Supplementary Materials: Creating a Regional MODIS Satellite-Driven Net Primary Production Dataset for European Forests

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This supplement provides additional information on the 12 forest inventory datasets (Table S1), it documents the methodology for estimating carbon increment (Equations (S1)–(S4)) and carbon stocks using forest inventory data (Equation (S5)) as well how auxiliary information were derived using forest inventory data (Tables S2 and S3 and Equations (S6)–(S10)). We also provide as Supplementary Results additional images to complement the publication (Figures S1–S10).

1. Supplementary Methods and Analysis

Forest inventory data from 12 European countries is used (Table S1), which have varying sampling technique as well as inventory design [1]. 8 countries use Fixed Area plots (Belgium, Czech Republic, France, Italy, Norway, Poland, Romania, Spain), 3 countries Angle Count Sampling plots or Bitterlich sampling (Austria, Germany and Finland) and 1 country a stand-wise survey system or taxation (Estonia).

The plot area for the Fixed area plot ranges between 12.6 and 1963.5 m^2 and the basal area factor for the angle count sampling between 1.5 and 4. 6 countries have their plots arranged in clusters with 2–18 plots per cluster, while 5 countries have single plots. The grid distance between the clusters/single plots range from 0.5 to 11 km. Due to the different spacing, the area covered by the inventory system and the relative forest cover the number of plots on forest vary from 2495 (Belgium) to 69853 (Spain).

Most inventory systems employ a minimum diameter threshold (usually 5 or 7 cm). The inventory data thus covers only trees bigger than the threshold. Only Estonia and Finland assess all trees that reach breast height of 1.3 m (DBH threshold of 0 cm).

Our data cover the following 4 methods to estimate tree carbon increment $CARB_{INC}$: (1) repeated observations of fixed area plots (FPM) and (2) repeated angle count sampling (ACM); (3) increment cores (COR); and increment predictions from (4) tree growth models (MOD). Tree growth model predictions were used if no increment observations, neither from repeated observations nor from increment cores, were available.

6 countries provided repeated observations from two consecutive inventory measurements using a permanent plot design (Table S1) and we were able to estimate two subsequent tree carbon stocks for each inventory plot. After accounting for mortality and harvesting, the difference between the carbon stock estimates divided by the inventory measurement interval is the tree carbon increment [2].

3 countries with repeated observation (Belgium, Norway, and Poland) have fixed area plots so we used the Fixed area Plot Method (FPM). The remaining countries (Austria, Finland, and Germany) use angle count sampling [3] and we used the Angle Count Method (ACM) [4].

For countries without repeated observations, we applied the CORe method for France, Romania and the region Sicily in Italy, since diameter increment rates from increment cores were available [5], or employed empirical forest growth models (MOD) to estimate increment rates [6] for countries without increment cores (Estonia, Czech Republic, Spain and the regions Trento and Piemonte in Italy).

Table S1. Summary of the properties of the different forest inventory datasets, Sampling system ACS (Angle Count Sampling), FAP (Fixed Area Plots), k (Basal area factor) only for countries with ACS and Plot area only for FAP, Plot layout (single plots or cluster of plots), Grid distance between clusters/plots, Min. DBH is diameter threshold for sample trees (inventory covers only trees bigger than threshold), availability of repeated observations, time period covered (period 2 only for countries with repeated observations).

Country	Number of Plots	Sampling System	k ($m^2 \cdot ha^{-1}$)	Plot Area (m^2)	Plot Layout	Grid Distance (km)	Min.DBH (cm)	Repeated Observations?	Increment Method	Period 1	Period 2	Reference
Austria	9562	ACS (FAP)	4	21.2	clusters of 4 plots	3.889 × 3.889	5	yes	ACM	2000–2002	2007–2009	[7]
Belgium	2495	FAP	-	3 circles: 63.6, 254.5 and 1017.9	single plots	1 × 0.5	7	yes	FPM	1996–1999	2009–2013	[8]
Czech Republic	13929	FAP	-	2 circles: 28.3 and 500	clusters of 2 plots	2 × 2	7	no	MOD	2001–2004	–	[9]
Estonia	19930	Taxation	-	-	-	-	0	no	MOD	2000–2010	–	[10]
Finland	6442	ACS	2 (south) 1.5 (north)	-	clusters of 14 to 18 plots	6–8 (south) 6–11 (north)	0	yes	ACM	1996–2003	2004–2008	Tomppo and Tuomainen in [1]
France	33152	FAP	-	3 circles: 113, 255 and 706	single plots	2 × 2	7.48	no	COR	2006–2011	–	Nikolas et al. in [1]
Germany	6153	ACS	4	-	clusters of 4 plots	4 × 4 (2000–2002) 8 × 8 (2008)	7	yes	ACM	2000–2002	2008	[11]
Italy (Sicily)	1270	FAP	-	2 circles: 12.6 and 132.7	single plots	0.5 × 0.5	4.5	no	COR	2009	–	[12]
Italy (Trento)	150	FAP	-	1 circle: 600	single plots	1 × 1	2.5	no	MOD	2003	–	[13]
Italy (Piemonte)	13750	FAP	-	1 circle: 50.3–176.7	single plots	0.5 × 0.5	7.5	no	MOD	2002	–	[14]
Norway	9200	FAP	-	250	single plots	3 × 3	5	yes	FPM	2000–2004	2005–2009	Tomter et al. in [1]
Poland	17281	FAP	-	200, 400 or 500	cluster of 5 plots	4 × 4	7	yes	FPM	2005–2008	2010–2013	[15,16]
Romania	5509	FAP	-	2 circles: 200 and 500	cluster of 4 plots	4 × 4 (mountains) 2 × 2 (lowlands)	5.6	no	COR	2008–2012	–	Marin et al. in [1]
Spain	60033	FAP	-	4 circles: 78.5, 314.2, 706.9 and 1963.5	single plots	1 × 1	7.5	no	MOD	2000–2008	–	Alberdi et al. in [1]

2. Fixed Area Plot Method (FPM)

Three countries (Belgium, Norway, Poland) have fixed area plots and repeated observations and the fixed area plot method is used [4].

