



**Validation of
modelled forest
biomass in Germany
using BETHY/DLR**

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Validation of modelled forest biomass in Germany using BETHY/DLR

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Abstract

We present a new approach to the validation of modelled forest Net Primary Productivity (NPP), using empirical data on the mean annual increment, or MAI, in above-ground forest stock. The dynamic biomass model BETHY/DLR is used to estimate the NPP of forest areas in Germany, driven by remote sensing data from VEGETATION, meteorological data from the European Centre for Medium-Range Weather Forecasts (ECMWF), and additional tree coverage information from the MODIS Vegetation Continuous Field (VCF). The output of BETHY/DLR, Gross Primary Productivity (GPP), is converted to NPP by subtracting the cumulative plant maintenance and growth respiration, and then validated against MAI data derived from German forestry inventories. Validation is conducted for 2000 and 2001 by converting modelled NPP to stem volume at a regional level. Our analysis shows that the presented method fills an important gap in methods for validating modelled NPP against empirically derived data. In addition, we examine theoretical energy potentials calculated from the modelled and validated NPP, assuming sustainable forest management and using species-specific tree heating values. Such estimated forest biomass energy potentials play an important role in the sustainable energy debate.

1 Introduction

Models of carbon uptake by plants play an important role in answering questions concerning the mechanisms driving the carbon cycle and the roles of terrestrial carbon sinks and sources (Cox et al., 1999). Carbon uptake by plants, measured as Gross Primary Productivity (GPP), can be predicted by simple models that describe the physical, chemical, and plant physiological processes of plant development, as well as the interactions between plants and the atmosphere. Such “deterministic” models (sometimes also called “mechanistic” or “Monteith-type” models) calculate photosynthesis following the methods of Monsi and Saeki (1953) and Monteith (1965).

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data from the International Institute for Applied Systems Analysis (IIASA), and monthly PAR data from the Goddard Institute for Space Studies. Validation of CASA was performed against atmospheric CO₂ concentration data from NOAA and the Geophysical Monitoring from Climate Change Flask Sampling Network, and obtained R^2 values between 0.09 and 0.67.

When the LUE approach is integrated into a coupled soil-plant-atmosphere model, such as the Atmosphere–Land Exchange (ALEX) model, daily estimates of evapotranspiration and carbon assimilation fluxes can also be obtained (Anderson et al., 1997). Recently, more sophisticated models have begun to be developed that take this integrative approach even further. In computing the uptake of carbon by plants, these so-called “dynamic” models take into account the complex interactions between plants, soil, and the atmosphere, but also account for the carbon released by both plants and soil in a manner that respects the conservation of energy and momentum. At present, only a few dynamic models have been published. Examples are the Lund-Potsdam-Jena (LPJ) model developed by Prentice et al. (1992) and modified by Bondeau et al. (2007), the Equilibrium Terrestrial Biosphere Model (BIOME3) by Haxeltine and Prentice (1996), and the ORganizing Carbon and Hydrology in Dynamic EcosystEms (ORCHIDEE) model by Krinner et al. (2003). These global models are driven by meteorological input data, and phenology is calculated internally from those inputs using per-species physiological parameters. The spatial resolution for dynamic models can range from degrees, for global models such as Prentice et al. (1992) and Haxeltine and Prentice (1996), to kilometres, for regional models such as Wisskirchen (2005). Model outputs are typically GPP, NPP and NEP, total ecosystem respiration, and evapotranspiration.

This study used the Biosphere Energy Transfer Hydrology (BETHY/DLR) model, a dynamic model based on the Jena Scheme of Atmosphere Biosphere Coupling in Hamburg (JSBACH) by Knorr (1997), which was designed for global applications (see also Knorr and Heimann, 2001). It was modified by Wisskirchen (2005) for application to regional modelling.

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energy economy for Germany (and, of course, the rest of the world), and so developing methods for estimating, and ultimately forecasting, these potentials is of great importance (BMVBS, 2010).

2 Model description

BETHY/DLR is a soil-vegetation-atmosphere-transfer (SVAT) model. SVAT models track the plant-mediated transformation of atmospheric carbon dioxide into energy-storing hydrocarbons such as sugars, a process known as carbon fixation. BETHY/DLR models photosynthesis, and takes into account environmental conditions that affect it. Photosynthesis is parameterized following the combined approach of Farquhar et al. (1980) and Collatz et al. (1992), and treats separately the “light” and “dark” reactions of photosynthesis at the leaf level. A benefit of this design is that the photosynthetic rate can be mechanistically limited either by light availability or by the abundance of the carboxylation enzyme Rubisco, the key player in the Calvin cycle that fixes carbon. In addition, so-called C3 and C4 plants are distinguished in BETHY/DLR because significant differences exist between their carbon fixation physiologies; in particular, C4 plants such as sugar beet and corn can fix more atmospheric CO₂ at higher temperatures than can C3 plants such as barley and wheat.

In a second step, the rate of photosynthesis is extrapolated from leaf to canopy level taking into account both canopy structure and the interactions between soil, atmosphere, and vegetation. For closed canopies (trees, shrubs, and crops) the photosynthetic rate depends on the Leaf Area Index (LAI), a per-species metric of leaf upper surface area per unit ground area. To model self-shading, photosynthetic rate is reduced exponentially from the canopy top to the soil. In this approach, radiation absorption in the canopy is approximated in BETHY/DLR using the so-called “two-flux scheme” of Sellers (1985) with three canopy layers.

Besides photosynthesis, other energy transfers also need to be tracked. BETHY/DLR’s energy balance model takes into account heat fluxes between the

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vegetation and the atmosphere above it, as well as the cooling effect of evapotranspiration from the soil and vegetation. Soil heat flux is also estimated, and the storage of heat in the canopy and in the air layer above the canopy is considered.

The water cycle must also be modelled. In BETHY/DLR three water reservoirs are considered: soil water, snow, and “skin” or “intercepted” water on leaves and other parts of the vegetation. These reservoirs change in time and space depending on precipitation, temperature and evapotranspiration. A “bucket model” is used for calculating soil water dynamics, using the plant rooting depth as the depth of the soil core. In the bucket model, water availability for plants is governed by the soil water content above the permanent wilting point (at which water is so tightly bound by soil particles that it is unavailable to plants) and below the field capacity (at which the soil is full and further water added by precipitation or snowmelt runs off). The distribution of water within the soil is not modelled in BETHY/DLR, although this would be a worthwhile addition. Water limitation is considered by calculating the demand for evapotranspiration using the approach of Monteith (1965) with the criteria of Federer (1979), which state that evapotranspiration cannot be greater than the limit set by the soil water supply and the water uptake physiology of a plant’s roots.

