ACRP

Final publishable Project-Report

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1 Project Data

Short title	MOTI	
Full title	Comparing MODIS Satellite versus Terrestrial Inventory driven Carbon Estimates for Austrian Forests	
Project number	B068671	
Program/Program line	ACRP 3rd Call for Proposals	
Applicant	Institute of Silviculture, BOKU University of Natural Resources and Life Sciences, Vienna Univ.Prof. Dr. Hubert Hasenauer	
Project partners	• Centre for Global Change and Sustainability, University of life sciences, Vienna, Austria • Prof. Dr. Steven W. Running, Numerical Terradynamic Simulation Group (NTSG) Missoula Montana, USA • Dr. Klemens Schadauer, Institute of Forest Inventory, Forest Research Centre (BFW) Vienna, Austria.	
Project start and duration	01.07.2011	24 months
Reporting period	01.07.2011 to 30.6.2013	

Synopsis:
Net primary productivity (NPP) is a measure for carbon uptake by forests, which is of invaluable importance regarding climate change, carbon sequestration, carbon neutrality or forest ecosystem management. This project shows that satellite data, terrestrial field measurements and the results of simulation models can be combined to utilize their relative assets.
It was possible to identify stand density as the key variable to explain discrepancies between satellite-driven and terrestrial productivity estimates.
Using the suggested approach it is possible to derive realistic large scale forest productivity estimates in an efficient way. However a method to get large scale stem carbon estimates have yet to be developed.

2 Technical /Scientific Description of the Project

2.1 Executive summary

Brief description of the project

The purpose of this study is to compare Net Primary Productivity (NPP) estimates from MODIS satellite information with productivity estimates derived from the Austrian National Forest Inventory. Different models for estimating forest productivity and carbon stocks will get applied. Subsequently analyzing the error structures of each dataset and solving the spatial and temporal difficulties in direct comparisons are major goals. Successful resolution of these issues will allow more efficient use of currently collected data.

Results and conclusions of the project:

Within the MOTI project a conceptual framework to reconcile different methods for estimating forest productivity/net primary productivity was developed (Hasenauer et al. 2012).
As net primary productivity (NPP) is a measure for carbon uptake/carbon sequestration by forests (unit amount carbon per area unit per year), this subject is of invaluable importance in any project dealing with climate change, carbon sequestration, carbon neutrality or forest ecosystem management. It serves as the foundation for better understanding and combining conceptual different data sources and utilizing them to the best extent.
Extensive analysis of forest productivity estimates using satellite data, data collected by terrestrial field measurements and the results of simulation models highlighted that productivity derived from satellite-data or simulation models represent a potential, which is not reached in most cases (figure 1).

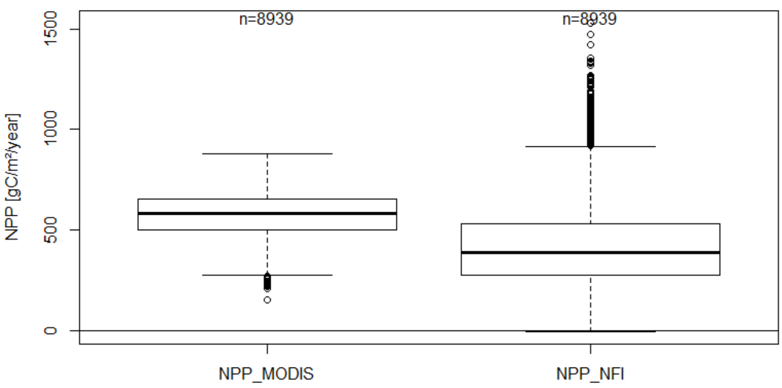

Figure 1: Forest productivity for Austria using two different methods, Satellite-based (NPP_MODIS) and terrestrial data (NPP_NFI) showing a distinct difference between the two data sources (Neumann et al.)

It was possible to identify stand density as the key variable to explain discrepancies between satellite-driven and terrestrial productivity estimates (figure 2). Stand density is a surrogate for inter-tree-competition and is in Austria mainly affected by management, disturbances but also environmental conditions.
Other variables like ecoregion, elevation, water availability, tree species or tree age in contrast proofed to be not relevant for explaining these differences.
By combining these two very different data sources (satellite-driven and terrestrial data) one can utilize the strength of both, the complete coverage of large areas with satellite-driven data (see figure 2) and representation of the actual forest conditions by the results of a terrestrial sample plot system.

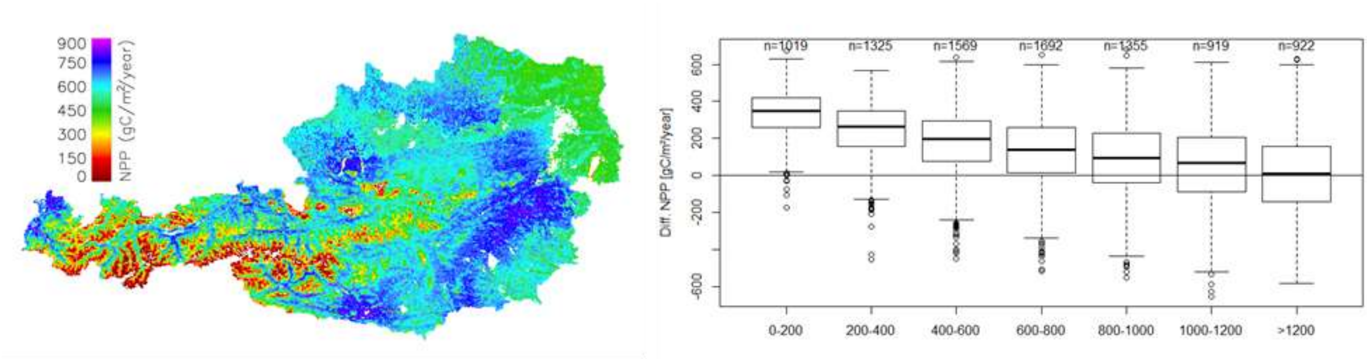

Figure 2: left: example of full coverage of productivity on a national scale, right: relationship of stand density and agreement of satellite and terrestrial data (for dense forests with a high stand density the results are the same on average) (Neumann et al.)

Outlook and summary

By combining satellite data with field measurements it is possible to derive realistic large scale forest productivity estimates in an efficient way. This will make carbon sequestration programs vastly more efficient and more economically interesting for a larger audience. This is of particular importance for countries and areas without forest inventory data or featuring large forest cover.
Some steps are necessary to close this gap. The link between forest productivity (NPP) and stem carbon allocation has to be found. Biogeochemical models like the already used Biome BGC can be useful here (Hasenauer et al. 2012). Also the question on the amount and quality of terrestrial data to reach a satisfying accuracy of the results has to get examined and answered.
Further research is necessary to confirm the proposed concept for other forest ecosystems or other inventory data sets.
Preliminary research show that the concept of stand density being the most important factor to explain the difference between MODIS and terrestrial NPP is also valid for other European countries like Norway or Spain, which supports the prior assumption and encourages to extent the research focus.

2.2 Details on content and result of the project

Initial situation / motivation for the project

Carbon dioxide (CO_2) is one of the most abundant greenhouse gases, increasing from 278 ppm in pre-industrial times up to 391 ppm in 2010. According to IPCC, this has contributed to temperature increase in many parts of the world. The trend of increasing CO2 as well as temperature is expected to continue (IPCC WGI, 1996). The world's forest and carbon sequestration due to forest management is an important part of the global carbon cycle and hence is of interest not only to the forest community (Percy et al. 2003). Unmanaged forests are assumed being in an equilibrium state where the same amount of carbon is released due to respiration and decomposition than the amount that get fixed by photosynthesis (Odum 1969). By looking at the stadial phases of forests, one can observe carbon uptake during the optimum stage, carbon neutral behaviour in mature stands and carbon release in the breakdown and regeneration phase (Pietsch and Hasenauer 2005). The transition from a carbon sink to a carbon source is an elementary process in ecosystem dynamics. A positive carbon balance therefor can be ensured, when regular timber harvesting is done and the wood is not used for energy generation, in this case the CO_2 get released again. Permanent storage of these natural carbon stocks is of growing interest in climate change mitigation.
A core area of climate change research is carbon monitoring. Focusing on the terrestrial carbon cycle, two contrasting approaches are possible:

1. Top-down: using biophysical principles to derive the productivity of a site,
2. Bottom-up: combining detailed field measurements for a site.