Carbon increment using the fixed area plot method is derived according to Equation (S1).

$$CARB_{INC} = (C_2 - C_1 + C_{mort} + C_{harv})/time \quad (S1)$$

$CARB_{INC}$ is carbon increment of trees (gC·m^{-2}·year^{-1}), C_1 and C_2 are the sum of carbon estimates at time 1 and 2 (Table S1), C_{mort} is the sum of carbon of trees that died between the two inventory measurements and C_{harv} the carbon of trees that were harvested and removed between the measurements. time is the duration of the period between the two inventory measurements [years]. The carbon estimates C_i (gC·m^{-2}) are estimated using the tree carbon estimation methods.

3. Angle Count Sampling Method (ACM)

Three countries (Austria, Finland and Germany) have angle count sample plots and repeated observations. Deriving increment using inventory data collected with the angle count sampling technique can be done with three methods: the difference method, the starting value method or the end value method. All methods deliver unbiased results, with starting value method and end value method having the lowest error [4]. We selected the same increment calculation method then the local forest inventory organizations. The general equation is given in Equation (S2).

$$CARB_{INC} = inc_{survivors} + inc_{ingrowth} \quad (S2)$$

$inc_{survivors}$ is carbon of survivor trees (present at both inventory measurements) and $inc_{ingrowth}$ is increment of ingrowth trees (present only at the second measurement) all in (gC·m^{-2}·year^{-1}). For Austria the starting value method is used [17]. Finland we use the starting value method as well. Since the NFI in Finland do not have a diameter threshold for selecting sample trees (Table S1), estimating $inc_{ingrowth}$ is not necessary. In Germany the end value method is used [4]. The required information of previous dimension of sample trees is obtained using DBH- and age-dependent growth functions [18].

4. Core Method (COR)

For France, Romania and the Italian region of Sicily the core method is used [6,19]. For this method in principle, diameter increment from increment cores [5] are used to determine the tree dimensions in the past. From diameter increment the volume increment of single trees is derived. Multiplying with an expansion factor and adding the single tree results per plot provide carbon increment (Equations (S3) and (S4)).

$$CARB_{INC} = \sum VOL_{INC} * EF \quad (S3)$$

$$EF = CARB_{TREE}/VOL \quad (S4)$$

With VOL_{INC} volume increment (m^3·ha^{-1}·year^{-1}), EF Expansion factor for deriving carbon (gC·m^{-3}), $CARB_{TREE}$ total tree carbon [gC] and VOL tree volume (m^3) (see following section).

Due to differences in the available data the method differs by country. For Sicily VOL_{INC} is already provided by the Regional forest inventory of Sicily and we only have to multiply with expansion factor EF to derive carbon increment (Equation (S3)).

For France and Romania historic diameter was reconstructed using increment cores. By applying the carbon calculation methods (see following section) using the current and historic dimensions of trees we are able to calculate two estimates of carbon stock. Carbon increment is derived as the difference of the two carbon stock estimates (analogous to Equation (S1)).

5. Increment Models (MOD)

For Czech Republic, Estonia, Spain and the Italian provinces Trento and Piemonte we employ empirical increment models.

In Spain volume increment on tree level is already provided in the database of the Spanish NFI (http://www.magrama.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/ifn3.aspx). It is estimated using species-, DBH- and height-dependent regression models. Carbon increment is derived using expansion factors, similar as in Equations (S3) and (S4).

In Czech Republic the development of diameter and height is calculated using Korf functions [20] fitted using NFI data. Stem number development is estimated using Reineke's rule [21]. These stand variables are estimated for year 2010 and allow estimating carbon stocks for this year. The Carbon increment is calculated as the difference of the two carbon stock estimates.

In Estonia volume increment on stand level is derived with empirical models dependent on stand age, tree species, bonity (site index) and density [10]. Carbon increment is estimated according to Equation (S3) using expansion factor derived from carbon calculation methods (see following section).

In Italy (Trento and Piemonte) we estimate increment on stand level with an empirical model that is dependent on species, growing stock and mean height [22]. Again by applying Equation (S3) and expansion factors *EF* derived from carbon calculation methods we obtain carbon increment.

6. Tree Carbon Estimation

Carbon estimates are needed for the carbon increment estimates and are derived using the country-specific calculation method employed by the local forest inventory organization and documented in a comprehensive volume [23]. In Czech Republic, we use a similar but slightly different method, since the method used by the local forest inventory organization is not reproducible and not available in published form.

Tree carbon is the sum of the biomass in the compartments stem, branches, foliage and coarse roots multiplied with the carbon fraction factor (Equation (S5)).

$$CARB_{TREE} = (BM_{STEM} + BM_{BRANCH} + BM_{FOLIAGE} + BM_{ROOT}) * CF \quad \text{(S5)}$$

$CARB_{TREE}$ is total carbon of a tree [kg], BM_{STEM} biomass of stem, all biomass compartments in (kg), BM_{BRANCH} biomass of branches, $BM_{FOLIAGE}$ biomass of foliage, BM_{ROOT} biomass of roots, CF the carbon fraction to convert biomass into carbon (kg/kg). The biomass calculation methods and carbon fraction CF for 5 important European tree species (*Fagus sylvatica*, *Quercus robur*/*Q. petraea*, *Betula* sp., *Picea abies* and *Pinus sylvestris*) are described in detail in [23]. For all other species a separate carbon calculation method is used or the method from another similar species is applied according to the methodology of the local forest inventory organizations.