Autotrophic respiration is modelled in BETHY/DLR as the sum of maintenance respiration and growth respiration. Maintenance respiration is determined by plant-specific dark respiration rates, while growth respiration is proportional to the difference between GPP and maintenance respiration. For estimating NEP, heterotrophic soil microbe respiration is calculated as a function of temperature, scaled by the annual NPP and the effect of soil moisture (neglecting, for modelling purposes, other heterotrophic respiration).

The output of BETHY/DLR is a time series of NPP in daily steps, at the resolution and projection of the land cover classification. Here 1 km² resolution is used, in a latitude-longitude projection using the WGS84 (World Geodetic System 1984) datum. An overview of the input data used in this study and the internal model processes acting upon them is presented in Fig. 1.

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3 Input data

The inputs of the BETHY/DLR model are three remote sensing datasets derived from SPOT-VEGETATION and MODIS, meteorological data provided by ECMWF, and two further datasets describing soil type and land elevation.

3.1 Remote sensing data

Per-pixel Leaf Area Index (LAI) time series were used to determine vegetation phenology. These time series were based on CYCLOPES (Carbon cYcle and Change in Land Observational Products from an Ensemble of Satellites) ten-day composite datasets, which can be downloaded from the POSTEL (Pole d'Observation des Surfaces continentales par TEledetection) databank. Criteria for the identification of gaps and outliers in the CYCLOPES datasets were defined and crosschecked against a hand-validated dataset. For each identified gap or outlier, harmonic analysis (HA), a type of superpositioning transformation, was applied to estimate a corrected value (Niklaus et al., 2011). Following this procedure, a global mean error of 9% was found across a longer time series. Despite these gaps and outliers, the CYCLOPES dataset is the most consistent LAI dataset available (Garrigues et al., 2008); it was also chosen because it is available in the needed form of ten-day composites.

The CYCLOPES dataset also provides land cover and land use information for the year 2000, available as the product Global Land Cover 2000 (GLC2000). The Land Cover Classification System of the Food and Agriculture Organization of the United Nations (FAO), using 22 different land cover classes, was used to derive GLC2000 (Bartholome et al., 2002; DiGregorio and Jansen, 2001). The CYCLOPES LAI and GLC2000 datasets are both available as $10^{\circ} \times 10^{\circ}$ maps in rectangular projection, with latitude and longitude using the WGS84 datum. Complete coverage of the study area (Germany) is available.

In order to make the GLC2000 land use/land cover classification useable for NPP modelling with BETHY/DLR, the GLC2000 vegetation classes were translated to

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BETHY/DLR's forest-related vegetation types. Each vegetation type in BETHY/DLR is described by biochemical parameters such as the maximum carboxylation rate and the maximum electron transport rate, encapsulating the maximum rates of, respectively, the light and dark reactions of photosynthesis. The internal parameterisation of BETHY/DLR allows a given GLC2000 vegetation class to be represented as a fraction of two BETHY/DLR vegetation types. In the context of this study, only four GLC2000 classes represented forest types found within Germany; the BETHY/DLR representation of these four classes is shown in Table 1.

To obtain information about fractional land cover, an additional dataset was used. The MODIS Vegetation Continuous Fields (VCF) dataset (DeFries et al., 2000; Hansen et al., 2002; Hansen et al., 2003) contains annual global data on percent tree cover at a spatial resolution of 500 m square, and is available for 2000 to 2005. For use in BETHY/DLR, the high-resolution VCF data were aggregated to match the spatial resolution of the CYCLOPES data using a Geographic Information System (GIS). For GLC2000 class 6 (“Tree cover, mixed leaf type”), a weighting factor of 0.5 between deciduous and coniferous forest types was used (without scaling of those weights by the VCF fractional land cover). This approximation was assumed to be adequate, since only 15 % of German forest areas are described as mixed forest in the GLC2000, and since VCF contains no further information about the proportion of deciduous to coniferous trees. A similar approach was described by Jung (2008) using the AVHRR Continuous Field of Tree Cover dataset.

3.2 Meteorological data

In addition to remote sensing data, BETHY/DLR needs meteorological input data (Table 2). The ECMWF (European Centre for Medium-Range Weather Forecasts) provides this data at a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$ and a temporal resolution of up to four times per day. The data are produced by ECMWF's climate model analysis of meteorological station measurements of air temperature (at 2 m height), wind speed (at 10 m height), soil water content (in the four uppermost layers), and cloud cover.

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Daily precipitation values were obtained from the ECMWF INTERIM dataset. From these data we calculated daily mean, minimum and maximum temperatures, daily mean cloud cover at three heights, and relative humidity. Daily temperature values were reconstructed at the 1 km^2 resolution of the land cover data, adjusting for the elevation difference between the ECMWF data and the elevation of each modelled pixel using the temperature gradient of the international standard atmosphere ($-0.65 \text{ K per } 100 \text{ m}$).

The daily average photosynthetically active radiation (PAR) was calculated from global radiation following the method of Burridge and Gadd (1974). This method calculates PAR from the incident sunlight for the given day and year, modified by atmospheric transmission, which depends on the degree of cloudiness. Daily average cloud cover was calculated using a weighted sum of each cloud layer. This approach leads to more exact results than the direct use of radiation forecast data, and is thus preferable to the direct use of ECMWF radiation data (Wisskirchen, 2005). Global radiation was calculated for each location at each one-hour time step.

The volumetric soil water content was needed to calculate the soil water budget of the model. Information about the soil type was taken from the International Soil Reference and Information Centre-World Inventory of Soil Emission Potentials (ISRIC-WISE) dataset, which has a resolution of 5×5 arcminutes. It is a harmonization of the global FAO-UNESCO Soil Map of the World (FAO-UNESCO, 1974).

4 Eddy crosscheck

Before validating BETHY/DLR's modelled NPP for NUTS-1 regions across all of Germany, we performed a quick crosscheck of BETHY/DLR GPP results with eddy covariance flux tower measurements provided by FLUXNET. Two tower sites were selected, one in the Hainich forest and one in the Tharandt forest. The Hainich tower is to the west of Jena, Germany, in a mixed deciduous beech forest, while the Tharandt tower is south of Dresden in a coniferous forest. For both sites Level 4 data,

providing information about GPP, are available for 2000 and 2001. These data were crosschecked against BETHY/DLR's modelled GPP, as annual sums at each station (Table 3).