In the first approach (top-down), satellite-derived information from sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) is used to estimate Net Primary Productivity (NPP). Principles derived from a simplification of a process-based ecosystem model are used to calculate NPP based on surface reflectance (Running et al. 2004, Zhao & Running 2010). Estimates are provided on a 1 x 1 km grid as annual sums.
A method using similar biochemical and biophysical principles and assumptions are biogeochemical models like Biome BGC (Running & Hunt 1993, Thornton et al. 1997). As this model does not need detailed ground measurements in can also be referred to as a „top-down-approach".
In the second method (bottom-up), within the framework of an assessment system (often called Forest Inventory) individual trees are measured and biomass functions are applied to calculate the carbon stock. Within the Austrian National Forest Inventory (NFI) system, inventory plots are distributed according to a robust statistical sampling design and get remeasured every 7 years (Schadauer et al. 2005, Gabler and Schadauer 2006). The two most recent recording periods available for this study were 2000-2002 and 2007-2009, giving periodic 7-year increments, which cannot be attributed to individual years.

The data recording systems of the two methods differ not only in their principles for deriving carbon, but also in their spatial and temporal resolution. MODIS NPP values are available on a 1 x 1 km pixel grid net and are annual mean estimates. Inventory systems measure individual trees on sampling plots, which are distributed in case of Austria on a fixed grid system of 3.89 x 3.89 km, and offer periodic mean increment results.
For details on the methodology please see the following chapters.
For a given forest area, both methods should ideally deliver comparable productivity estimates. Earlier studies in validating satellite-driven productivity estimates used flux tower measurements which provide information on gas exchange but not productivity. Up until now, there is still no well-established procedure which includes a thorough error assessment utilising forest productivity data derived from National Forest Inventories (e.g. the Austrian NFI).
Therefor the scope of the MOTI project is to assess the comparability of Net Primary Productivity (NPP) estimates from MODIS satellite information with productivity estimates derived from the Austrian National Forest Inventory between 2000 and 2009. For this period overlapping data records are available, thus allowing statistically supportable comparisons. The MODIS driven NPP estimates will come from two sources: (1) the available online databases and (2) calculated with the 'offline' code developed by the NTSG Lab using Austrian daily climate data and the vegetation distribution map developed by the BFW (Austrian Research Dentre of Forests). We are specifically interested in analyzing the error structures of each dataset and solving the spatial and temporal difficulties in direct comparisons. Solving these issues will allow more efficient use of currently collected data and might allow for new future applications.

Objectives of the project

Main research questions are the following:

- *Do the different data recording systems with their specific algorithms for deriving NPP produce comparable results across different forest biome types, regions, soil types and elevation gradients?*
- *Is it possible to harmonize temporal differences between the recording systems?*
- *How to handle the spatial related differences of MODIS vs. the inventory?*
- *What is the error structure according to the different methods and how does this affect the resulting NPP estimates with respect to the signal to noise ratio?*
- *Are there any other issues to consider such as soil degradation effects, forest management, and large disturbance regimes (e.g. wind throw, fire, etc.)?*

Methods and results

Several publications were developed in the framework of the MOTI-project dealing with the research questions and corresponding topics and are presented in the last chapter of this report. This section summarizes and discusses the outcomes and methods of two key publications encompassing the main research focus of the MOTI-project. The theoretical concept of comparing different productivity estimates in Hasenauer et al. (2012) and its elaborated and refined application in Neumann et al. Concluding the research questions mentioned in the previous chapter get discussed in detail. The other publications developed within this project get cited at their relevant position in the discussion.

Hasenauer et al. 2012 „Reconciling satellite with ground data to estimate forest productivity at national scales“

In this paper the focus is on the conceptual challenge in comparing “space based” Moderate Resolution Imaging Spectroradiometer (MODIS) satellite driven Net Primary Production (NPP) with terrestrial “ground based” productivity estimates. Several MODIS NPP datasets are analysed, two available online (NCEP2 and GMAO in figure 4) and one improved dataset using local input data with higher quality (ZAMG in figure 4). The ground based data source is forest increment data from 151 long term research plots with a well-documented management history. Biomass Functions were applied to derive ground based carbon increment estimates based on repeated tree observations from the inventory plots. Terrestrial NPP is the sum of carbon increment of trees and carbon flow into litter fall. In addition the biogeochemical simulation model BIOME-BGC was used a diagnostic tool for exploring conceptual constraints among the two methods.
Several essential, important outcomes are presented in this study and can be summarized as follows,

- MODIS satellite driven annual NPP estimates provide a continuous productivity estimate across Austria (see figure 3) and no significant differences between different daily climate input data sets were evident (figure 4).

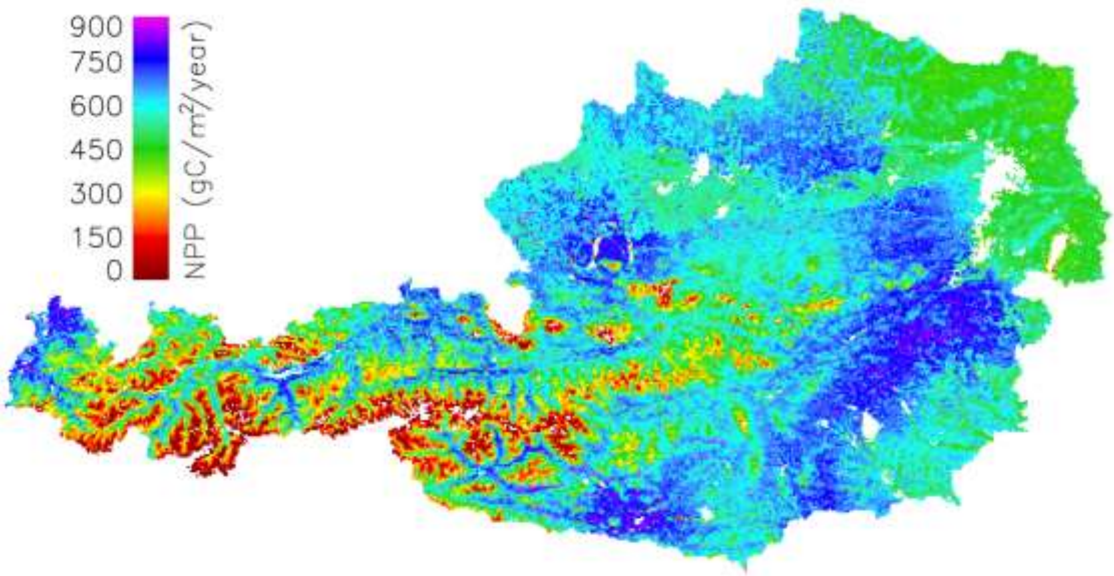

Figure 3: annual mean MODIS NPP for period 2000-2010 for Austria (improved dataset using local data, ZAMG) (Hasenauer et al., 2012).

- MODIS NPP predictions provide forest productivity estimates of fully stocked forests with a complete crown cover. This is confirmed by the results of BIOME-BGC model simulations. An improved MODIS NPP dataset using local climate data with high quality show more variation and more agreement with the BGC-results (figure 4).