Volume required in Equation (S4) is estimated using local volume functions.

7. Stand Variables

Using the forest inventory data several stand variables at plot level are derived to describe the stand characteristics for Table 1 and for Figures S6–S10: Basal area, Stem number, Mean diameter, Mean height, Stand density index, Dominant species and Mean Age.

Basal area is the sum of basal area of all trees on a sample plot

$$BA = \sum(DBH^2/40{,}000\ \pi\ nrep) \quad \text{(S6)}$$

With BA basal area per hectare ($m^2 \cdot ha^{-1}$), DBH diameter at breast height [cm], nrep the represented stem number by a given tree [/], for Fixed Area plots calculated according Equation (S6), for Angle count sample plots according Equation (S7).

$$nrep = 10{,}000/Aplot \quad \text{(S7)}$$

$$nrep = 4\ k/(DBH^2\ \pi) \quad \text{(S8)}$$

With DBH [m], k basal area factor of an angle count sample ($m^2 \cdot ha^{-1}$), Aplot the size of a sample plot (m^2) (see Table S1) and nrep is the represented stem number of a single tree (ha^{-1}).

Stem number NHA is the sum of nrep for all trees on a plot per hectare.

Mean quadratic diameter DG is derived using basal area and stem number and represents the mean diameter weighted by the basal area of each single tree.

$$DG = (4\ BA/NHA/\pi)^{0.5} \quad \text{(S9)}$$

Stand density index [21] is a measure of stand density and competition.

$$SDI = NHA\ (DG/25)^{1.605} \quad \text{(S10)}$$

Dominant species is the tree species that contributes most to the plots basal area. For the sake of clarity and comparability we aggregate the original tree species provided by the NFI into 7 tree species groups (TSG) according to their leaf shedding and growth behaviour. TSG 1 to 3 cover coniferous species and TSG 4 to 7 broadleaf species (Table S2).

Table S2. Tree species groups (TSG) used in this study, description and selected tree species.

TSG	Description	Selected Species Included Therein
1	Light demanding conifers	*Pinus sylvestris, P. nigra, P. cembra, P. radiata, Larix* sp.
2	Shade tolerant conifers	*Picea* sp., *Pseudotsuga* sp., *Abies* sp.
3	Mediterranean conifers	*Cupressus* sp., *Pinus pinea, Pinus* sp. not included in TSG 1
4	Fast growing deciduous	*Betula* sp., *Populus* sp., *Alnus* sp., *Salix* sp., *Robinia* sp., *Eucalyptus* sp.
5	Light demanding, slow growing deciduous	*Quercus robur, Q. petreae, Fraxinus* sp., *Castanea* sp.
6	Shade tolerant, slow growing deciduous	*Fagus* sp., *Tilia* sp., *Ulmus* sp., *Acer* sp., *Carpinus* sp.
7	Evergreen broadleaf	*Olea europea* or *Quercus* sp. not included in TSG 6

Some forest inventories provide tree age estimates on stand level, while others give age estimates for single trees. Either age classes (e.g., 21–40 years) or discrete values (e.g., 34 years) are given. To harmonize the age estimates, we use 8 consistent age classes (0–20 years, 21–40, 41–60, ... 121–140, >140). If a forest inventory dataset provided age estimates for single trees, we calculated the mean age and then classified the plots according to the 8 age classes.

8. Supplementary Results and Analysis

We provide here additional images not presented in the paper.

Figure S1 provide a direct pixel-to-plot comparison of MODIS EURO and NFI NPP for each inventory plot along with statistics analogue to Figure 4 showing the country median NPP.

Figures S2–S5 show for the four regions (North Europe. Central-West Europe, Central-East Europe and South Europe) the effect of Elevation, Latitude and Longitude on the NPP discrepancy ΔNPP between MODIS EURO and NFI NPP.

Figures S6–S9 show NPP discrepancy ΔNPP for both MODIS NPP sources, MODIS GLOB using global climate data [24] and MODIS EURO using local European climate data [25] for tree age, tree height, MODIS Land cover type and Dominant species.

Figure S10 show the effect of Stand density Index (SDI) [21] on MODIS EURO and on NFI NPP separately. This image suggests that the pattern in Figure 6 is mainly due to NFI NPP, which is more affected by SDI than MODIS EURO.

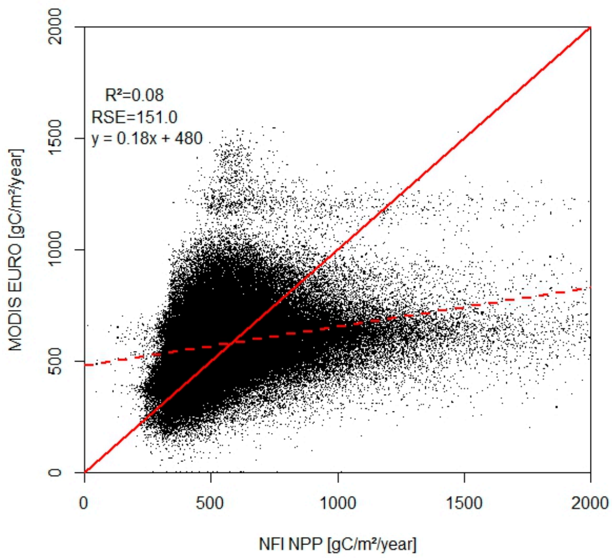

Figure S1. Direct pixel-to-plot comparison of MODIS EURO using European climate data and NFI NPP, solid line is 1:1 line, dashed line represents the linear trend of the 12 countries, Coefficient of determination R^2, Residual standard error (RSE) and the trend function are given.