Because BETHY/DLR underestimated annual GPP sums by 20 %–30 % for both stations over both years, a further analysis of monthly GPP sums was performed (Fig. 2).

BETHY/DLR's GPP estimates qualitatively follow the measured GPP for the coniferous forest at Tharandt over both years, but with a slight underestimation (Fig. 2A and B). This finding accords with the results of Wisskirchen (2005), who also observed good agreement between measured and modelled NEP at Tharandt. For the mixed deciduous forest of the Hainich station in 2000, BETHY/DLR's estimated GPP is good up to May and from September onwards. However, June, July and August exhibit a strong depression of the modelled GPP, responsible for the overall underestimation for this year (Fig. 2C). For Hainich in 2001 the modelled GPP is overestimated in May, but underestimated in all other months in the growing season (Fig. 2D).

Overall, BETHY/DLR models monthly GPP well for coniferous forest, with an underestimation of yearly GPP of less than 30 %. For deciduous forest the underestimation of yearly GPP is also less than 30 %, but monthly GPP shows an RMSE of up to 25 (Table 3). In particular, BETHY/DLR seems to strongly underestimate the peak of productivity during the middle of summer, perhaps due to the more heterogeneous development patterns of the species in this vegetation group.

Comparisons of GPP calculated by other vegetation models, such as BIOME-BGC, ORCHIDEE and LPJ, with eddy covariance flux tower measurements revealed an overall RMSE of 30 % for forests in climate zones from boreal to Mediterranean (Jung, 2008). This magnitude of error corresponds well with our findings.

5 Validation strategy

To validate BETHY/DLR's modelled NPP, we used empirical data on the growth increment of timber-growing stocks. These data describe the above-ground woody parts

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of trees with a diameter greater than 7 cm, given as solid tree volume (including bark). For Germany, these timber stock increment data are provided by the National Forest Inventory (NFI) classified by forest, tree species, and age class. The aim of this ongoing large-scale survey is to establish statistically reliable central monitoring of the development of Germany's forests, to allow assessment of each forest's status and production potential. The NFI survey uses a permanent set of sampling sites, based on a nationwide 4 km × 4 km grid. Samples are taken at randomly chosen sites from this set, using a uniform procedure across all of Germany. This sampling procedure fulfils accuracy requirements at the national level, but more intensive sampling is conducted for greater accuracy in some smaller federal states, such as Bremen and Hamburg. From a statistical point of view the maximum error of the NFI survey regional level data is about 12 % for coniferous forest and below 8 % for deciduous forest, calculated from the data of BMELV (2004).

For each sampling site, the NFI surveys about 150 characteristics, such as tree species composition, timber volume, and growth, using an angle-count sampling method at each corner of the site. Furthermore, sampling circles with defined radii are drawn to survey tree species composition, tree heights, deadwood, ground vegetation and other characteristics. A more detailed description can be found in BMELV (2004).

The first NFI survey was conducted in 1987, and was restricted to the ten states of the former West Germany. The second NFI survey was carried out in 2003 and covered all of Germany. The NFI data are freely available at the NUTS-1 level (BMELV, 2004).

In order to validate the modelled NPP against these NFI surveys, the highly detailed NFI data had to be processed. In a first step, the tree species reported in the NFI statistics were grouped into BETHY/DLR's two temperate forest classes, coniferous and deciduous. Coniferous forest in Germany is mainly composed of spruce (~57 %) and pine (~33 %), while Germany's deciduous forest is dominated by beech (~48 %) and oak (~25 %). It was therefore assumed that all parameters (standing timber stock and increment of timber stock, in particular) of these two forest classes could be estimated

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as the sum of the metrics for the two principal species, plus an estimated value for all of the secondary species.

The NFI data were then used to calculate the mean annual net increment of the total above-ground biomass (B_T), which was then compared to the modelled NPP. To calculate B_T for a NUTS region, the above-ground biomass of coniferous (B_c) and deciduous (B_d) trees were summed (Eq. 1).

$$B_T = B_c + B_d \quad (1)$$

As described above, we calculated B_c and B_d as the sum of the net increment of the total above-ground biomass of the two dominant species (\hat{B}) plus an estimate for the tertiary species (\tilde{B}). Both B_c and B_d , represented simply as B , were thus calculated following Eq. (2).

$$B = \sum_{s=1}^2 \hat{B}_s + \tilde{B} \quad (2)$$

The index s represents the two dominant species of the forest class.

Since tree biomass depends upon age, \hat{B} was calculated using per-species age-dependent net biomass increments, β , for the ten age classes in the NFI data, as shown by Eq. (3).

$$\hat{B}_s = \sum_{a=1}^{10} \beta_{s,a} \cdot A_{s,a} \quad (3)$$

The index a represents the age classes, and A represents the proportional area occupied by each age class (given in the NFI data).

Since values for β are not given by the NFI, the NFI's species- and age-dependent net increments of the outer bark volume V , expressed in $\text{m}^3 \times \text{a}^{-1} \times \text{area}^{-1}$, are used. To convert timber stock biomass into absolute dry biomass, species-dependant conversion factors (ε) are needed (Table 4). Furthermore, species- and age-dependant

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conversion factors, P , are needed to estimate the total above-ground biomass. P represents the fraction of total above-ground biomass, including branches of less than 7 cm diameter and needles/leaves, that is outer bark (Table 4). Given these values, β was calculated as shown in Eq. (4).

$$\beta_{s,a} = \frac{V_{s,a} \cdot \varepsilon_s}{P_{s,a}} \quad (4)$$

Because the first NFI was conducted before 1989, values for V are only available for the ten states of the former West Germany. For the five states of the former East Germany, values for V were taken from yield tables (Erteld, 1963).

For this study values of ε were taken from Dieter and Englert (2001). Since only a single source of values for P was found, the accuracy of these values is unknown.