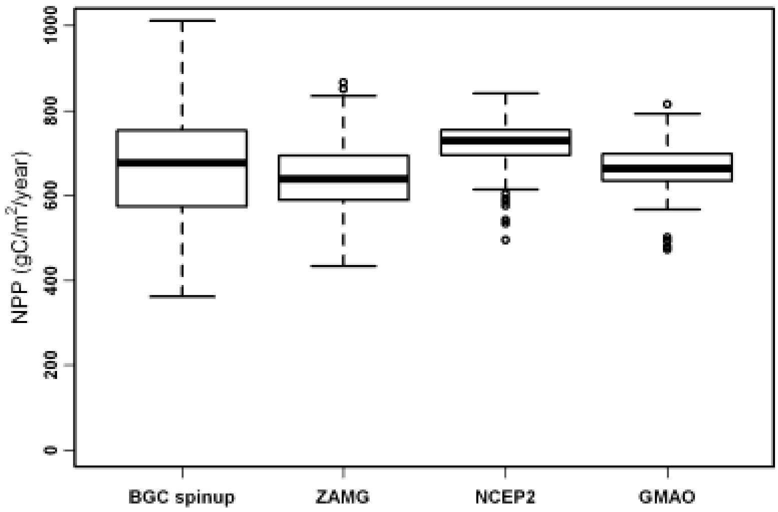

Figure 4: Example for a continuous 11-year average MODIS 1 by 1 km Net Primary Productivity (NPP) estimation for 2000 through 2010 across Austria (Hasenauer et al., 2012).

- Terrestrial driven NPP predictions compare well with MODIS driven estimates given high stand density. The influence of stand density seems to be a crucial variable in combining the two data sets (figure 5).

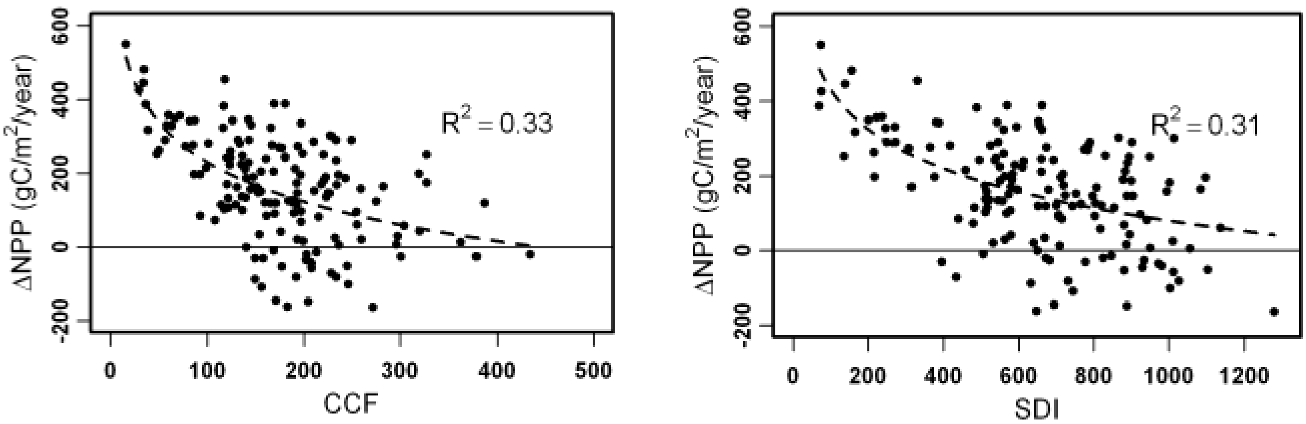

Figure 5: stand density measures and difference MODIS NPP minus terrestrial NPP, stand density SDI on top, crown competition factor CCF on bottom, dashed lines are trend lines fitted with a logarithmic model (Hasenauer et al., 2012).

- With known management history BGC-model runs can properly reproduce the current conditions on the inventory plots (see figure 6)

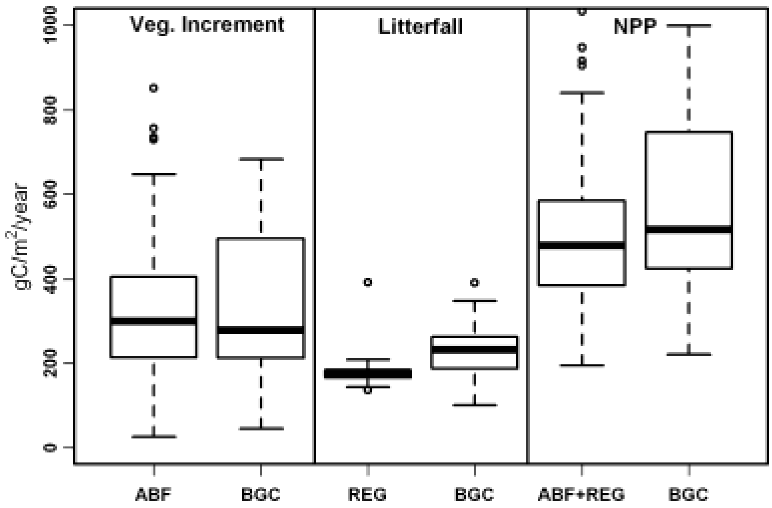

Figure 6: Comparison of the dry carbon vegetation Increment (Veg. Increment), Litterfall and total Net primary Production (NPP) calculated with the Austrian Biomass functions (ABF) versus simulated BIOME-BGC (BGC) (Hasenauer et al., 2012).

- After addressing stand density, computed forest productivity estimates compared well with MODIS-based estimates. Combining both methods could enhance the ability to generate forest productivity assessments across large forest areas (figure 7).

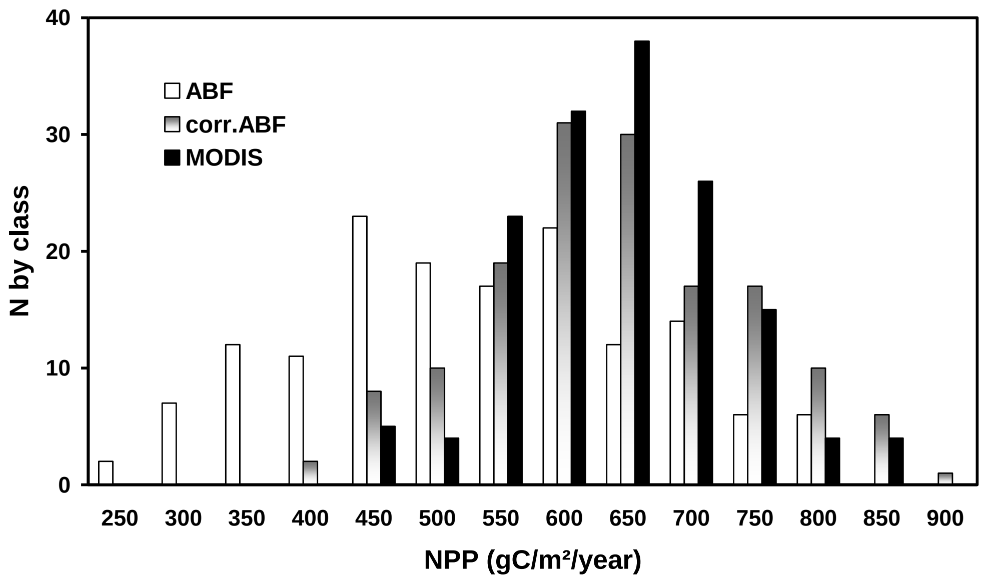

Figure 7: Frequency distribution for different NPP estimates (class with 50 gC/m²/year). Where ABF are the NPP estimates prior to its correction for stand density effects, corr.ABF the NPP results from ABF after applying the correction function for stand density effects using the Crown Competition Factor (CCF), and MODIS the satellite driven estimates using the Austrian local climate data (Hasenauer et al., 2012).

Neumann et al. "Comparing MODIS Satellite with terrestrial Inventory Data to estimate the NPP of Austrian Forests"

As a logical next step the concept of Hasenauer et al. (2012) has to get tested to ensure that the hypothesis are valid throughout different ecological regions, elevation gradients and whether it is applicable to routine forest inventory data too.
Neumann et al. therefor utilizes a different dataset of ground based measurements, the data of the Austrian Forest Inventory for the inventory periods NFI 6 and NFI 7 (2000-2002 and 2007-2009). Analogical to Hasenauer et al. (2012) the same MODIS NPP datasets including an improved one using local weather data are used. The objectives of this paper are to assess the applicability of forest inventory data for the proposed concept, do an error analysis and assess effects of variables as elevation, species composition or stand density and assess the impact of large scale disturbances.
While Hasenauer et al. (2012) used long-term research plots for the analysis this paper focusses on applying the proposed concept to regular forest inventory data for Austria.