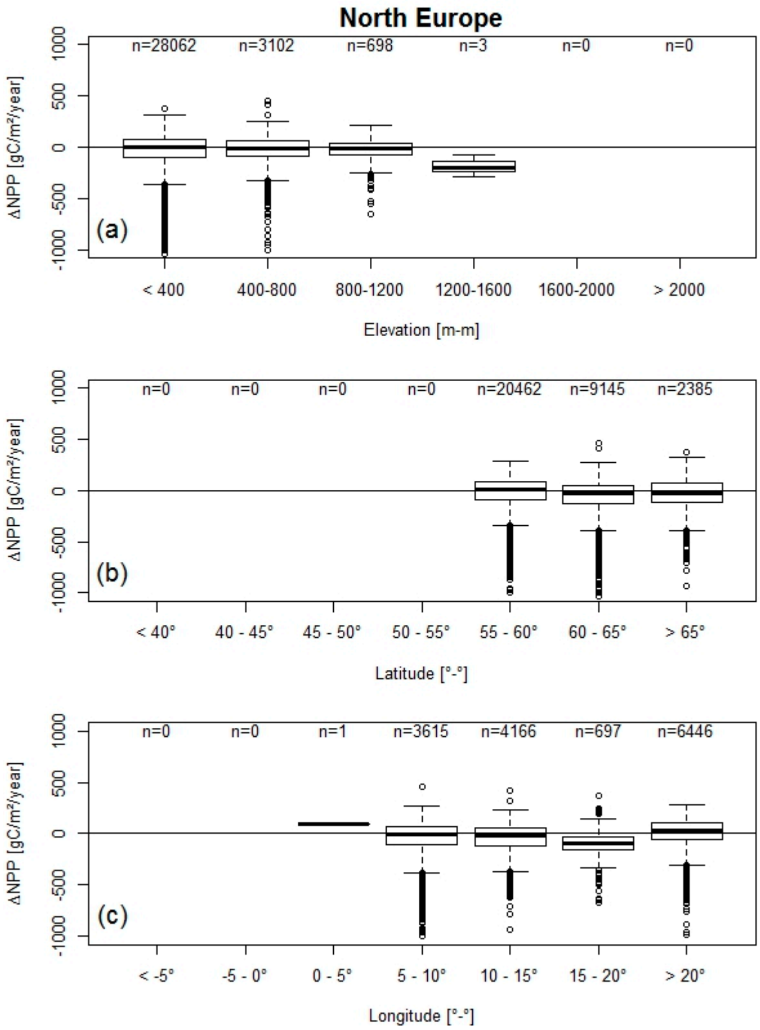

Figure S2. NPP Difference (ΔNPP) MODIS EURO minus NFI NPP for North Europe by Elevation classes (**a**), by Latitude (**b**) and by Longitude (**c**), the box represent the Median and the 25th and 75th percentile, the whiskers extent to 1.5 of the interquartile range, values outside this range are indicated by dots, on the top the number of values represented by the boxplots are given.