To calculate \tilde{B} it was assumed that a weighted average of the biomass increments of the two dominant tree species, \hat{B} , would be representative for the tertiary species (Eq. 5). Statistical analysis indicated that the error of this approach is less than 6%.

$$\tilde{B} = \frac{\tilde{A} \cdot \tilde{V} \cdot \tilde{\varepsilon}}{\tilde{P}} \quad (5)$$

\tilde{P} and \tilde{V} represent the arithmetic averages of the weighted average means of P and V respectively. Since both depend on tree age and species composition, they were thus calculated using Eq. (6) (\tilde{P} being calculated analogously using P).

$$\tilde{V} = \frac{\sum_{s=1}^2 \left(\frac{\sum_{a=1}^{10} V_{s,a} \cdot A_{s,a}}{\sum_{a=1}^{10} A_{s,a}} \right)}{2} \quad (6)$$

$\tilde{\varepsilon}$ was calculated using the arithmetic mean of ε , following Eq. (7).

$$\tilde{\varepsilon} = \frac{\sum_{s=1}^2 \varepsilon_s}{2} \quad (7)$$

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Before the modelled results could be validated, they needed to be aggregated to the NUTS-1 level at which the NFI data are given. To accomplish this, the modelled NPP was first transferred to a GIS, taking into account the equi-rectangular WGS84 datum map projection. Then, in order to allow comparison of the datasets, the above-ground biomass of the modelled NPP was calculated. Because the modelled NPP does not specify which parts of the plant contain the accumulated carbon, the below-ground carbon content had to be estimated and removed. Furthermore, the NPP (in units of carbon) was converted to above-ground biomass (in units of dry weight) by applying a conversion factor (Eq. 8).

$$B = \frac{NPP \cdot \lambda}{(1 + R)} \quad (8)$$

R represents the ratio of the increment of below- to above-ground biomass, while λ is a conversion factor from NPP to total biomass. Species-specific values for R were taken from Pistorius and Zell (2005). Since the GLC2000 gives no information about tree species distribution, a mean value of R for each of the two temperate forest classes modelled by BETHY/DLR (coniferous and deciduous) was calculated (deciduous: 0.19 ± 0.08 , coniferous: 0.23 ± 0.04). To check the numbers upon which these calculations were based, the corresponding allocation factors for above-ground biomass were also calculated using the same dataset (deciduous: 0.81, coniferous: 0.84); these values agree closely with previously reported values (Zhou et al., 2006), supporting our estimated values for R . The value for λ was set to 2, which is seen as representative for both deciduous and coniferous trees (Houghton et al., 1997).

After these calculations and conversions, the above-ground biomass derived from the BETHY/DLR model output was compared to the above-ground biomass calculated from NFI statistics in order to validate BETHY/DLR's estimates of NPP.

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6 Results and discussion

Figure 3 depicts annual modelled NPP for Germany in 2000 and 2001 at this study's spatial resolution of 1 km^2 . For both years the major forests of southern Germany (the Spessart, the Palatinate, and the Black Forests) are clearly identifiable from their high NPP values, whereas the northern forested areas, such as the Harz mountains, have substantially lower NPP. The mean annual NPP for 2000 was $139 \text{ [tC km}^{-2} \text{ yr}^{-1}]$ with a maximum of $547 \text{ [tC km}^{-2} \text{ yr}^{-1}]$; for 2001 the mean annual NPP was $137 \text{ [tC km}^{-2} \text{ yr}^{-1}]$ with a maximum of $544 \text{ [tC km}^{-2} \text{ yr}^{-1}]$. Total annual modelled NPP was thus $21.6 \times 10^6 \text{ tC}$ for 2000 and $21.3 \times 10^6 \text{ tC}$ for 2001.

Conversion of these NPP values to above-ground biomass as described above gives annual totals of $52.3 \times 10^6 \text{ t}$ for 2000 and $51.8 \times 10^6 \text{ t}$ for 2001. The value estimated from NFI's data is $82.7 \times 10^6 \text{ t}$ (for both of 2000 and 2001). Our modelled NPP thus shows an underestimation of 37% for both years compared to empirical data. Furthermore, large areas with very low NPP can be identified, especially at the borders of larger forests such as the Black Forest of southwestern Germany. This is because these areas are considered to be forest according to GLC-2000, but MODIS VCF indicates very low forest cover fractions (down to one part per thousand). Such areas of conflicting land cover information are shown as blue pixels in Fig. 3.

To compare results for coniferous and deciduous trees separately, linear regressions of estimated above-ground biomass from modelled NPP against the empirical data from the NFI are presented in Fig. 4.

Figure 4 shows that BETHY/DLR underestimates the net increment of above-ground biomass for both deciduous and coniferous trees. The R^2 values of 0.74 and 0.76 for deciduous trees indicate a high degree of correlation, however. The correlation for coniferous trees is even stronger, with R^2 values of 0.95 and 0.93, but the underestimation is also higher here. In order to quantify the predictive accuracy of BETHY/DLR's NPP estimates, the root mean square error (RMSE) was calculated for all four plots; for coniferous trees the RMSE is 1.87 (2000) and 1.93 (2001), and for deciduous trees, 1.53 (2000) and 1.48 (2001).

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the NFI database, the forest areas of GLC2000, and the forest areas for the intersection of GLC2000 and MODIS VCF.

From Fig. 5B it is apparent that NFI and GLC2000 deciduous forest area estimates differ markedly; an underestimation of 66 % for Schleswig-Holstein (SW) and an overestimation of 106 % for Bavaria (BY) is observed, for example. For coniferous forest (Fig. 5A) the two area estimates are more comparable, with a mean difference of 20 %. These imbalances are reduced when looking at the total forest areas for deciduous and coniferous trees across all of Germany; total coniferous forest area estimates are 42 400 km² (NFI) and 47 100 km² (GLC2000), and for the deciduous forest, 60 800 km² (NFI) and 61 100 km² (GLC2000). It can also be seen in Fig. 5A and B that the GLC2000 underestimates forest areas for the northern states of Germany such as Schleswig-Holstein (SH) and Lower Saxony (NI), whereas it overestimates the forest areas for southern states such as Bavaria (BY) and Baden-Württemberg (BW).

In aggregate, then, GLC2000 represents forest area well, but its spatial distribution is not comparable with the NFI data. We hypothesize that the medium-scale forest structure found in most parts of Germany is not adequately described by the GLC2000, due to the difficulty of accurately classifying a heterogeneous land cover distribution even with a resolution of 1 km² (Mayaux et al., 2006).

According to the Land Cover Classification System (DiGregorio and Jansen, 2001) used in deriving GLC2000, the GLC2000 class “Broadleaved Deciduous Closed to Open (100–40) % Trees” includes all forest areas with a forest fraction from 40 % to 100 %, a very wide range. In order to describe the forest cover fraction more precisely, the MODIS VCF product was combined with the GLC2000 to produce the area estimates used as inputs by BETHY/DLR. Figure 5A and B show the coniferous and deciduous forest areas that result from this combination of MODIS VCF and GLC2000. Clearly this approach led to underestimations of the forest area in Germany, both for coniferous (47 %) and deciduous (59 %) forest. This underestimation occurs because only areas reported as forested in the GLC2000 were carried forward to be combined with the MODIS VCF coverage data; areas designated as non-forest

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in GLC2000, but with a non-zero forest cover fraction in VCF, were neglected. As a result, those forest areas which were underestimated by GLC2000, such as Lower Saxony or Schleswig-Holstein, led to substantial underestimations of the increment of above-ground biomass.

