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# A Global Forest Growing Stock, Biomass and Carbon Map Based on FAO Statistics

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Currently, information on forest biomass is available from a mixture of sources, including in-situ measurements, national forest inventories, administrative-level statistics, model outputs and regional satellite products. These data tend to be regional or national, based on different methodologies and not easily accessible. One of the few maps available is the Global Forest Resources Assessment (FRA) produced by the Food and Agriculture Organization of the United Nations (FAO 2005) which contains aggregated country-level information about the growing stock, biomass and carbon stock in forests for 229 countries and territories. This paper presents a technique to downscale the aggregated results of the FRA2005 from the country level to a half degree global spatial dataset containing forest growing stock; above/below-ground biomass, dead wood and total forest biomass; and above-ground, below-ground, dead wood, litter and soil carbon. In all cases, the number of countries providing data is incomplete. For those countries with missing data, values were estimated using regression equations based on a downscaling model. The downscaling method is derived using a relationship between net primary productivity (NPP) and biomass and the relationship between human impact and biomass assuming a decrease in biomass with an increased level of human activity. The results, presented here, represent one of the first attempts to produce a consistent global spatial database at half degree resolution containing forest growing stock, biomass and carbon stock values. All results from the methodology described in this paper are available online at www.iiasa.ac.at/Research/FOR/.

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# 1 Introduction

Biomass (the quantity of living plant material) is most abundant in forests. Tropical forests account for 50% of Earth's total plant biomass, although they occur on only 13% of the ice-free land area; other forests contribute an additional 30% of global biomass (Chapin et al. 2002). Knowing the spatial distribution of forest biomass is important for many reasons, including: calculating the sources and sinks of carbon that result from converting a forest to cleared land (and vice versa); and to enable measurement of change through time (Houghton 2005). With respect to the Kyoto Protocol and potential follow up protocols not only information on the spatial distribution of forests is essential, but also its associated biomass. For example, forest biomass may be altered without a change in forest area. Many factors act to alter forest biomass, including selective wood harvest, forest fragmentation, ground fires, shifting cultivation, browsing, grazing and accumulations of biomass in growing and recovering (or secondary) forests (Houghton 2005).

Currently, information on forest biomass is available only from a mixture of sources, including in-situ measurements, national forest inventories, administrative-level statistics, model outputs and biomass distribution derived from regional satellite products. These data tend to be regional or national, based on different methodologies and they are not easily accessible. Although proposals have been made for the use of satellites to address the lack of data (Hese et al. 2005), there are currently few global spatial forest biomass products available for the earth science community. The scarcity of those maps reflects the diffculty to derive such maps. On a regional level attempts to use satellite data for the extrapolation of ground measurements have been made (Laporte 2006).

The currently available maps on global biomass distribution are either relatively old and are only available in the form of a general ecosystems map (Olson et al. 2001) or they are outputs of current global dynamic vegetation models which are still under development with respect to carbon allocation and will need to be improved (Kucharik et al. 2006). Moreover, these maps tend to reflect the long term potential, but do not reflect the current status of human induced activities (Hu et al. 1996). Even though these models are not calibrated in terms of biomass itself, these models are already in use to derive these highly important figures on global biomass emissions (Hoelzemann et al. 2004).

Another map which provides average biomass values per country is the database of the Global Forest Resources Assessment (FRA) produced by the Food and Agriculture Organization of the United Nations (FAO 2005). This dataset contains aggregated country-level information about the growing stock, biomass and carbon stock in forests for 229 countries and territories. However, for use in spatially explicit analysis and modeling, this information is required at a finer level of detail than country level. In addition, many of the countries had diffculties in providing data, creating gaps which prevent global analysis.

The growing stock in yield tables is usually determined by age, stocking degree, yield level and species (Assmann 1970). Shvidenko et al. (2007) are using NPP to describe the yield level. The stocking degree and the rotation period are influenced by human activity. There is a relationship between NPP and biomass and additionally a relationship between biomass and human impact (Keeling and Phillips 2007). By using this relationship a simple but plausible downscaling model is developed. Such an approach is feasible since both NPP as well as human impact are available at least on a half degree resolution.

The technique described here illustrates one plausible way of downscaling the aggregated results of the FRA2005 from the country level to a half degree global spatial dataset containing forest growing stock; above-ground, below-ground, dead wood and total forest biomass; and aboveground, below-ground, dead wood, litter and soil carbon.