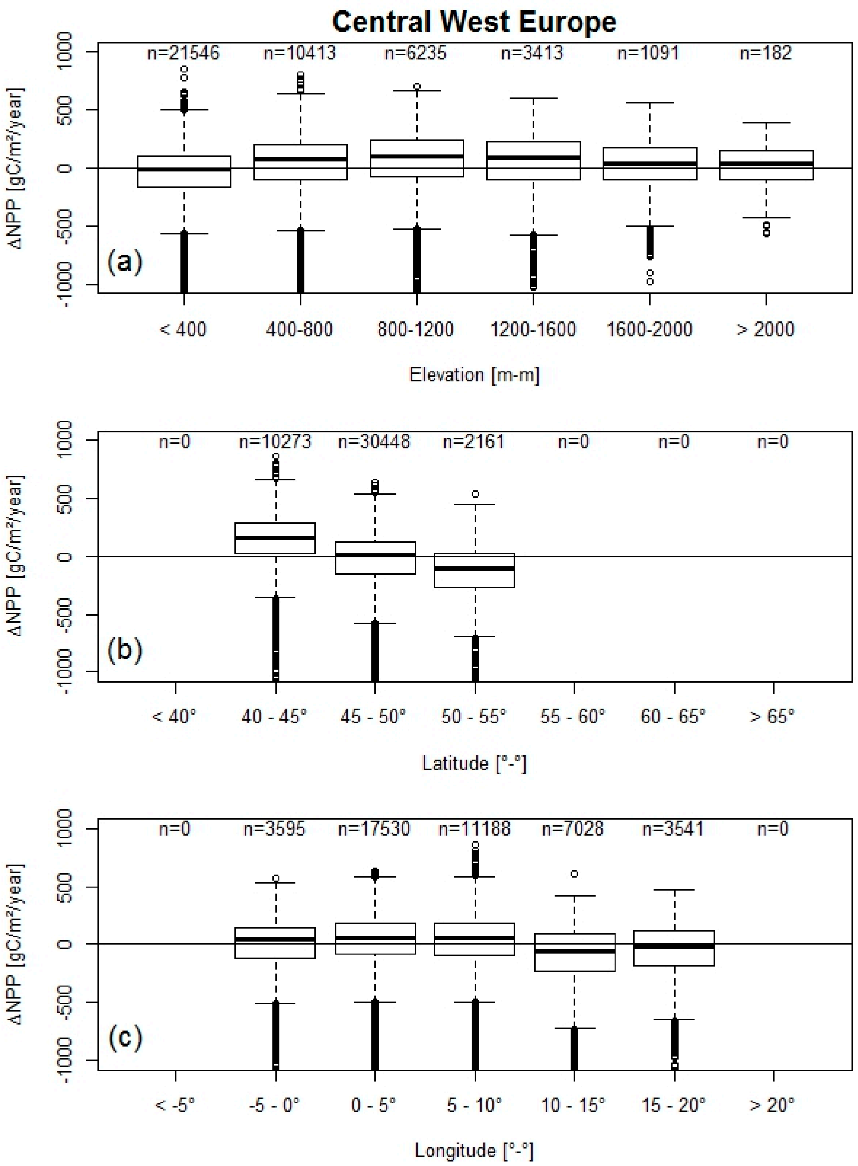

Figure S3. NPP Difference (ΔNPP) MODIS EURO minus NFI NPP for Central-West Europe by Elevation classes (**a**); by Latitude (**b**) and by Longitude (**c**), Properties of illustration analogous to Figure S2.

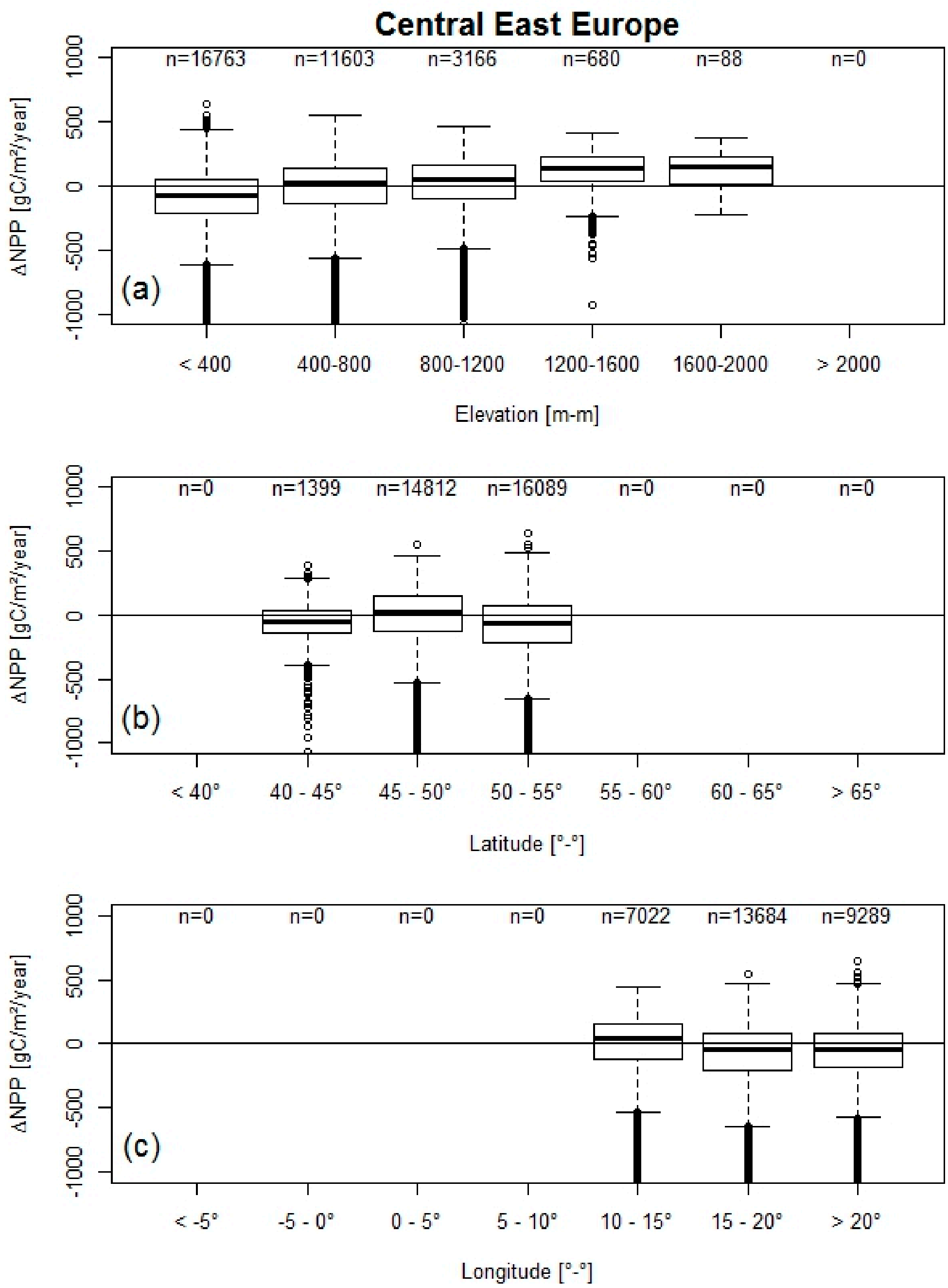

Figure S4. NPP Difference (ΔNPP) MODIS EURO minus NFI NPP for Central-East Europe by Elevation classes (**a**); by Latitude (**b**) and by Longitude (**c**), Properties of illustration analogous to Figure S2.