5 Other land cover datasets with higher resolution, such as CORINE (100 m × 100 m) and MERIS GlobCover (300 m × 300 m), are available for Germany, and their land use structures show a better agreement with the NFI data. Since BETHY/DLR requires land cover and LAI inputs to be at the same spatial resolution, and since no higher-resolution LAI products are available yet for Germany, these finer-grained land cover
10 datasets unfortunately could not be used. Exploratory analysis shows, however, that the combination of GlobCover and VCF leads to an underestimation of forest area of 24 %, while the combination of CORINE and VCF yields an underestimation of only 7 %. This agrees with the findings of EEA (2006), which estimated the reliability of the CORINE classes 311 (coniferous forest) and 312 (deciduous forest) at better than
15 85 %. We conclude, therefore, that while area-wide land cover products at high resolution are needed and useful, high-resolution datasets for plant physiology parameters such as LAI must also keep pace if these products are to be of maximal utility.

Finally, it should be taken into account that NFI statistics can only produce mean values for the mean annual increment; these values were estimated from the difference
20 between the first NFI survey, in 1987, and the second, in 2003. Until NFI conducts a third survey year, the effects of climatic variability cannot be captured by the NFI statistics.

7 Estimation of energy potentials

A further objective of this study is to derive energy potentials both from modelled NPP
25 and from NFI data. The energy potential of forests is of considerable importance to the sustainable energy discussion and the development of sustainable energy policy.

To estimate theoretical energy potentials, species-specific lower heating values (H) can be used to convert from absolute dry above-ground biomass. Heating values

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represent the maximum energy obtainable from the combustion of biogenic solid fuels, and are given in megajoules per kilogram. Since the GLC2000 gives no information about tree species, but does differentiate between deciduous and coniferous trees, mean heating values representative of each tree class were used. For this study, heating values for deciduous and coniferous trees were calculated for each NUTS-1 unit (Table 5), taking into account the relative abundance and age distribution of tree species in each region. Heating values for the main deciduous (oak and beech) and coniferous (pine and spruce) tree species can be found in many sources; see, for example, Kaltschmidt and Hartmann (2009) and Grammel (1989). We assume sustainable management of forest biomass; following this assumption, only the mean annual net increment of forest biomass is used to calculate theoretical energy potential.

Since B (above-ground biomass; see Eq. 8) is determined for absolute dry conditions, we calculated the energy potential (J) as shown in Eq. (10).

$$J = B \times H \quad (9)$$

Using this equation, theoretical energy potentials for 2000 and 2001 were estimated from the above-ground biomass previously calculated from modelled NPP (Fig. 6). Although the validation previously conducted had demonstrated a systematic underestimation of NPP, no correction was applied here to compensate for this, since such correction would have resulted in an incorrect spatial distribution of estimated energy potentials.

Comparison with Fig. 3 shows that those forest areas having the highest NPP values also have the highest theoretical energy potentials. This is also true, *mutatis mutandis*, for low NPP and energy potential, and is valid for both 2000 and 2001. Analysis revealed that the mean theoretical available energy potential for coniferous forest is $17.5 \text{ [TJ km}^{-2} \text{ yr}^{-1}]$ for 2000 and 2001, while for deciduous forest these values are $25.0 \text{ [TJ km}^{-2} \text{ yr}^{-1}]$ (2000) and $24.6 \text{ [TJ km}^{-2} \text{ yr}^{-1}]$ (2001). Maximum values of $25.7 \text{ [TJ km}^{-2} \text{ yr}^{-1}]$ (coniferous forest) and $25.4 \text{ [TJ km}^{-2} \text{ yr}^{-1}]$ (deciduous forest) were found.

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The NFI data were also used to estimate empirical energy potentials, using Eq. (10) for all thirteen NUTS-1 units in Germany (Table 5). These estimates of energy potential are partitioned into the two main tree classes.

Since it was shown previously that underestimation existed both for the areas of forests (as derived from remote sensing) and for modelled NPP, it is unsurprising that the empirical energy potential estimated from NFI data is 37 % higher than the theoretical estimate from modelled NPP.

8 Conclusions

For this study we modelled the Net Primary Productivity (NPP) of German forests for 2000 and 2001 using the dynamic biomass model BETHY/DLR. We presented a new method for the validation of modelled NPP using empirical data related to the mean annual increment in outer bark volume. Modelled NPP was converted and aggregated to a net increment of above-ground biomass per NUTS-1 unit for comparison to these empirical data. With this method we showed a high degree of correlation between modelled and empirical NPP, although the modelled NPP underestimated the empirical NPP. A comparison with data from two eddy covariance flux towers revealed that BETHY/DLR represents annual productivity patterns well (particularly for coniferous forest) but with substantial underestimation.

In a second step, the sustainable theoretical energy potential of the above-ground biomass was estimated, using heating values to convert estimated above-ground biomass to energy units. For comparison, energy potentials were also calculated from empirical data, which revealed that modelled energy potentials are underestimated by 37 %, a consequence of the prior underestimation of modelled NPP.

Reasons for this pattern of underestimation were discussed; in particular, it was shown that GLC2000 does not represent the spatial distribution of forest areas well due to its limited resolution. We thus argue that 1 km² resolution is insufficient to describe the heterogeneous small-scale structure of mid-European forests. For future

modelling, the use of higher-resolution land cover products might allow more accurate NPP estimation; this should be tested in future research. To facilitate the use of such products, however, there is a need for matching high-resolution datasets for vegetation metrics such as LAI.

5 Modelled NEP, NPP and GPP are typically validated using eddy flux tower measurements, but such measurements are not available in many areas. Our presented validation method could therefore be helpful in the assessment of model outputs both at a broader spatial scale, and in less developed countries. Our method will, additionally, allow the development of a downscaling procedure for empirically derived NUTS-level data, allowing NUTS data to be partitioned into smaller spatial units. Our MAI-based validation method should, however, be tested in additional countries, and should be
10 comprehensively compared to validation using eddy measurements, so that the benefits and drawbacks of each method are clearly understood.