**Table 1.** Used datasets.

| Dataset | Values | C/G | Source |
|---|---|---|---|
| Growing stock | $m^3$/ha | C | FAO (2005) |
| Biomass stock | Mt | C | FAO (2005) |
| Carbon stock | MtC | C | FAO (2005) |
| Forest area | ha | C | FAO (2005) |
| Country | Country Name | G | CIESIN (2005b) |
| NPP | 3 to 1373 gC/$m^2$/year | G | Cramer et al. (1999) |
| Human influence | 0–100% | G | CIESIN (2002) |
| Land area | 0–3091 square km | G | CIESIN (2005a) |
| Forest share | 0–100% | G | JRC (2003) |

C/G = Information given for country (C) or for grid points (G)

# 2 Material and Methods

## 2.1 Used Datasets

A variety of datasets were used in this approach and are listed in Table 1 and described below. The FRA2005 provides global tables containing values on growing stock, biomass and carbon. Growing stock is available in $m^3$/ha, while biomass stock and carbon stock are in Mt per country. Biomass is given as fractions of above-ground, below-ground, dead-wood and total biomass. Carbon is given as above-ground carbon, below-ground carbon, carbon in dead wood, carbon in litter and soil carbon. The biomass stock and carbon stock were recalculated into values per hectare by dividing the given value by the forest area also given in the FRA2005.

In all cases, the number of countries providing data in the FRA2005 is incomplete, although the majority of forest area is found in relatively few countries. The last column of Table 4 shows the number of countries with available values for that parameter. In particular, the carbon pools in litter and soil were reported by less than 50 countries. Of the 151 countries that reported forest biomass: 87 have used the IPCC good practice guidance biomass expansion factors exclusively; 41 have used the IPCC factors in combination with factors from other sources; 13 have used national data – either direct estimates or national expansion factors; 5 have used factors/models from FAO and FAO/UNECE publications; and 5 are based on expert estimates FAO (2005). In the FRA tables, values of above ground biomass can be found for 146 countries. In the calculations only 145 values have been used as one country was too small to represent at least one half-degree grid.

The NPP data set contains modeled annual net primary production (NPP) for the land biosphere from seventeen different global models (Cramer et al. 1999). This data set was created in the mid-1990s with 17 models available at that time. It uses data from Remote Sensing Based Models, Models of Seasonal Biogeochemical Fluxes and Models of Process and Pattern (Function and Structure).

The human influence map was taken from CIESIN (2002). Nine global data layers were used to create this global “human footprint” map. The layers describe human population pressure (population density/population settlements), human land use and infrastructure (built up areas, night-time lights, land use/land cover), and human access (coastlines, roads, railroads, navigable rivers).

The forest share of a country was taken from FAO (2005) and the forest share on a grid was taken from the global land-cover product GLC2000 (JRC 2003). Pure forest classes are assumed to be covered 100% by forest, the GLC2000 classifications “Mosaic: Tree Cover / Other natural vegetation” have 50% and “Mosaic: Crop-land / Tree Cover / Other natural vegetation” have 20% tree coverage. The tree coverage for the $0.5 \times 0.5$ degree grid was calculated by summing up the tree cover of the given $1 \times 1$ square kilometer grid of GLC2000 on the area of $0.5 \times 0.5$ degree grid and dividing it by the total grid area.

According to the FRA2005, the total global forest area equates to 39 520 250 $km^2$. In comparison, using the satellite derived GLC2000 (all classes with tree cover excluding burnt area), we calculated a total global forest area of 39 794 530 km$^2$. The global difference is below 1% and the probability that there is no difference between them, done with a country-wise pairwise t-test, is 94% (see Table 4).

The difference between the forest cover given in the FRA2005 for each country and a half degree aggregated map produced from the GLC2000 show some scatter (Fig. 1). This difference can occur for several reasons. One reason is, that different forest definitions and threshold values (e.g. canopy coverage %) are applied. Another reason is that the grid size of 0.5°×0.5° does not adequately represent the country borders. This obviously has a greater impact on smaller countries.

