allow industries to reduce their production capacities or be closed. For further details of the modelling approach of the depreciation rates, capital operating costs, and investment costs as applies, we refer to Lauri et al. 2014.

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## A2 The G4M model

### What is G4M?

The Global Forest Model (G4M) is applied and developed by IIASA (Gusti, 2010a; Gusti, 2010b; Gusti et al., 2008; Gusti and Kindermann, 2011; Kindermann et al., 2008a; Kindermann et al., 2006) and estimates the impact of forestry activities (afforestation, deforestation and forest management) on biomass and carbon stocks. By comparing the income of used forest (difference of wood price and harvesting costs, income by storing carbon in forests) with income by alternative land use on the same place, a decision of afforestation or deforestation is made. As G4M is spatially explicit (currently on a 0.5° x 0.5° resolution), different levels of deforestation pressure at the forest frontier can also be handled. The model can use external information, such as wood prices and information concerning land use change estimates from GLOBIOM. As outputs, G4M produces estimates of forest area change, carbon sequestration and emissions in forests, impacts of carbon incentives (e.g. avoided deforestation) and supply of biomass for bioenergy and timber.

### Forest management option and impacts

The available woody biomass resources is estimated by G4M for each forest area unit determined by mean annual increments, which are based on net primary productivity (NPP) maps from (Cramer et al., 1999a) and from different downscaling techniques as described in (Kindermann et al., 2008b). This information is then combined with national data sources (e.g., National Forest Inventories) to provide further and more detailed information concerning biomass stocks and forest age structure.

The main forest management options considered by G4M are variation of thinning levels and choice of rotation length. The rotation length can be individually chosen but the model can estimate optimal rotation lengths to maximize increment, stocking biomass or harvestable biomass. Increment is determined by a potential Net Primary Productivity (NPP) map (Cramer et al., 1999b) and translated into net annual increment (NAI). At present this increment map is static and does not change over time. Age structure and stocking degree are used for adjusting NAI.

The model uses external projections of wood demand per country (estimated by GLOBIOM) to calculate total harvest iteratively. In G4M, the potential harvest amount per country is estimated by choosing a set of rotation lengths that maintain current biomass stocks. If total harvests are less than the wood demand, the model changes management grid per grid (starting from the most productive forest) to a rotation length that optimizes forest increment and thus allows for more harvest. This mimics the typical observation that used forests (in many regions) are currently not managed optimally with respect to yield. The rotation length is updated for each five years' time step. If harvest is still too small and there is unused forest available, the unused

forest will be taken under management. If total harvests are greater than the demand, the model will change management to maximize biomass rotation length, i.e. to manage forests for carbon sequestration. If wood demand is still lower than the harvest potential, used forest can be transferred into unused forest. Thinning is applied to all used forests, and the stands are thinned to maintain a specified stocking degree. The default value is 1 where thinning mimics natural mortality along the self-thinning line. The model can also consider the use of harvest residues e.g. for bioenergy, using a cost curve algorithm.

### **Carbon price and forest mitigation**

Introducing a carbon price incentive means that the forest owner is paid for the carbon stored in forest living biomass if its amount is above a baseline, or pays a tax if the amount of carbon in forest living biomass is below the baseline. The baseline is estimated assuming forest management without the carbon price incentive. The measures considered as mitigation measures in forest management in G4M are:

- Reduction of deforestation area;
- Increase of afforestation area;
- Change of rotation length of existing used forests in different locations;
- Change of the ratio of thinning versus final fellings; and
- Change of harvest intensity (amount of biomass extracted in thinning and final felling activity).

These activities are not adopted independently by the forest owner. The model manages land dynamically and one activity affects the other. The model then calculates the optimal combination of measures. The introduction of a CO<sub>2</sub> price gives an additional value to the forest through the carbon stored and accumulated in the forest. The increased value of forests in a regime with a CO<sub>2</sub> price hence changes the balance of land use change through the net present value (NPV) generated by land use activities toward forestry. In general, it is therefore assumed that an introduction of a CO<sub>2</sub> price leads to a decrease of deforestation and an increase of afforestation. This might not happen at the same intensity though. Moreover, less deforestation increases land scarcity and might therefore decrease afforestation relative to the baseline.

### **Model applications**

Recently, the model was applied to project the future EU forest CO<sub>2</sub> sink as affected by recent bioenergy policies at a national level. The results were used by several EU member states to construct their individual Forest Management Reference Levels (Böttcher, et al. 2012).

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### A3 Detailed description of method to assess the biowaste potential

The availability of biowaste in year x on NUTS3 level can be established as:

$$\text{MSW generated per capita (kg/capita)} \times \\ \text{biowaste fraction (\%)} \times \\ \text{population of the NUTS3 area (persons)}.$$

A further distinction is made between the separately collected biowaste and biowaste as part of mixed waste.