This new MAI-based validation method will be useful in validating modelled NPP; as
15 we demonstrated here, that also allows the further estimation of other metrics, such as bioenergy potentials. Such estimates of forest energy potentials play an important role in planning for a sustainable economy. More broadly, accurate and precise model results, crosschecked against empirical data, are needed for a better understanding of optimal forest management and the future possibilities of renewable energy.

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Table 1. Translation of GLC2000 vegetation classes to BETHY/DLR vegetation types with weighting factors.

GLC2000 class	BETHY/DLR type	Weighting factor
Tree cover, broadleaved, deciduous closed (glc-2)	Temperate broadleaved deciduous trees	MODIS VCF
Tree cover, broadleaved, deciduous open (glc-3)	Temperate broadleaved deciduous trees	MODIS VCF
Tree cover, needle-leaved, evergreen (glc-4)	Evergreen coniferous trees	MODIS VCF
Tree cover, mixed leaf type (glc-6)	Temperate broadleaved deciduous trees	0.5
	Evergreen coniferous trees	0.5

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Table 2. Summary of meteorological input data from ECMWF, including short names and code numbers.

Parameter	ECMWF short name	ECMWF code number
Volumetric soil water layer 1	SWVL1/(SWL1)	039
Volumetric soil water layer 2	SWVL2/(SWL2)	040
Volumetric soil water layer 3	SWVL3/(SWL3)	041
Volumetric soil water layer 4	SWVL4/(SWL4)	042
Geopotential	Z	129
Large scale precipitation	LSP	142
Convective precipitation	CP	143
10 m U-velocity	10U	165
10 m V-velocity	10V	166
2 m temperature	2T	167
Low cloud cover	LCC	186
Medium cloud cover	MCC	187
High cloud cover	HCC	188

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Table 4. Per-species percentage of timber stock biomass (without bark) to total above-ground biomass (P) from Kramer and Krüger (1981), max ε from Dieter and Englert (2001), and min ε from Kaltschmidt and Hartmann (2009). / = no value.

<i>Species</i>	ε [$\text{t} \times \text{m}^{-3}$]		P per age calss									
	min	max	<i>I</i>	<i>II</i>	<i>III</i>	<i>IV</i>	<i>V</i>	<i>VI</i>	<i>VII</i>	<i>VIII</i>	<i>IX</i>	<i>X</i>
Spruce	0.38	0.43	0	0.48	0.25	0.17	0.17	0.13	0.12	0.13	/	/
Pine	0.43	0.49	0	0.33	0.25	0.19	0.19	0.18	0.15	0.16	/	/
Beech	0.56	0.66	0	0.00	0.49	0.32	0.19	0.16	0.14	0.13	0.15	/
Oak	0.58	0.64	0	0.56	0.21	0.19	0.12	0.11	0.12	0.11	0.08	0.08

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Table 5. Total forest areas, estimated increment of above-ground biomass from NFI data, heating values, and empirical energy potentials of woody biomass for Germany's NUTS-1 regions, partitioned into deciduous and coniferous tree classes.

NUTS-1 region	Overall forest area [ha]	Tree Type	AGB increment [tons yr ⁻¹]	Heating Value [MJ kg ⁻¹]	Empirical energy potential [PJ yr ⁻¹]
Hesse	813 092	deciduous	3 384 016	18.4	62.3
		coniferous	3 037 591	19.3	58.7
			6 421 607	18.8	121.0
Schleswig-Holstein	154 602	deciduous	876 626	18.4	16.1
		coniferous	571 957	19.5	11.1
			1 448 583	18.8	27.3
Lower Saxony, Hamburg & Bremen	1 081 248	deciduous	4 091 784	18.4	75.3
		coniferous	4 966 180	19.9	98.9
			9 057 965	19.2	174.2
North Rhine-Westphalia	835 763	deciduous	3 700 153	18.4	68.1
		coniferous	3 733 869	19.1	71.3
			7 434 021	18.7	139.4
Rhineland-Palatinate	794 432	deciduous	3 527 763	18.4	64.9
		coniferous	2 972 838	19.3	57.5
			6 500 601	18.8	122.4
Baden-Wuerttemberg	1 281 409	deciduous	4 869 976	18.4	89.6
		coniferous	6 564 707	19.2	125.8
			11 434 683	18.8	215.4
Bavaria	2 386 027	deciduous	7 253 796	18.4	133.5
		coniferous	13 642 971	19.3	263.2
			20 896 766	19.0	396.6
Saarland	92 131	deciduous	674 469	18.4	12.4
		coniferous	318 401	19.2	6.1
			992 871	18.7	18.5
Brandenburg & Berlin	973 017	deciduous	1 519 005	18.4	27.9
		coniferous	4 058 284	20.9	84.7
			5 577 289	20.2	112.6
Mecklenburg-Western Pomerania	492 673	deciduous	1 787 216	18.4	32.9
		coniferous	1 817 119	20.3	36.9
			3 604 336	19.4	69.8
Saxony	471 290	deciduous	1 090 393	18.4	20.1
		coniferous	2 057 192	19.7	40.5
			3 147 585	19.2	60.5
Saxony-Anhalt	454 640	deciduous	1 241 898	18.4	22.9
		coniferous	1 737 999	20.4	35.4
			2 979 897	19.5	58.2
Thuringia	490 276	deciduous	1 356 655	18.4	25.0
		coniferous	1 864 346	19.4	36.1
			3 221 001	19.0	61.1
<i>Germany</i>	10 320 601		82 717 205	19.1	1579.9
<i>Uncertainty</i>				± 1.25	± 103.5

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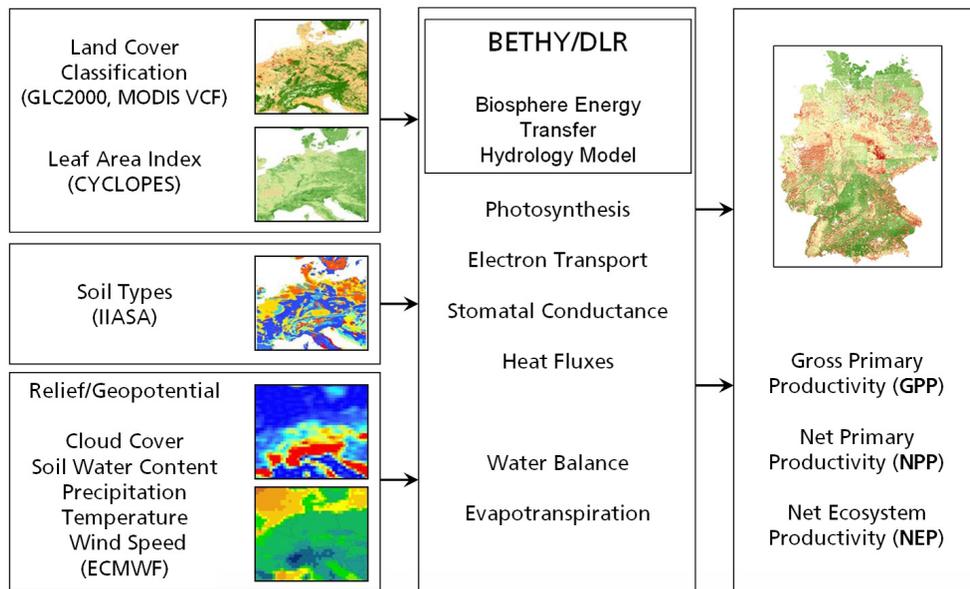