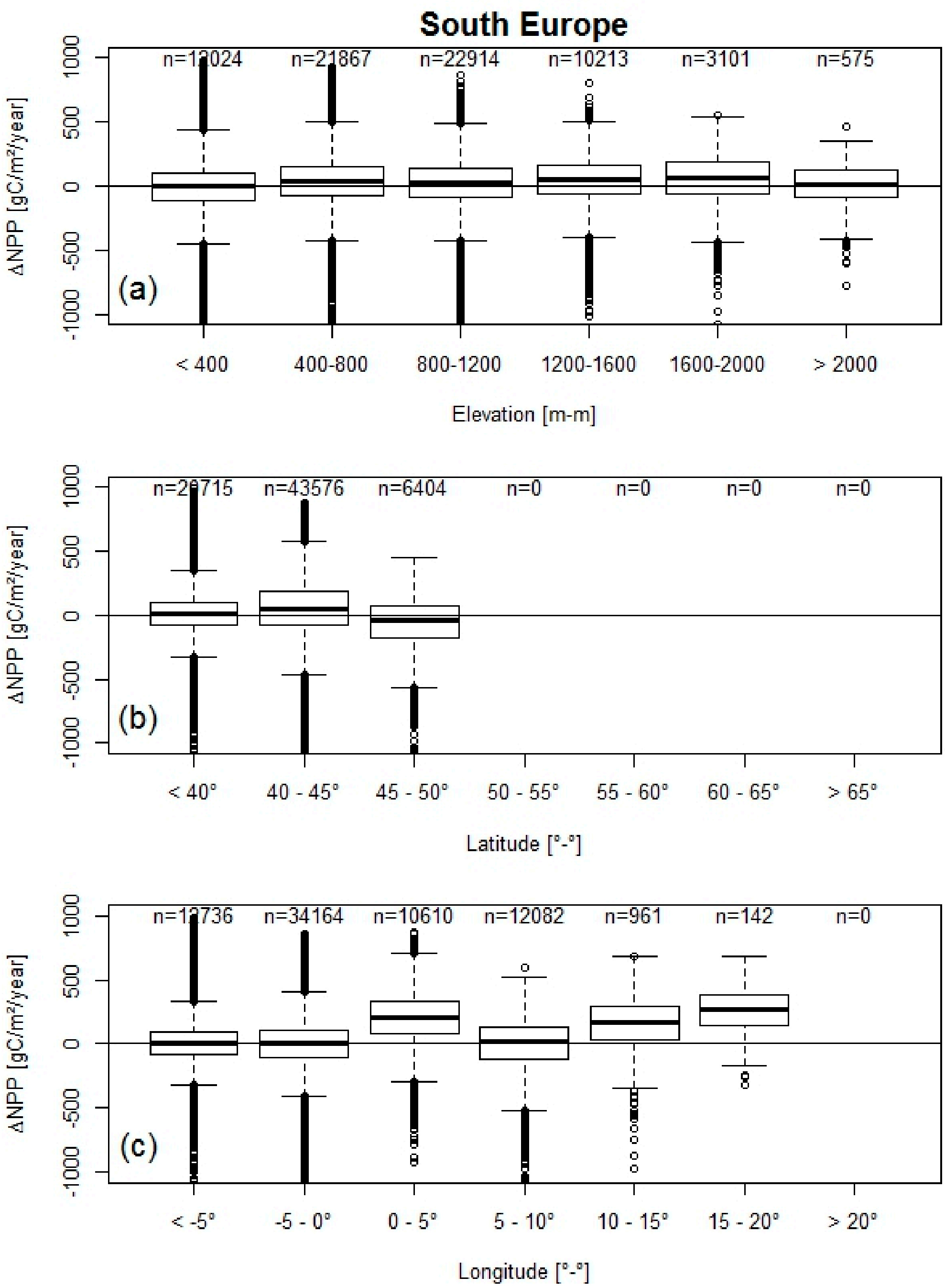

Figure S5. NPP Difference (ΔNPP) MODIS EURO minus NFI NPP for South Europe by Elevation classes (**a**); by Latitude (**b**) and by Longitude (**c**), Properties of illustration analogous to Figure S2.

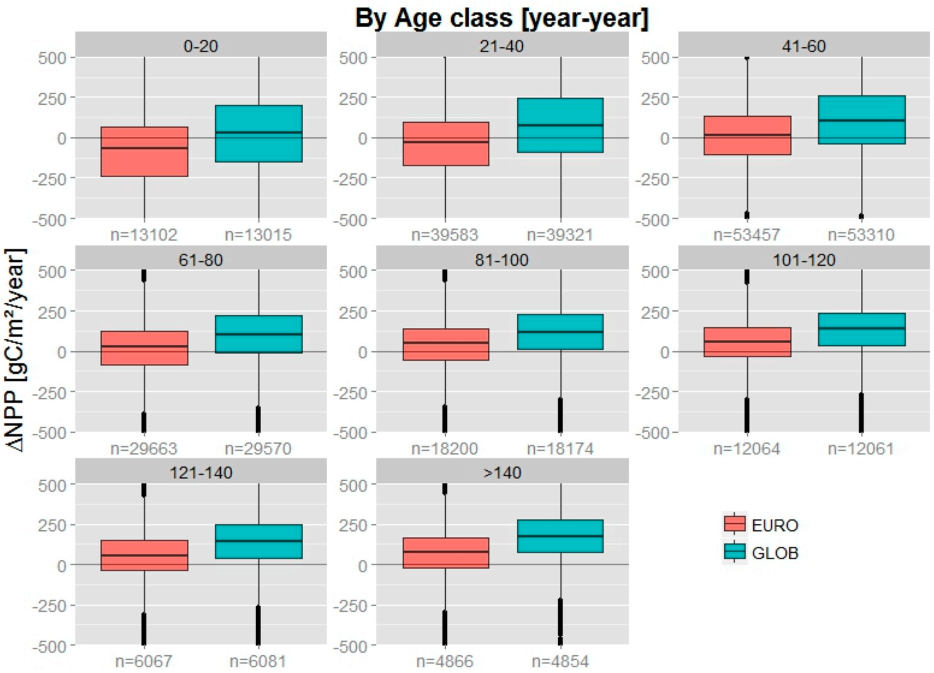

Figure S6. Difference ΔNPP for MODIS EURO minus NFI NPP (red boxes at left side) versus MODIS GLOB minus NFI NPP (blue boxes at right side) grouped by Age classes. Properties of illustration analogous to Figure S2. Under the plots the number of represented samples are given.