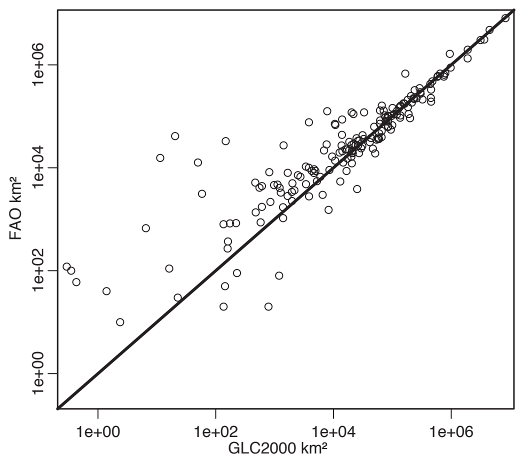


**Fig. 1.** Forest area of countries given in FAO (2005) and calculated from JRC (2003).

## 2.2 Methodology to Derive Above Ground Biomass

A number of studies have outlined that both biomass and NPP are related in the sense that both are dependent on water availability, temperature and the availability of nutrients (Koch et al. 2004, Richards and Brack 2004). This relationship was found to be either linear (Whittaker and Likens 1973) for the temperate zone or quadratic, as a recent study suggests that aboveground biomass plateaus in mid to high NPP levels (Keeling and Phillips, 2007). We have used a linear relationship between NPP values given in Cramer et al. (1999) and biomass. Furthermore, it has been suggested that biomass accumulation is clearly influenced by human activity (Keeling and Phillips 2007). By applying thinning and clear cut management, the growing stock of a managed forest is lower than the growing stock of pristine forests. E.g. unmanaged spruce forests in central Europe have an age of more than 400 years when they reach senescence. Managed forests are harvested with an age around 100 years. During the ages from 100 to 400 years, spruce forests have a high growing stock which will lead to higher average values in unmanaged forests. On the other hand protecting forests against damage (e.g. fire, insects) will lead to higher amounts of biomass in managed forests.

Based on such findings we assume that if biomass is known on a country level, it can be downscaled based on the two factors NPP and human impact. Biomass as described here is therefore a function of NPP and human impact expressed as:

$$\text{Biomass} = c_0 \times \text{NPP} \times \text{Human} \qquad (1)$$

Where $c_0$ = a factor describing the slope between NPP, human influence (Human) and the estimated Biomass (A list of all abbreviations is given in Table 2). An increasing NPP will cause a linear increase of the biomass. An increasing human influence will cause a decrease of the biomass. We assume, that managed forests have half of the biomass than forests without human influence. So human influence values have to be scaled that 1 represents areas with 100% human activity and 2 represents areas with no human activity.

The biomass of a certain grid cell (Grid value$_i$) is calculated with the biomass given in FRA2005 for the country in which the grid is located (Country value$_j$) multiplied by the NPP (NPP$_i$) and the human influence (Human$_i$) of the grid and divided with the average product of NPP and human influence for grids located in this country. The average is calculated by summing up the product of NPP, human influence, grid area (A$_l$) and forest share (ForShare$_l$) for all grids from a country and dividing this by the sum of grid area multiplied with forest share.

Equation 2 was used for country ($j$) to modify the former constant country value per hectare, so that the average value per country is still the same but on grids with a higher NPP and a lower human activity the value will be higher than on grids with a low NPP and high human activity. This approach is used to calculate all variables (i. e. growing stock, litter, soil).

$$\text{Grid value}_i = \frac{\dfrac{\text{Country value}_i \cdot \text{NPP}_i \cdot \text{Human}_i}{\sum_{l \in L_j} \text{NPP}_l \cdot \text{Human}_l \cdot \text{A}_l \cdot \text{ForShare}_l}}{\sum_{l \in L_j} \text{A}_l \cdot \text{ForShare}_l} \quad (2)$$

**Table 2.** Symbols used in equations.

| | |
|---|---|
| A | Grid area ($km^2$) |
| Biomass | Forest biomass (t/ha) |
| Country value | Given value per country (e.g. tC/ha) |
| $c_x$ | Coefficients |
| ForShare | Forest share (1) |
| Grid value | Downscaled value (e.g. tC/ha) |
| Human | Human influence (1) |
| Index $i$ | Index for grid cells |
| Index $j$ | Index for countries |
| Index $l$ | Index for grid cells located in country j |
| $L_j$ | Array of grid cells located in country j |
| $m^3$ | Growing stock ($m^3$/ha) |
| NPP | Net primary productivity (gC/$m^3$/Year) |