The Austrian Forest inventory system uses a systematic and permanent sample plot design (selection of sample trees by diameter, angle count samples or Bitterlich samples). To have comparable results a terrestrial NPP estimate using re-measurement data for inventory plots and climate data get calculated. Terrestrial NPP is the sum of carbon increment of trees and carbon flow into litter fall. Conversion factors and allometric functions get applied to estimate carbon pools in tree compartments. Increment calculation is based on the results of re-measurement data of the inventory plots. Carbon flow into litter fall get estimated with functions using climate data as input. Terrestrial NPP get compared with NPP estimates based on MODIS-data (Moderate Resolution Imaging Spectroradiometer) using different climate datasets.
The results of the study can be summarized as follows:

- Terrestrial driven NPP (median NFI_SVM 387.0 gC/m²/a) predictions represent actual productivity of trees assessed by the inventory system. MODIS NPP overestimates inventory NPP by 33 % (median MODIS_ZAMG 579.8 gC/m²/a). MODIS NPP using coarse global climate data set tend to overestimate even more (median MODIS_NCEP2 739.0 gC/m²/a) (figure 8).
- Choosing the starting value method (NFI_SVM) for increment estimation results in smaller variation. The median is similar in comparison with the results using the difference method (NFI_DM). A MODIS dataset using local high quality climate data better compare with the inventory data regarding mean and variation (figure 8).

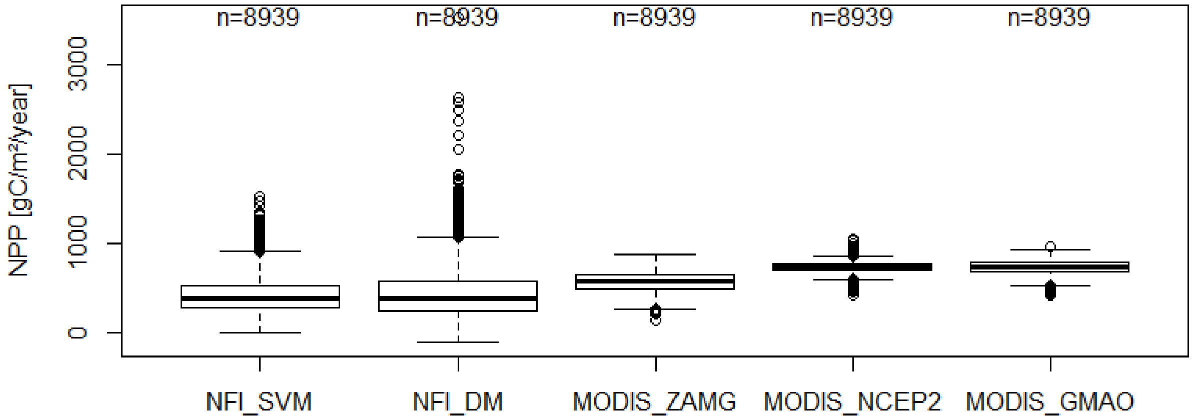

Figure 8: Comparison of different NPP estimates: the first two use inventory data, NFI_SVM increment is calculated with the starting value method, NFI_DM with the difference method, MODIS_ZAMG is a MODIS NPP estimate using local Austrian climate data, MODIS_NCEP2 and MODIS_GMAO are online available MODIS NPP datasets (Neumann et al.)

- The most important factor explaining the deviation of satellite-based and terrestrial NPP estimates is competition represented by stand density (figure 9). While grouping the results by other variables do not show similar trends (figure 10).

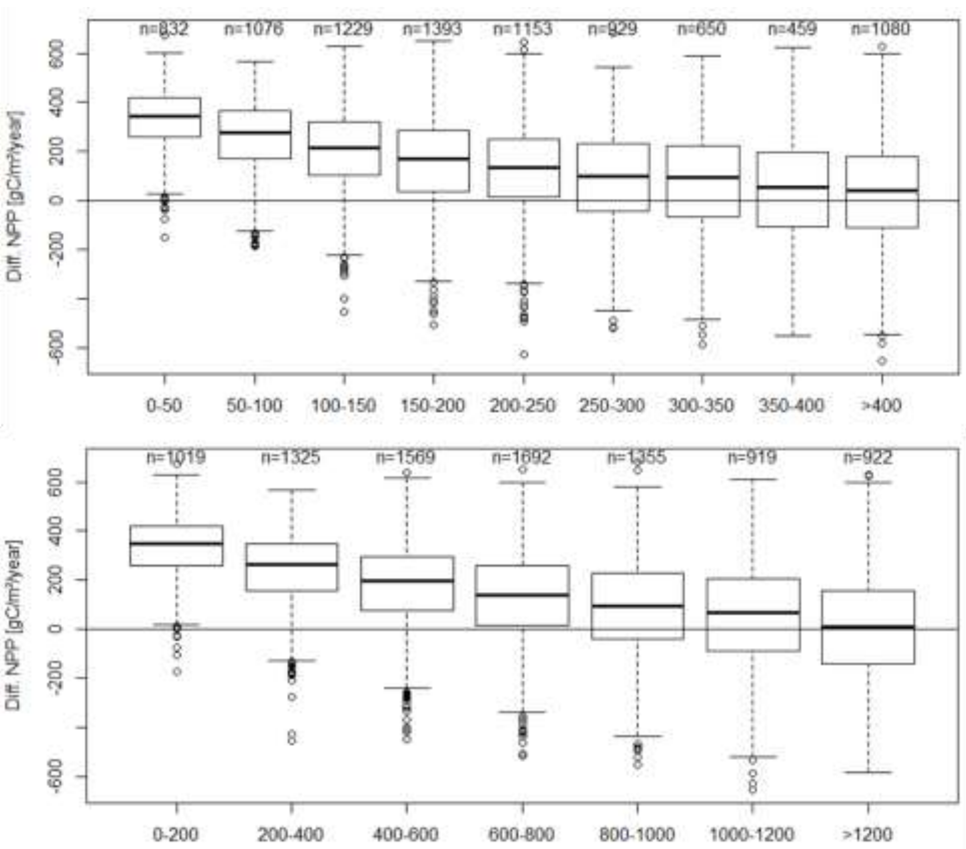

Figure 9: results of difference of MODIS NPP minus terrestrial NPP on the plot level, upper image shows the dependency with SDI, the lower with CCF, above the boxplot the number of samples represented are shown (Neumann et al.)

- Without addressing these effects the MODIS NPP estimates represent a potential productivity assuming fully stocked stands with complete crown cover, while when correcting MODIS NPP for stand density the results represent actual forest productivity and compare well with the terrestrial NPP (figure 10). This supports that combining both methods will enhance our ability to generate forest productivity assessments across large forest areas. When correcting MODIS NPP for stand density it better agrees with inventory NPP (median NFI_SVM 387,0 gC/m²/a and median MODIS_ZAMG (SDI de-trended) 433,4 gC/m²/a vs. median MODIS_ZAMG (original data) 579.8 gC/m²/a.

By assuming or assessing the stand density and given a high quality MODIS NPP data set the estimation of actual forest productivity is possible for large areas with minimal costs and efforts.