Fig. 1. Model overview for BETHY/DLR. Left: input data, middle: internal model processes, right: outputs.

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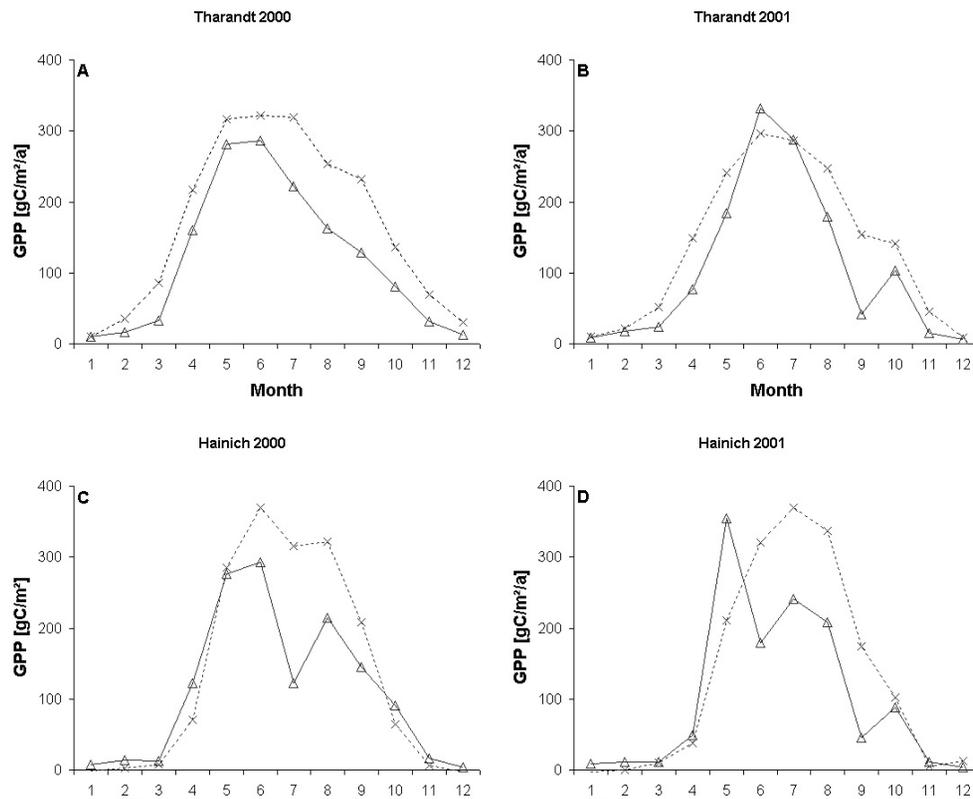


Fig. 2. Monthly GPP sums modelled with BETHY/DLR (solid lines) and measured with eddy flux towers (dashed lines) for the Tharandt and Hainich stations for 2000 and 2001.

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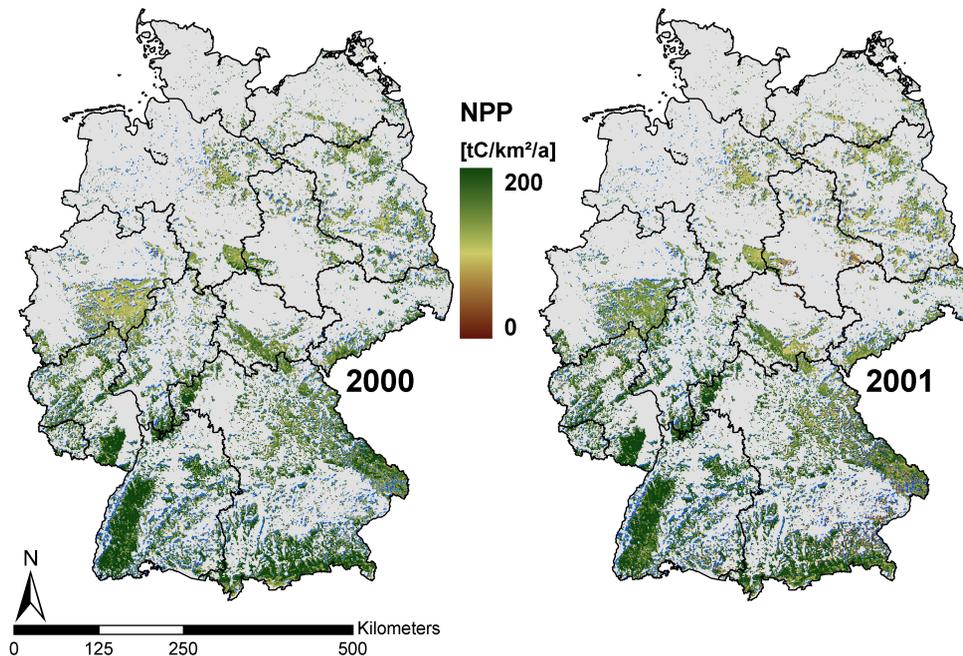


Fig. 3. Annual NPP of forest areas in Germany for 2000 and 2001. High NPP is shown in green, moderate NPP in yellow, and low NPP in red. Grey pixels represent areas which do not belong to the GLC2000 classes glc-2, glc-3, glc-4 or glc-6 (see also Table 1). Blue pixels represent pixels designated as forest in GLC2000, but that have less than 10% forest cover according to VCF; their modelled NPP is therefore close to zero despite being considered forest.