#### **MSW per capita**

European statistics provide information on the amounts of Municipal solid waste generated per capita in a country. (see Municipal waste generation and treatment, by type of treatment method, code tsdpc240, <http://epp.eurostat.ec.europa.eu/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=tsdpc240>). The data is available on country level (NUTS0). It is likely that differences exist in quantities of MSW per capita between regions and that the composition differs between urban and rural areas, etc. Eurostat has carried out a pilot on collection data on Municipal waste per capita by NUTS 2 regions (See Municipal waste by NUTS 2 regions - pilot project, Eurostat code: env\_rwas\_gen). The project covered however a limited number of countries and data collection has stopped after 2011. Therefore, for more recent years NUTS0 MSW per capita data will need to be used.

#### **Biowaste fraction**

Eurostat does not publish data on the share biowaste within municipal solid waste. This ratio has to be collected from statistical information and sorting analyses on national level. Arcadis and Eunomia (2010) have analysed literature on the share of biowaste in household waste in all the EU27 countries. In case no data could be found for a particular country, the study used the share of biodegradable municipal waste in municipal waste that is known for the year 1995 because of the implementation of the Landfill directive, multiplied with a factor of 56% biowaste in biodegradable municipal waste. The latter factor is based on composition of household waste in Pleven and Flanders and the assumption that total biodegradable waste consists of biowaste + paper + textiles + ½ of other fractions. The biowaste fractions established in Arcadis and Eunomia (2010) are used in S2BIOM as it forms the most up to date complete set of biowaste fractions for the EU27 currently available. For Croatia (the 28<sup>th</sup> EU country) BTG has assumed that the biowaste fraction is the average fraction of neighbouring countries Slovenia and Hungary. For the non-EU countries, no data on the biowaste fraction has been collected, instead the average biowaste fraction of 35.9% as established in Arcadis and Eunomia has been used.

### **Population data**

For a year in the past population data on NUTS3 level can be taken from Eurostat (code demo\_r\_gind3). Projections on the development of the total quantity of biowaste are assumed to be proportional to population growth. The main scenario on population development from Eurostat has been used to predict the population in 2020 (Eurostat code proj\_13npms). This information is only available on country level (NUTS0). In order to establish population data in 2020 and 2030 the NUTS3 level population data of year x needs to be multiplied with the expected change in population in 2020 and 2030 (or any other year in the future) compared to year x on national level.

The development of biowaste availability has not been linked to GDP growth, given the uncertainty of GDP development and the fact that many EU countries will reach or have reached decoupling with GDP. This is a conservative assumption, especially for European countries with still a relatively low GDP.

### **Separately collected biowaste versus biowaste in mixed waste**

Arcadis and Eunomia (2010) have analysed the percentages of biowaste that is collected separately or exist as part of mixed waste for the EU27 on country level. These numbers (base year 2008) were used in S2BIOM. In Arcadis and Eunomia (2010) also projections have been provided of the shares of biowaste going to the different treatment options like landfill, incineration, MBT<sup>33</sup>, composting, backyard composting, anaerobic digestion and others have been made for the years 2008-2020. It has been assumed that all countries meet the requirement of the landfill directive, e.g. that maximally 35% of the amount of biodegradable waste generated in base year 1995 is landfilled in 2020, even if current developments show that diversion from landfill has not been successful yet. Furthermore, the projections are based on policy views and current changes in treatment of biowaste in the member state concerned. For instance, some countries have a strong preference for MBT, others for incineration with energy recovery. For the year 2030 the same shares between treatment options are used as in the year 2020, as currently no policies are known that influence the production of biowaste after 2020.

### **Conversion factors**

The following table provides conversion factors that can be used to convert the mass to volumes and energy. The data has been retrieved from the biomass properties database developed in WP2 of S2BIOM.

	NVC <sub>ar</sub> MJ/kg	Moisture content (w% <sub>ar</sub> )	Basic density kg/m <sup>3</sup>
Biowaste as part of integrally collected municipal waste: Biodegradable waste of not separately collected municipal waste (excluding textile and paper)	10.8	27.2%	500
Separately collected biowaste: Biodegradable waste of separately collected municipal waste (excluding textile and paper)	4.3	55.6%	500

## A4 Detailed description of method to assess the post-consumer wood potential

Eurostat gives data on “wood waste”, but this includes not only post-consumer wood but processing wastes from agriculture forestry and fishing sectors. Because of this mixture of secondary wood processing and tertiary post-consumer wood within one category, Eurostat data cannot be used to determine the potential of post-consumer wood.