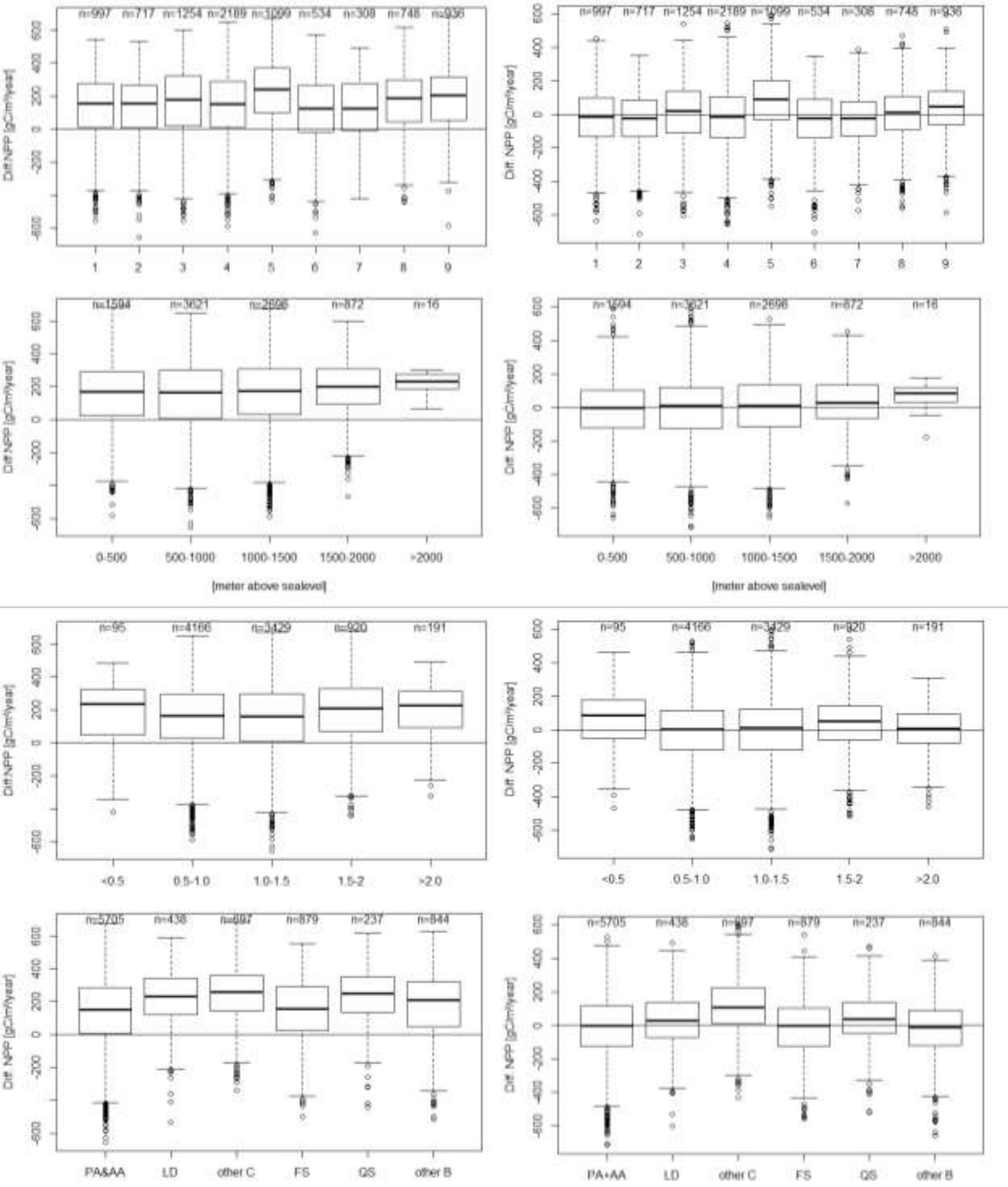

Figure 10: different groupings of difference of MODIS NPP minus terrestrial NPP on the plot level, left column show original data (from top to bottom: BFW-ecoregions, elevation, water balance deficit, main tree species, right column shows the same graphs but uses MODIS NPP, which got detrended for stand density (Neumann et al.)

The next section will explain the material and methods used to answer the research questions. It focusses on the methods used in Hasenauer et al. 2012 and Neumann et al. As these papers share the same climate data set and methodology to calculate MODIS NPP, this section is valid for both papers.

Climate data

The MODIS algorithm needs daily weather data, as well as the model to calculate carbon flow into litter fall. Three climate data sets are used:

- GMAO-dataset (from NASA Global Modelling and Assimilation Offices). The data are available for the period 2000 to 2006. MODIS NPP derived from this data set will be referred to as ‘GMAO’.
- NCEP2-dataset (from NOAA Earth system research laboratory) (Kanamitsu et al. 2002).
- Austrian local climate dataset (provided by the Austrian National Weather Centre, ZAMG).

As the climate data from the ZAMG does not have the appropriate format and resolution to use for model calculation a climate interpolation model was used. DAYMET is a climate interpolation model for interpolating climate data on a daily basis from surrounding permanent climate stations. It got recently adapted and validated for Austrian conditions (Hasenauer et al. 2003, Eastaugh et al. 2010). Minimum and maximum temperature, precipitation, vapour pressure deficit and incident short wave radiation got interpolated (Thornton et al., 1997). Based on these results, daily solar radiation and vapour pressure data are calculated according to Thornton et al. (2000). The current version of DAYMET (Petritsch and Hasenauer, 2011) requires longitude, latitude, elevation, slope, aspect and the horizon angle in east and west facing directions for each given plot. The meteorological data for running DAYMET were provided by the Austrian National Weather Center in Vienna and include daily weather records from 250 stations across Austria since 1961. For the analysis daily weather data at a 1 by 1 km grid across the country and for the inventory plots got generated.

MODIS - general

The storage system of MODIS data consists of 286 vegetated land tiles including forests. Each tile covers an area of 1200 x 1200 km or 1.44 Million pixels. The MOD17 algorithm provides an 8-day GPP/NPP estimate for each 1 x 1 km pixel. Thus each pixel observation can be easily assigned to a given location on the ground based on given longitudinal and latitudinal values. For our study we will use the improved MODIS NPP product which employs the correction routines for FPAR and LAI as developed by (Zhao et al., 2005). For each inventory plot we obtained a 3 x 3 km area (nine 1 x 1 km pixels). From these 9 pixels only those were used which were classed as a forest biome in MOD12Q1. For each of these a MOD17 NPP estimate got computed using as input the different climate data sets available. Therefor the difference between the MODIS NPPs driven by is that they were

generated with different daily climatology drivers and correspondingly modified Biome-Property-Look-UP-Table BPLUT (Zhao et al., 2006). The two data sets GMAO and NCEP2 are maintained by the Numerical Terra Dynamic Simulation Group (NTSG) while the Austrian local climate data (ZAMG) are maintained by the Institute of Silviculture at BOKU.
All variants of MODIS NPP were computed for period represented by the inventory data. The data would be available annually the periodic mean annual NPP for given time period was calculated to have a consistent temporal scaling with the forest growth data. The MODIS data from the online database was extracted and the offline algorithm of MODIS was applied to get the improved MODIS NPP estimates for the inventory plots using the local climate dataset.

MODIS - NPP

The MODIS algorithm provides annual Gross and Net Primary Production (GPP, NPP) estimates for a 1 x 1 km pixel (Running et al. 2004, Zhao & Running 2010). The algorithm calculates GPP as

$$GPP = \varepsilon_{\max} \cdot 0.45 \cdot SWrad \cdot FPAR \cdot f_{VPD} \cdot f_{Tmin} \qquad (1)$$

Where ε_{max} is the maximum light use efficiency as it depends on vegetation or biome types, *SWrad* is the short wave solar radiation load at the surface of which 45% (0.45) is photosynthetically active, *FPAR* the fraction of absorbed *PAR* (Photosynthetic Active Radiation), and f_{VPD} and f_{Tmin} which are multipliers between 0 and 1 addressing water stress due to vapour pressure deficit (VPD) and low temperature limits (T_{min}, daily minimum temperature). These values are stored in the Biome Property Type Look Up Tables (BPLUT) and cover 5 forest biome types: (i) ENF – Evergreen Needle leaf Forest, EBF – Evergreen Broadleaf Forest, DNF – Deciduous Needle leaf forest, DBF – Deciduous Broadleaf Forest, and MF – Mixed Forests. In addition 6 other non-forestry biome types are defined but not relevant for this study.
Annual Net Primary Production (NPP) is calculated from GPP by subtracting the autotrophic respiration components (i) maintenance respiration R_m and (ii) growth respiration R_g:

$$\boldsymbol{NPP} = \sum_{i=1}^{365} \boldsymbol{GPP} - \boldsymbol{R_m} - \boldsymbol{R_g} \qquad (2)$$