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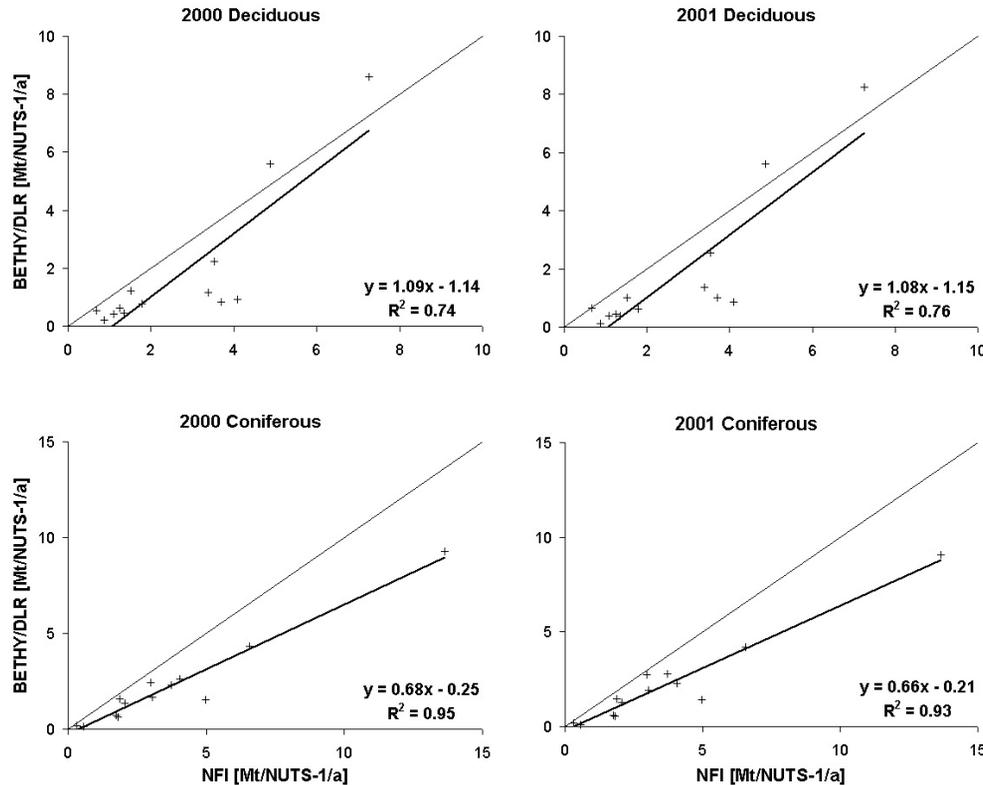


Fig. 4. Estimated above-ground biomass from modelled NPP versus empirical data from the NFI for Germany's deciduous and coniferous trees for 2000 and 2001. Each cross represents one NUTS-1 region. Thick lines show linear regressions. Values are given in megatons per NUTS-1 unit per year.

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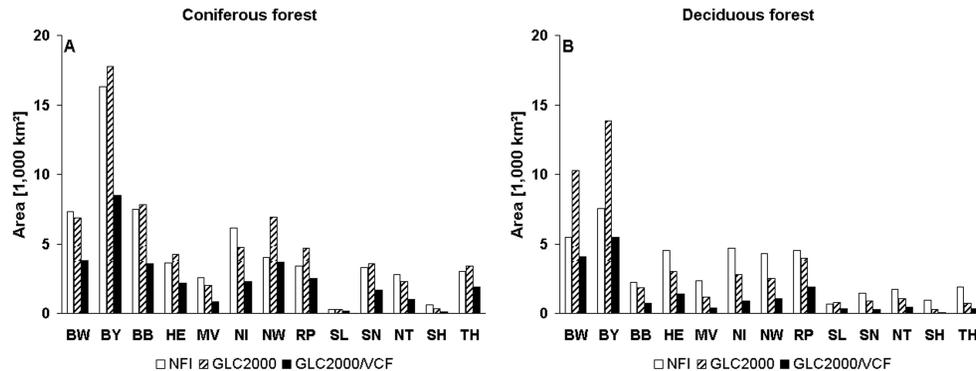


Fig. 5. Comparison of coniferous and deciduous forest areas from NFI, from GLC2000, and from the intersection of GLC2000 and VCF areas. Areas are given in 1000 km² per NUTS-1 unit. BW: Baden Wuerttemberg, BY: Bavaria, BB: Berlin/Brandenburg, HE: Hesse, MV: Mecklenburg-Western Pomerania, NI: Lower Saxony/Hamburg/Bremen, NW: North Rhine-Westphalia, RP: Rhineland-Palatinate, SL: Saarland, SN: Saxony, NT: Saxony-Anhalt, SH: Schleswig-Holstein, TH: Thuringia.

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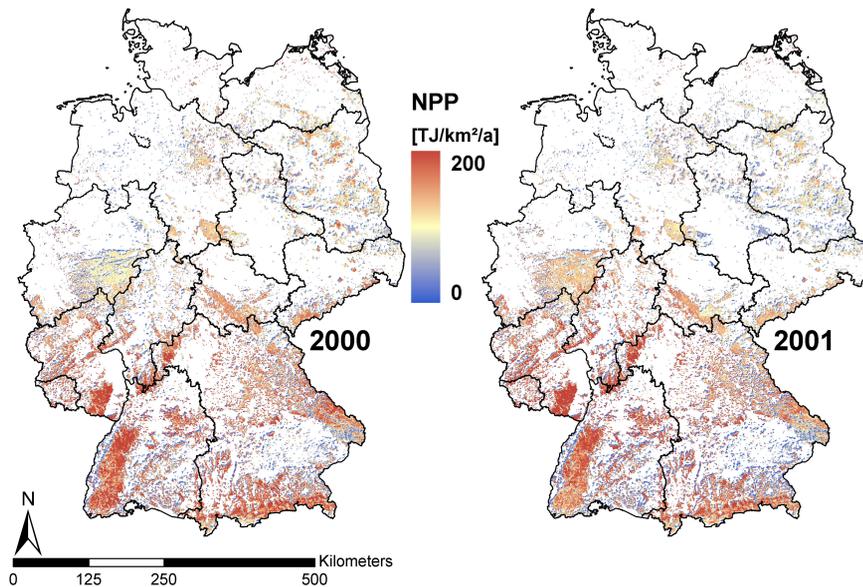


Fig. 6. Sustainable theoretically available energy potential, in terajoules per 1 km^2 pixel, of forest areas in Germany for 2000 and 2001. Low energy potentials are shown in blue, intermediate potentials in beige, and high energy potentials in red. White represents, as in Fig. 3, areas which are not designated as forested by GLC2000 (see Table 1).

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