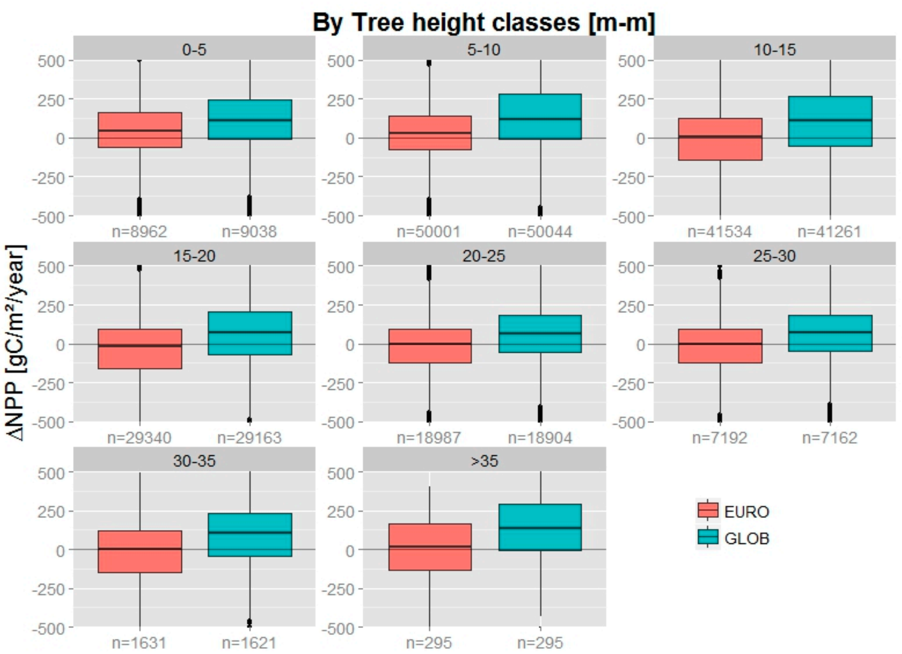

Figure S7. Difference ΔNPP for MODIS EURO minus NFI NPP (red boxes at left side) versus MODIS GLOB minus NFI NPP (blue boxes at right side) grouped by Tree height classes. Properties of illustration analogous to Figure S1.

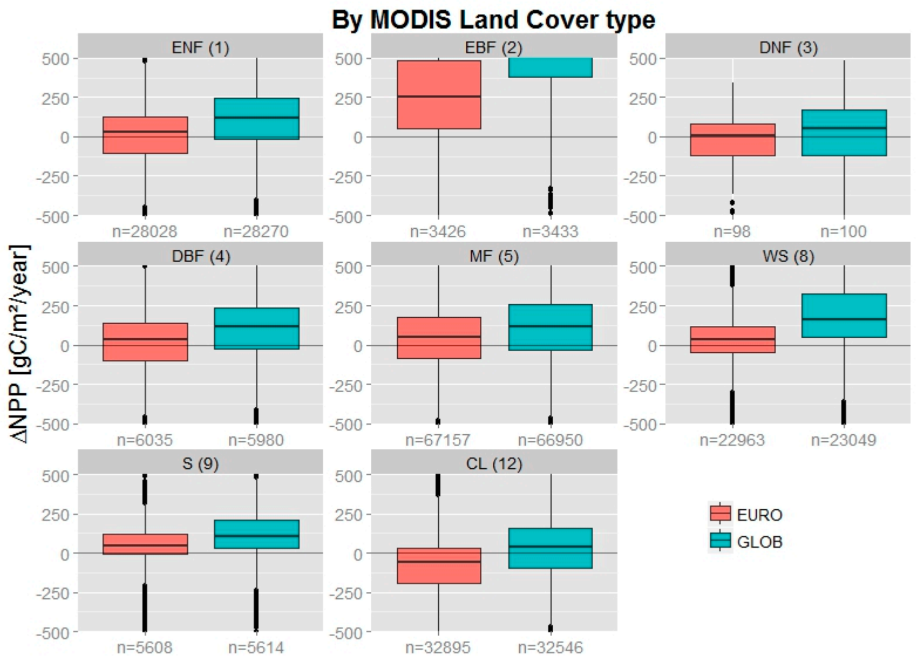

Figure S8. Difference ΔNPP for MODIS EURO minus NFI NPP (red boxes at left side) versus MODIS GLOB minus NFI NPP (blue boxes at right side) by MODIS Land cover types: we show 5 forest land cover classes (ENF evergreen needleleaf forest, EBF evergreen broadleaf forest, DNF deciduous needleleaf forest, DBF deciduous broadleaf forest, MF mixed forest) 2 classes that contain more than 10% Forest (WS woody savannahs, S Savannahs) and CL Cropland, since it is q very frequent land cover type due to Europe's forest fragmentation (in brackets the original MODIS Landcovertype code used for the in biome-property-lookup tables (BPLUTs) [26]). Properties of illustration analogous to Figure S1.