## 2.3 Filling Missing Values

Since the FAO datasets are incomplete we estimate values for grids which contain forest but are in a country where the FRA2005 gives no value. This was performed with a linear regression shown in Eq. 3.

$$\text{Grid value}_i = c_1 + c_2 \times \text{NPP}_i \times \text{Human}_i + c_3 \times \text{NPP}_i + c_4 \times \text{Human}_i + c_5 \times \text{m}^3_i \quad (3)$$

The value of a certain grid (Grid value$_i$) is calculated with NPP×Human, NPP, human activity and growing stock ($m^3$) of grid $i$. As only 147 countries provided a growing stock value, using the growing stock ($m^3$) in Eq. 3 it is not possible to create a growing stock map. Therefore only the NPP and human influence values are used to calculate the growing stock. The parameterization of Eq. 3 was done with grid cells from countries where FRA2005 gives values for them. The number of used grids and coefficients can be found in Table 3. Afterwards Eq. 3 was used on grid cells containing forest but located in countries where FRA2005 gives no value.

Statistics have been performed using R (R Development Core Team 2005) and spatial analysis was performed using the GIS software GRASS (GRASS Development Team, 2006).

**Table 3.** Parameters to fill up grids with Eq. 3 where no country value is given.

| Value | $c_1$ | $c_2$ | $c_3$ | $c_4$ | $c_5$ | $r^2$ | sd | n |
|---|---|---|---|---|---|---|---|---|
| $m^3$ | 136 | 0.211 | –0.253 | –60.8 | – | 0.44 | ±44.2 $m^3$/ha | 57 652 |
| BmAbove | –43.1 | 0.0191 | 0.0431 | 17.8 | 0.679 | 0.76 | ±32.9 t/ha | 53 038 |
| BmBelow | –2.11 | 0.0220 | –0.0135 | – | 0.142 | 0.69 | ±9.9 t/ha | 52 998 |
| BmDead | –46.4 | –0.0336 | 0.0582 | 28.6 | 0.142 | 0.41 | ±9.0 t/ha | 48 311 |
| BmTotal | –92.6 | –0.0299 | 0.154 | 46.8 | 0.969 | 0.76 | ±44.1 t/ha | 48 479 |
| CAbove | –23.0 | 0.00598 | 0.0258 | 9.74 | 0.346 | 0.75 | ±16.9 tC/ha | 53 038 |
| CBelow | –1.17 | 0.0116 | –0.00679 | – | 0.0637 | 0.72 | ±4.6 tC/ha | 52 992 |
| CDead | –23.2 | –0.0172 | 0.0297 | 14.3 | 0.0703 | 0.41 | ±4.5 tC/ha | 48 278 |
| CLitter | 10.2 | –0.00978 | 0.0127 | –4.17 | 0.0560 | 0.29 | ±4.1 tC/ha | 30 130 |
| CSoil | 207 | 0.211 | –0.446 | –78.0 | 0.615 | 0.19 | ±57.0 tC/ha | 27 823 |

$c_x$ = Significant coefficients ($\alpha = 0.05$); $r^2$ = Correlation; sd = Standard deviation; n = Number of grids used for parameterization

# 3 Results

In Fig. 3 the steps taken from the input maps to the derived carbon map is shown. Fig. 3D shows the downscaled map of carbon/ha in forests, which is a result of using Eq. 2 with the datasets: country values of tC/ha (A) from FAO (2005), human footprint (B) from CIESIN (2002) and NPP (C) from Cramer et al. (1999). In some cases country borders are visible and some regions have no value. It can also be seen, that carbon decreases in regions where the NPP is low e.g. if you go north in Siberia the values will decrease. The influence of human activity can be observed e.g. in the region north India, Nepal and Bhutan where a black line, showing high values, is caused by low human influence and high NPP values.

Regions without a value are calculated using Eq. 3. This step can be seen from Fig. 3D to E. This procedure seems to function well as most of the borders between missing and given regions are not visible in Fig. 3E and the correlation coefficients shown in Table 3 are many times in the range of $r^2 = 0.7$.