In its original approach the MODIS algorithm calculated the annual growth respiration as a function of annual maximum Leaf Area Index (LAI) obtained from the results of the MOD15 algorithm (Myneni et al. 2002). This resulted in an almost constant R_g since MODIS provides the saturated annual maximum LAI for forests which is unreasonable according to plant physiological principles. Thus, Zhao & Running (2010) modified the approach by assuming growth respiration to be approximately 25% of NPP (Ryan 1991, Cannell and Thornley 2000), resulting in the following equations:

$$NPP = \sum_{i=1}^{365}(GPP - R_m) - 0.25 \cdot NPP \qquad (3)$$

Where NPP can be computed as

$$NPP = 0.8 \cdot \sum_{i=1}^{365}(GPP - R_m) \quad \text{when} \quad \sum_{i=1}^{365}(GPP - R_m) \geq 0 \qquad (4)$$

$$NPP = 0 \quad \text{when} \quad \sum_{i=1}^{365}(GPP - R_m) < 0$$

Maintenance respiration is the proportion of GPP needed to maintain living organisms. In the MOD17 algorithm three different compartments are distinguished: (i) leaf area, (ii) fine roots and (iii) live wood. The total leaf biomass is computed from the MOD15 product LAI divided by the Specific Leaf Area (SLA, in LAI/kgC). Once the leaf area is known the fine roots and live wood compartments are derived from biome type multipliers.
For maintenance respiration the Q_{10} theory is applied (Ryan 1991). This approach describes the increase in maintenance respiration for living organs according to a temperature increase of 10°C and provides a maintenance respiration index (MRI) as a function of daily average air temperature (T_{avg}).

$$MRI = Q_{10}^{\left(\frac{T_{avg}-20}{10}\right)} \qquad (5)$$

In the original approach the maintenance respiration expressed by the Q_{10} ratio was assumed to be a constant of 2 for leaves, fine roots and live wood. For leaves Zhao and Running (2010) adopted the temperature–acclimated new Q_{10} equation as proposed by Tjoelker et al. (2001)

$$Q_{10} = 3.22 - 0.046 \cdot T_{avg} \qquad (6)$$

They used “base line maintenance respiration” at 20°C for the three different compartments (i) leaves, (ii) fine roots and (iii) live wood by forest biome.
Important remotely sensed drivers of the MODIS GPP/NPP estimates are FPAR and LAI. LAI is used to calculate the living biomass of the three living organs (i) leaf, (ii) fine root and (iii) live wood. This information is needed for calculating the maintenance respiration by compartment as outlined above (equations (4) to (6)). The input data of FPAR and LAI are a MOD15 product and provide an 8 day composite of maximum FPAR and the corresponding LAI. The MODIS FPAR and LAI are estimated with a canopy radiation transfer model using MODIS surface reflectance from red and near-infrared bands (Myneni et al. 2002). The vegetation types are defined according to the University of Maryland land cover classification

system – the Land_Cover_Type_2 data field in the MODIS land cover data product MOD12Q1 (Friedl et al. 2010) and cover 5 forest biome types.

Biome-BGC - NPP

As a diagnostic tool for analysing possible discrepancies in NPP estimates derived from MOD17 vs. ground based forest data we use the biogeochemical-mechanistic model BIOME-BGC. The model operates on a daily time step and simulates the cycle of energy, water, carbon and nitrogen within a given ecosystem. The model requires meteorological input data, such as daily minimum and maximum temperature, incident solar radiation, vapour pressure deficit and precipitation. Aspect, elevation, nitrogen deposition and fixation and physical soil properties are needed to calculate a wide range of daily ecosystem attributes. These include: canopy interception, evaporation, transpiration, soil evaporation, outflow, water potential and water content, LAI, stomatal conductance, assimilation of sunlight, shaded canopy fractions, growth and maintenance respiration, GPP, NPP, allocation, litter-fall, decomposition, mineralization, denitrification, leaching and volatile nitrogen losses. In the model, the carbon allocated to the leaves is multiplied by the specific leaf area (m^2 leaf area per kg leaf carbon) to calculate leaf area index (LAI, m^2 leaf area per m^2 ground area). LAI controls canopy radiation absorption, water interception, photosynthesis, and litter inputs to detrital pools. Net primary production (NPP) is based on gross primary production (GPP), calculated with the Farquhar photosynthesis routine (Farquhar et al. 1980), minus the autotrophic respiration. The autotrophic respiration includes the maintenance respiration and is calculated as a function of tissue nitrogen concentration (Ryan, 1991). Growth respiration is a function of the amount of carbon allocated to the different plant compartments (leaf, root and stem). The remaining NPP is partitioned to the leaves, fine and coarse roots and stems as a function of fixed allocation patterns.

Recent model improvements include species-specific parameters for all major tree species in Europe (Pietsch et al. 2005) and an improved self-initialization or model spin-up routine (Pietsch and Hasenauer, 2006).

Terrestrial forest growth data

As MODIS NPP data show some important differences in comparison to terrestrial data it is essential for any comparison to do a harmonization and develop a consistent and comparable data set of inventory NPP estimates. Both publications use inventory data derived with different sampling design and calculation methodology. However in both cases the same general structure to calculate NPP and stand characteristics were used.

The general formula for estimating “terrestrial NPP” is:

$$NPP = \frac{incCarb}{dur.inv.per.} + C_{Litter} \qquad (7)$$

where C_{Litter} is the flow of dry carbon into litter as defined in equation [gC/m²/year] (8), incCarb is the annual dry carbon increment of trees (above and below ground biomass) [gC/m²/period], dur.inv.per. is the time between two inventory measurements [a].

In Hasenauer et al. (2012) the re-measurement interval varies from 5 to 10 years. In Neumann et al. the re-measurement interval is 7 years. As the Austrian inventory measurements were recorded from 2000-02 and from 2007-09 and the Austrian forest inventory aims to do re-measurements in the same season as the previous measurement, therefor dividing the values by 7 to get annual increment, is correct in most cases and causes no systematic bias.
Regarding inventory plot design and biomass calculation method please see the references in Hasenauer et al. (2012) and Neumann et al.

The last compartment for estimating NPP from forest growth data is the carbon flow into litter fall (C_{Litter}). We selected the relationship proposed by Liu et al. (2004):

$$\ln(C_{Litter}) = 2.296 + 0.741 \cdot \ln(T) + 0.214 \cdot \ln(P) \qquad (8)$$

Where C_{Litter} is the carbon flow into litter fall in (g carbon/m^2/year), T is the mean annual temperature (°C), and P the mean annual precipitation (mm).

Stand variables
To describe the properties of the stand/trees represented by the inventory plots several variables were calculated.

$$BA = \Sigma \frac{dbh^2 \cdot \pi \cdot nrep}{40000} \qquad (9)$$

$$NHA = \Sigma nrep \qquad (10)$$

BA is basal area [m²/ha], NHA stem number [ha^-1]. Nrep is the represented number of trees per hectare of each sample tree and depends on plot area (fixed area plots) or on diameter (angle count sample). The dominant tree species represents the tree species which make up the biggest part of the plot basal area.
Stand density affects individual tree dimensions. Thus for characterizing the stand density related variation on the plots, we calculated the following two commonly used competition measures: CCF and SDI.
The Crown Competition Factor (CCF) according to Krajicek et al. (1961) depicts the sum of the species specific potential crown area (PCAi) divided by the area (A) (e.g. the plot area).

$$CCF = \frac{\sum PCA_i}{A} \cdot 100\% \qquad (11)$$

The potential crown area is derived from open grown tree dimensions (Hasenauer 1997) and defines the crown area of a tree at a given diameter at breast height assuming open grown growing conditions (tree is able to develop its unrestricted crown).
As a second index we obtained the Stand Density Index (SDI) according to Reinecke (1933):

$$SDI = NHA\left(\frac{dg}{25}\right)^{1.605} \qquad (12)$$

Where NHA is the number of trees per unit area [ha^-1] dg is the quadratic mean stand diameter at breast height [cm], 25 provides a reference dg and 1.605 is the slope parameter for the maximum carrying capacity. The index has been proven to be site and age independent and defines an estimate for the carrying capacity of a given forest type (Hasenauer et al. 1994).