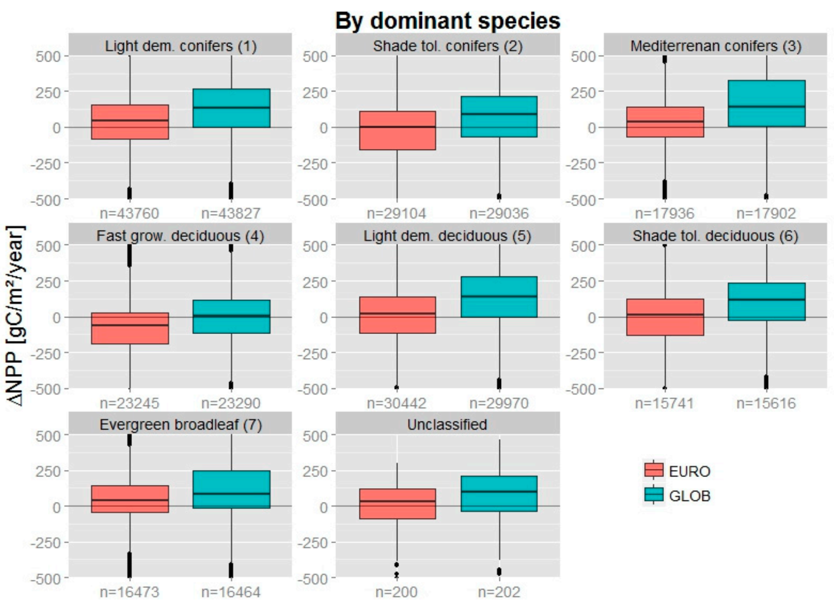

Figure S9. Difference ΔNPP for MODIS EURO minus NFI NPP (red boxes at left side) versus MODIS GLOB minus NFI NPP (blue boxes at right side) by dominant tree species, the first row show the coniferous tree species groups 1–3 (light demanding conifers, shade tolerant conifers and Mediterranean conifers) followed by the broadleaf TSGs 4–7 (Fast growing deciduous, Shade tolerant slow growing deciduous, Light demanding slow growing deciduous and evergreen broadleaf trees). Properties of illustration analogous to Figure S1.

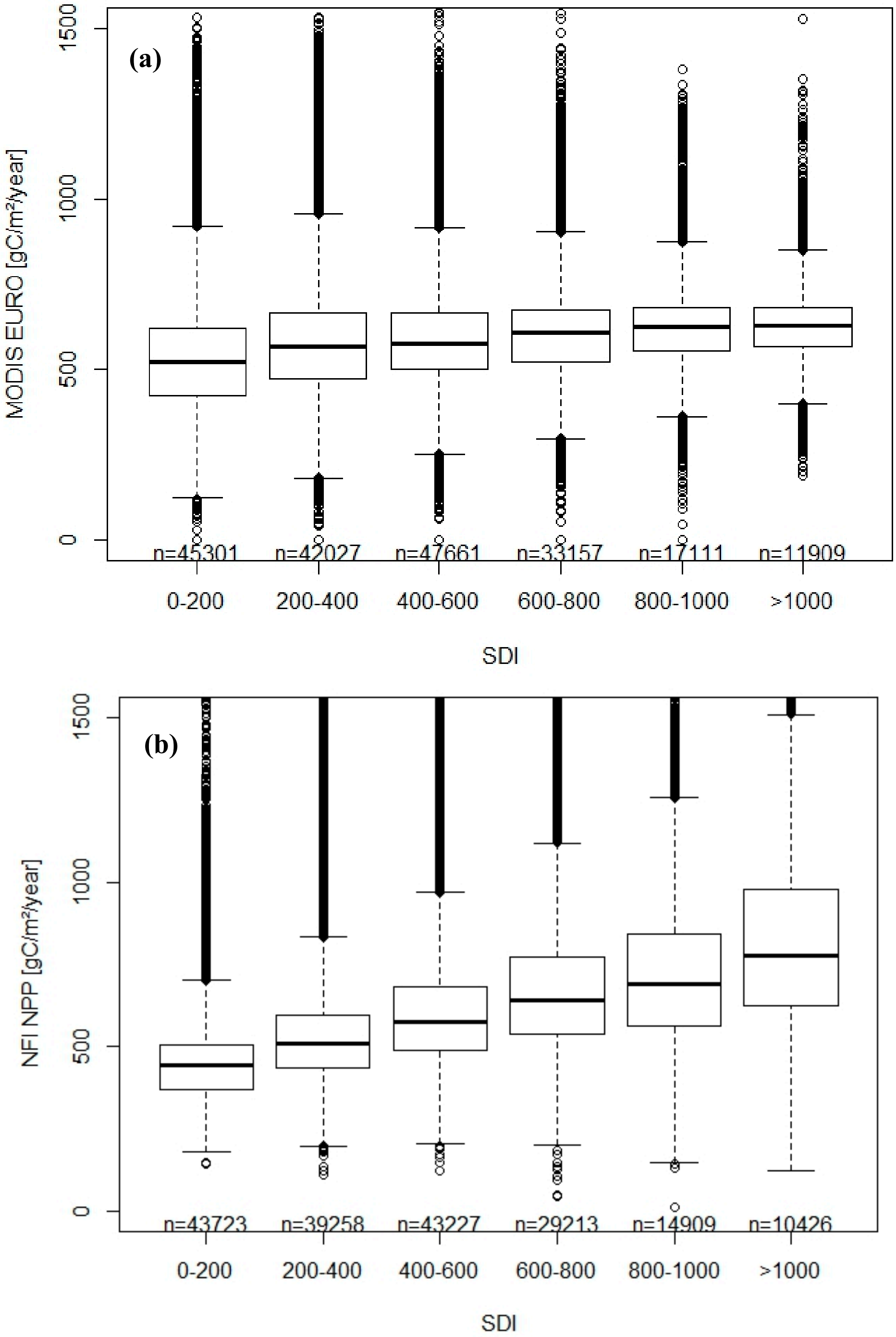

Figure S10. NPP estimates by Stand density Index: MODIS EURO (**a**) and NFI NPP (**b**) (SDI) classes [21]. Properties analogous to Figure S2.

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