This means that data needs to be collected from literature or from primary research. The latter is very time and cost intensive. In S2BIOM, data on post-consumer wood was obtained from forest biomass resource assessments done for the EUwood and EFSOS II studies (Mantau et al. 2010; UN-ECE/FAO 2011<sup>34</sup>). EUwood combines among others Eurostat and COST Action E31 data. The EFSOS II data on demolition wood is based on EU wood, but covers Europe as a whole instead of EU28. In order to determine the base potential PCW available for energy, it is necessary to estimate how much is used for material applications. In the Methodology report of the EUwood project<sup>35</sup>, a table is given on the availability of *PCW material* [for material recycling] and *PCW energy* for 2007, page 119-120, which have been used in S2BIOM as well.

The potential can be described as follows:

$$\begin{aligned} \text{PCW}_{\text{technical potential}} &= \text{PCW}_{\text{material}} + \text{PCW}_{\text{energy}} + \text{PCW}_{\text{disposed}} \\ \text{PCW}_{\text{sustainable potential}} &= \text{PCW}_{\text{energy}} + \text{PCW}_{\text{disposed}} \end{aligned}$$

in which:

$$\begin{aligned} \text{PCW}_{\text{material}} &= \text{PCW used for materials like panels and chipboards} \\ \text{PCW}_{\text{energy}} &= \text{PCW used for energy production} \\ \text{PCW}_{\text{disposed}} &= \text{landfilled and/or incinerated with MSW.} \end{aligned}$$

In S2BIOM, the current percentages of waste wood used in material applications, energy generation and landfilled are based on the above-mentioned studies, e.g. EU Wood and EFSOS II. In case of estimation of the future sustainable potential of post-consumer wood, one could also take into account relevant policy developments. For instance, The Circular Economy Package proposes a target of 75% of material recycling of packaging wood in 2030, this will be a challenge but the quality of packaging waste (mainly clean sawn wood) is suitable for recycling. The other waste wood fractions are more difficult to recycle; there are not too many options to recycle used panels (particle board, MDF, OSB, plywood). Recycling rates of other wood (besides packaging) are not expected to exceed 50%. Moreover, given the quality

34 UNECE (United Nations Economic Commission for Europe), FAO (Food and Agricultural Organization of the United Nations) 2011: The European Forest Sector Outlook Study II; Geneva

35 EU Wood (2010) Methodology report, real potential for changes in growth and use of EU forests EUwood. Call for tenders No. TREN/D2/491-2008.

requirements for material applications of wood, all hazardous waste wood can be assumed to be available for energy generation.

### ***Distinction between hazardous versus non-hazardous wood***

Eurostat differs between hazardous and non-hazardous wood, but unfortunately does not have a separate category for post consumer wood, but includes also processing wastes from agriculture, forestry and fishing sectors as part of wood waste. It will be necessary to collect data on the percentage hazardous wood on country level. For instance, according to Probos (2014)<sup>36</sup> in the Netherlands yearly around 1000-1400 ktonnes A/B wood and 80-120 ktonnes/year of hazardous C-wood<sup>37</sup> is produced in the period 2007-2012. This means that hazardous C-wood counts for 7.6% (7.4-7.8%) of total post consumer waste. According to a dedicated case study in the Bioxchange project, in Germany 17% of the PCW is hazardous. According to the same study in the Netherlands the share is lower, only 6%<sup>38</sup>.

### **Conversion factors**

The following table summarises conversion factors that can be used to convert mass to volumes and energy. The data has been retrieved from the biomass properties database developed in WP2 of S2BIOM.

	NVC <sub>ar</sub> MJ/kg	Moisture content (w% <sub>ar</sub> )	Basic density kg/m <sup>3</sup>
Hazardous post consumer wood	14.2	13.9	500
Non hazardous post consumer wood	16	13.1	500

36 De markt van resthout en gebruikt hout in 2012, Bosberichten 2014-04 (in Dutch)

37 Three main categories of post consumer wood can be distinguished, following the Dutch national Land Use Plan: A-quality: unpainted and untreated wood; B-quality: wood not mentioned under A-wood and C-wood: among others painted, lacquered and glued wood. A-quality wood can be recycled or used for material recycling. B-quality wood can be used for both applications as well, given that certain treatment is provided (removing paint) or emission reduction equipment. A- and B-quality wood are often provided as mixtures, therefore it is not possible to distinguish between both categories in statistics. Both qualities will be indicated as non-hazardous wood. C-quality (hazardous) consists of treated wood like: Wood treated with creosotes, wood treated with wood preservatives containing copper, chrome and arsenic (CC and CCA wood), wood treated with other means (fungicides, insecticides, etc.). C-wood is a distinct category, in general not suitable for material recycling (with the exception of material reuse of creosoted wood), but in general this wood can be combusted for energy generation, provided that sufficient measures are taken, especially advanced emission reduction measures.

38 Mark van Benthem, Nico Leek, Udo Mantau, Holger Weima; Markets for recovered wood in Europe: Case studies for the Netherlands and Germany based on the Bioxchange project