For some users the map of biomass per hectare of forest (E) will suffice. Others may want to know the values per grid. To satisfy these needs the land area (F) and the forest share (G) of a grid were overlaid. These steps are shown in Fig. 3E–H. Fig. 3H shows the carbon in forests on a certain grid. On this map only a few country borders can be seen. E.g. the border between Malaysia and Indonesia can still be seen, the borders around Egypt disappear.

Growing stock, biomass (above-ground, below-ground, dead wood) and carbon (above-ground, below-ground, dead wood, litter) and soil carbon, provided in the FAO (2005) at the country level, have been downscaled to a spatially explicit global half degree grid using exactly the same approach.

Fig. 2 compares above ground forest carbon identified in the FRA2005 with the results of this paper. Differences are caused by different forest cover between the FRA2005 and GLC2000 and the coarse 0.5°×0.5° grid resolution. Pictures of the other carbon pools look quite similar to Fig. 2. Small countries tend to capture not enough grids to represent their area. This can be observed in Figs. 1 and 2 where FAO gives higher values for small countries. The reason for this is that countries need to occupy the majority of a grid to own the whole grid.

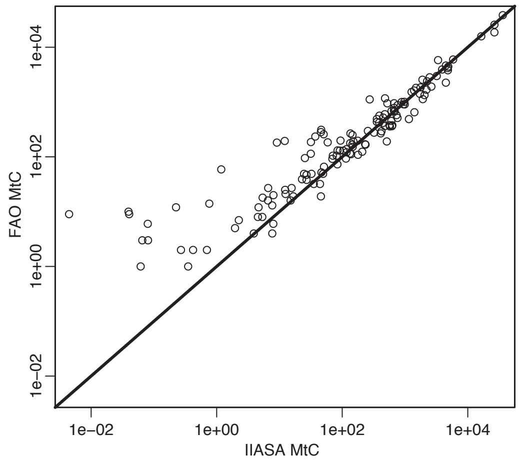


**Fig. 2.** Above ground carbon for countries given in FAO (2005) and calculated.

**Table 4.** Comparison of Model and FAO values.

| Value | Σ | | Δ | p | n |
|---|---|---|---|---|---|
| Forest Area | 39 794 530 | $km^2$ | 0.69% | 0.94 | 221 |
| $m^3$ | 465 992 | $Mm^3$ | 5.25% | 0.19 | 147 |
| BmAbove | 472 086 | Mt | 2.25% | 0.66 | 145 |
| BmBelow | 125 058 | Mt | –0.44% | 0.94 | 140 |
| BmDead | 82 823 | Mt | –0.79% | 0.86 | 104 |
| BmTotal | 676 911 | Mt | 1.65% | 0.75 | 110 |
| CAbove | 233 764 | MtC | 2.43% | 0.63 | 143 |
| CBelow | 61 959 | MtC | –0.19% | 0.97 | 138 |
| CDead | 41 000 | MtC | –0.47% | 0.91 | 102 |
| CLitter | 22 765 | MtC | 1.65% | 0.45 | 48 |
| CSoil | 397 870 | MtC | 1.79% | 0.51 | 43 |

Σ = Global sum from the IIASA model; Δ = Difference between IIASA model and FAO table 100 · (IIASA – FAO) / IIASA;
p = Probability that the difference between IIASA model and FAO is 0;
n = Number of compared countries

In Table 4 the results from the method described in this paper (total values) are presented, along with the difference compared to the values of the original FRA2005 tables. The total forest area is 39 800 000 $km^2$, which is 0.69% above the given values of 221 countries from FRA. The global growing stock is $466 \times 10^9$ $m^3$ which is 5.25% above the given values from 147 countries from FRA. The above ground biomass is $472 \times 10^9$ t,