Water availability is an important driver of tree productivity and the used models (Zhang et al 2009). Therefor to analyse the effect of water availability on the results a simple annual water balance index was calculated to get an estimate for water limitation for each inventory plot. This was done only in Neumann et al.

$$WBD = ET0 / precip \qquad (13)$$

precip is annual precipitation sum of the period 2000-2010, ET0 is potential evapotranspiration of the period 2000-2010 and was estimated with the method of Blaney-Criddle (Blaney and Criddle 1950).

$$ET0 = p \cdot (0.46 \cdot T\_mean + 8) \cdot 365 \qquad (14)$$

p = 0.2729 is a function of latitude and was calculated for a latitude of 47.5°. *T_mean* is the mean temperature of the period 2000-2010.

To assess the effects of the geographical location and environmental conditions like geology, precipitation, temperature, etc. different ecoregions (in german: Wuchsgebiete) were assigned to the inventory plots in Neumann et al. The framework and methodology of the “Wuchsgebiete” were developed and published by Kilian et al. 1994. This system groups regions with similar environmental, macro-climatic and geological conditions.

Discussion of research questions

- *Do the different data recording systems with their specific algorithms for deriving NPP produce comparable results across different forest biome types, regions, soil types and elevation gradients?*

Satellite-based models, biogeochemical models and forest inventory data produce comparable results when processed and analysed in a harmonized way. Comparison of MODIS and inventory NPP estimates show strong agreement of the two methods given fully stocked stand with high stand density (Hasenauer et al. 2012, Neumann et al.). Such a converging behaviour of the two datasets is not apparent using any other grouping variable (Neumann et al.).

- *Is it possible to harmonize temporal differences between the recording systems?*

The available datasets have very different temporal resolution. Generally MODIS NPP estimates are available as 8-day values, the values are often aggregated to annual NPP means. Similarly Biome BGC results are calculated on a daily basis and can be aggregated to any temporal scale desired. Inventory systems however give values representative for the time period between two inventory measurements. As shown in previous studies it is possible to split the periodical increment results of the Austrian forest inventory to annual values (Huber et al. 2010). In the presented publications (Hasenauer et al. 2012, Neumann et al.) for BGC and MODIS NPP results mean annual values for the period 2000-2010 were calculated to allow for comparison with inventory results. In other words the daily/annual values were aggregated to mean annual values for the period 2000-2010. This ensures comparability and does not add additional variation by partitioning the periodic increments as done in Huber et al. (2010).

- *How can we handle the spatial related differences of MODIS vs. the inventory?*

MODIS data is available on a 1 x 1 km continuous pixel grid (see figure 1), while inventory plots have a specific location defined by x- and y-coordinates in a certain projection system. This difference causes some constraints and problems in comparing these two datasets. The use of MODIS NPP data for comparison and validation purposes is not recommendable due to a mismatch of MODIS gridded pixels and observations caused by gridded artefacts (Tan et al. 2006), mixed land cover and surface reflectance information and uncertainties in information provided by the model to build up the lookup tables (Yang et al. 2006). Therefor it is suggested that pixels get aggregated within cluster and for each cluster the mean get calculated. In the presented analysis a patch consisting of 3 by 3 pixels was used representing the mean of an area of 9 km^2.
The inventory plots of the Austrian forest inventory are grouped into clusters of 4 plots each. In the analysis no aggregation of plot results was done. However several levels of aggregation are possible, on cluster level, district, regional or even national level. This aggregation will remove variation and smooth results.

- *What is the error structure according to the different methods and how does this affect the resulting NPP estimates with respect to the signal to noise ratio?*

NPP estimates using data from forest inventory are strongly driven by increment of stem carbon between two inventory periods. Therefor having a sound unbiased and robust estimate of increment is crucial. Stem carbon is calculated by the Austrian forest inventory the same way then stem volume. One can utilize the knowledge gained in research of volume increment for carbon increment. Increment estimates using inventory plots show big variation and even negative values under certain conditions. Therefor a method with smaller variation but unbiased mean values is important for sound results. Different calculation methods for inventory data was analyzed and compared to understand the effect of using different methods (Hasenauer & Eastaugh 2012, Eastaugh & Hasenauer 2012).
Another method that provides increment results with less variation is presented in Eastaugh & Hasenauer (2013b).
Due to its easier application the starting value method was chosen in Neumann et al.
MODIS and inventory NPP agrees well given high stand density (fully stocked stands). This picture is unaffected by choosing different methods for estimating stand density, the stand density index (SDI) (Reinecke 1933) and crown competition factor (CCF) (Krajicek et al. 1961).
This can be explained by the fact that the algorithms underlying the MODIS-model assume fully stocked stand (Waring et al. 2006) and cannot account for changing stand density. By applying different groupings of the results like elevation, water balance index or main tree species no converging trend of the MODIS and inventory NPP can be observed. In contrast there is constant overestimation of inventory NPP by MODIS NPP.
Pan et al. (2006) experienced lower NPP predictions using forest growth data and used an available soil water index to improve the MODIS calculations. Given the available data the results do not show apparent discrepancies regarding water balance index.
The result of different biomass calculation methods can be very big especially at bigger dimensions of trees (Thurnher et al 2013). This will also effect any increment calculation based on biomass results.

- *Are there any other issues to consider such as soil degradation effects, forest management, and large disturbance regimes (e.g. wind throw, fire, etc.)?*

By identifying stand density as the key variable to explain the discrepancies between MODIS and NFI NPP forest management seems to be the most important issue to consider, as management immediately affects stand density. Other effects as soil degradation or large scale disturbances (e.g. wind and bark beetle outbreaks) and their effects on forest ecosystem productivity are being intensively studied (Seidl et al. 2008, Seidl et al. 2011). In the last decade heavy storms causing large areas affected by wind throw or windbreak happened in the years 2002, 2007 and 2008. Therefore the effects of these storm events should be represented by the available inventory data.
However analysis showed that in comparison to the total number of plots (~9000 plots) only a small proportion have indication for storm damage (219 and 440 plots). Furthermore these

plots show similar inventory NPP values suggesting that although a plot was affected by a disturbance the effect on the productivity is rather minor (figure 11).

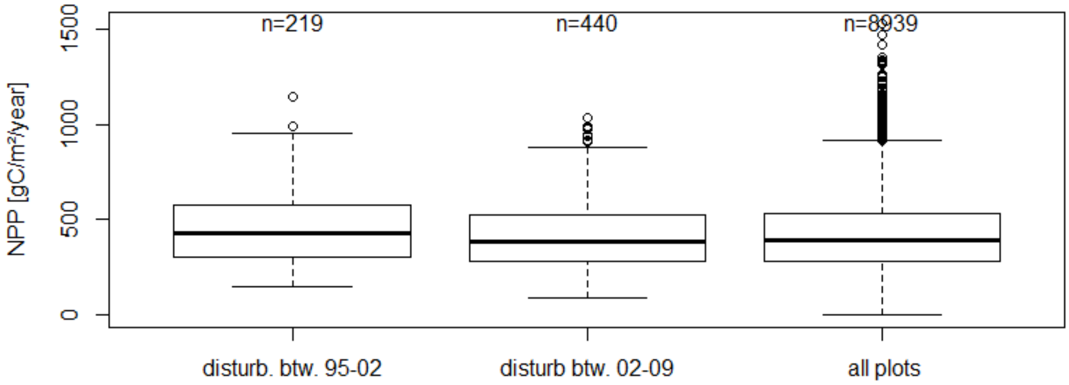

Figure 11: two subsets of plots with evidence of disturbance (left: before NFI6 between 1995-2002, middle: before NFI7 between 2002-2009) in comparison with all plots (right)

In process-based modelling forest management (like thinning and harvesting) can be implemented with models. With known management history biogeochemical models can properly reproduce current forest condition (Hasenauer et al 2012). If this information is not available thinning and harvesting models can be applied as shown in Thurnher et al (2011) and Thurnher et al (2013b).

2.3 Conclusions to be drawn from project results

By analysing and combining different data sources for forest growth data it was possible to identify the key issues explaining discrepancies between the data sources and to outline a conceptual framework for an innovative approach to assess forest productivity using a combination of remote sensing, climate and terrestrial data.
The data sources used are satellite-driven MODIS NPP data, terrestrial NPP based on inventory plot data and the results of the biogeochemical model Biome BGC.
MODIS NPP and NPP derived with Biome BGC show good agreement on average, when using a high quality climate data set for the model calculation. As both models simulate fully stocked stands the results represent a potential NPP and are representative for forests with high stand density and no artificial (man-made) or natural disturbances. As most forests in the world do not have these properties it is essential to incorporate this effect into the modelled results to get realistic productivity estimates.
Forest inventory systems offer information on forest condition on a systematic sampling design, thus avoiding systematic biases, and can serve as a data source for getting realistic results. As they provide among other information carbon stocks, carbon allocation patterns, carbon and volume increment or measures for stand density and competition.
It was possible to show that stand density measures, the stand density index (Reinecke 1933) and the crown competition factor (Krajicek et al. 1961) are the only stand variables that allow to properly explain the discrepancy between MODIS NPP and inventory NPP. Using

the stand density derived from forest inventory it is possible to correct MODIS NPP by doing so getting more realistic productivity estimates which are on average equal to inventory NPP. These results can be used for system analysis, simulation models, carbon sequestration etc. It allows for assessing forest productivity without the need for intensive field work using a permanent inventory plots design with repeated measurements. An assessment of stand density is sufficient to derive the means to correct MODIS NPP to get realistic productivity estimates. This can be carried out cheaper and faster than several measurements of inventory plots. Furthermore there might be also other sources for estimating stand density like airborne Laser-scanning, LiDAR or LandSAT (Luther et al. 2006) then can be utilized for this purpose.

However further research is necessary to confirm this concept for other forest ecosystems or other inventory data sets. Another important next step would be to use these findings to develop a method to get carbon stock estimates rather than net primary productivity. Preliminary research show that the concept of stand density being the most important factor to explain the difference between MODIS and terrestrial NPP is also valid for other European countries like Norway or Spain, which supports the prior assumption and encourages to extent the research focus (see figure 12).

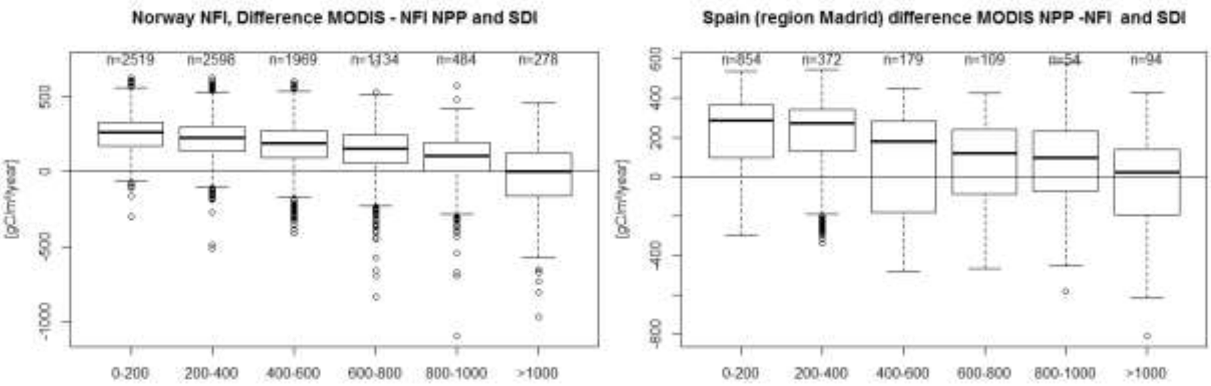

Figure 12: stand density index and difference of MODIS and inventory NPP for Norway and a region in Spain

If the mentioned challenges are solved the method will be relevant for a numerous different transdisciplinary application, ranging from system analysis, ecosystem restoration, carbon stock assessment (eg. REDD+) to validation of results from forest ecosystem modelling work or inventory systems.

2.4 Work and time schedule

WP no.	Title Work Package (WP)	Duration (months)
1	DATA – Forest inventory and MODIS data preparation	4
2	ERROR – Error structure and related scaling problems of forest inventory versus MODIS driven estimates	8
3	MODELING – Regional analysis of the different conceptual approaches and modelling	7
4	SUMMARY – Summary and dissemination of the results, reporting	5

Project Workflow Plan (PWP) – Gantt Diagram:

	2011						2012												2013					
	07	08	09	10	11	12	01	02	03	04	05	06	07	08	09	10	11	12	01	02	03	04	05	06
DATA																								
Forest inventory and MODIS data preparation		4 Months																						
ERROR																								
Error structure and related scaling problems								8 Months																
MODELLING																								
Regional analysis and modelling															7 Months									
SUMMARY																								
Summary and dissemination of results, Reporting																					5 Months			
				M1 - M3																				
												M4 - M6												
																			M7 - M10					
M1 - M13 ... Milestones																								M11 - M13

2.5 Annex

Publications and dissemination activities

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3 Outlook

Summarizing the previously stated findings, by analysing and combining different data sources for forest growth data it was possible to identify the key issues explaining discrepancies between the used data sources (MODIS NPP data, terrestrial NPP data and results of the model Biome BGC) and to outline a conceptual framework for an innovative approach to assess forest productivity.

MODIS NPP and NPP derived with Biome BGC show good agreement on average, when using a high quality climate data set for the model calculation.

It was possible to show that stand density measures are the only stand variables that allow to properly explain the discrepancy between MODIS NPP and inventory NPP.

Therefor it is essential to incorporate stand density effects into the modelled results to get realistic productivity estimates. Following the proposed method this can be done using inventory plot data. There are also other sources for estimating stand density like airborne Laser-scanning, LiDAR or LandSAT then can be utilized for this purpose.

As shown by combining satellite data with field measurements it is possible to derive realistic large scale forest productivity estimates in an efficient way. This will make carbon sequestration programs vastly more efficient and more economically interesting for a larger audience. This is of particular importance for countries and areas which lack forest inventory data or featuring a large forest cover. If the mentioned challenges are solved the method will be relevant for a numerous different transdisciplinary application, ranging from system analysis, ecosystem restoration, carbon stock assessment (eg. REDD+) to validation of results from forest ecosystem modelling work or inventory systems.

Some steps are necessary to close this gap. The link between forest productivity (NPP) and stem carbon allocation has to be found. Biogeochemical models like the already used Biome BGC can be useful here.

Some recommendations and suggestions of research focus for future projects dealing with this topic:

- as climate data is a strong driver in MODIS NPP algorithm it is crucial to use a high quality, fine scale climate data set
- when using data from field measurements much attention should be put on data compilation and analysis. Different inventory designs require accurate work to produce comparable and correct results.
- Biomass functions or biomass expansion factors are essential tools in carbon stock and carbon increment assessment. However a comparison of different biomass caclulation methods show that effect of biomass calculation method can be very big.

Therefor a critical selection and testing routine should be done whenever using biomass functions or biomass expansion factors in future research.

- As consistent large scale assessments of carbon stock are and will be of major importance in ecosystem management research should be pushed in this direction. Several pathlines were drafted by this project, combining satellite data with field measurement, combine satellite data with other sources for stand density or biogeochemical modelling runs.