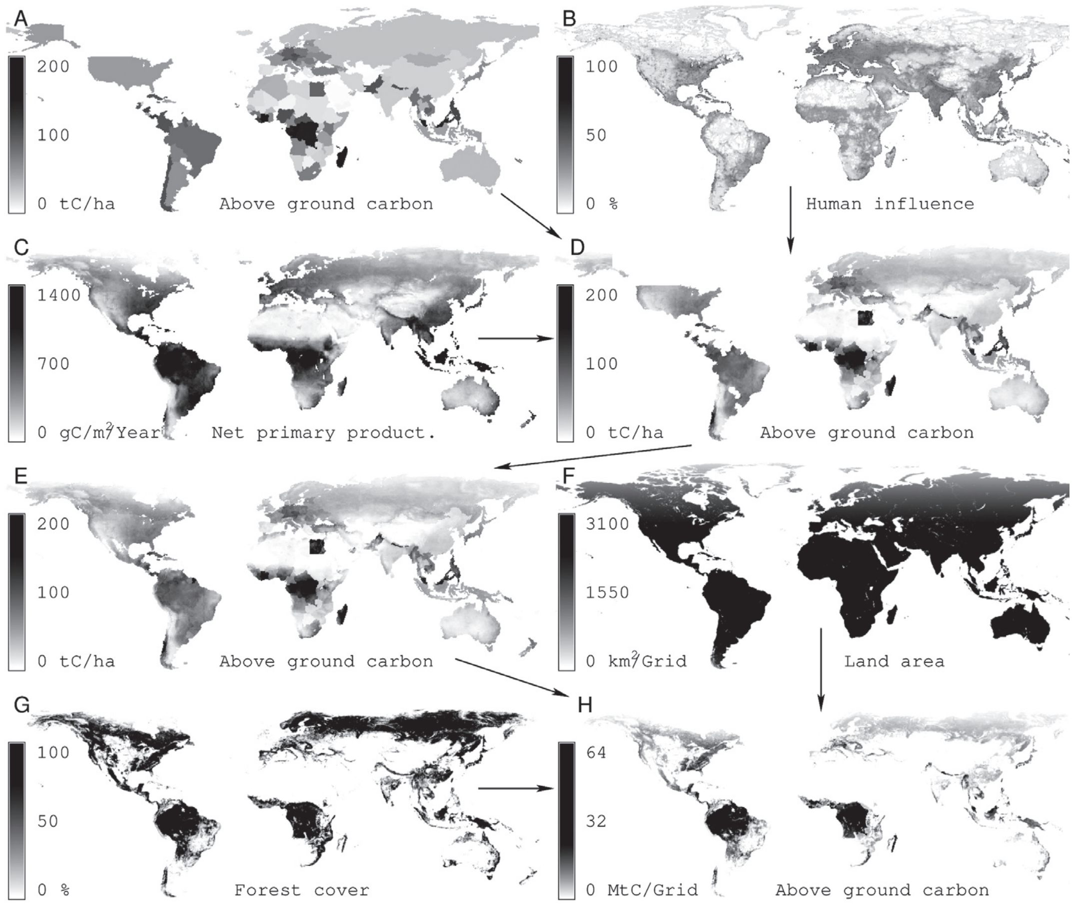


**Fig. 3.** Downscaling county values to grid values. A. Country values of above ground tC/ha in forests – some countries don´t provide values; B. Human footprint; C. NPP in gC/m$^2$/year; D. tC/ha in forests; E. tC/ha in forests – completed; F. Land area in km$^2$/half degree Grid; G. Forest share; H. MtC/Grid.

the below ground biomass $125 \times 10^9$ t, the dead biomass $83 \times 10^9$ t and the total biomass $677 \times 10^9$ t. Here the total biomass is not equal to the sum of above ground, below ground and dead biomass because the total biomass was generated from the values for total biomass given in the FRA2005 tables. The above ground carbon is $234 \times 10^9$ tC, the below ground carbon $62 \times 10^9$ tC, the carbon in dead wood $41 \times 10^9$ tC, the carbon in litter $23 \times 10^9$ tC and the carbon in forest soils $398 \times 10^9$ tC.

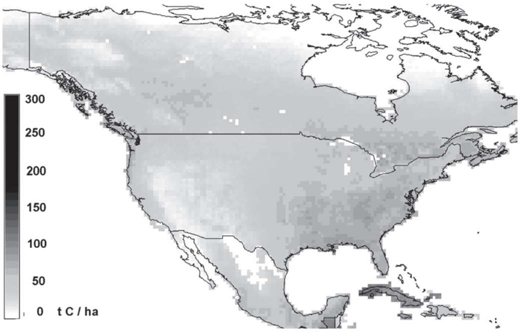


**Fig. 4.** Above ground Carbon Map – US (tC/ha in forests).

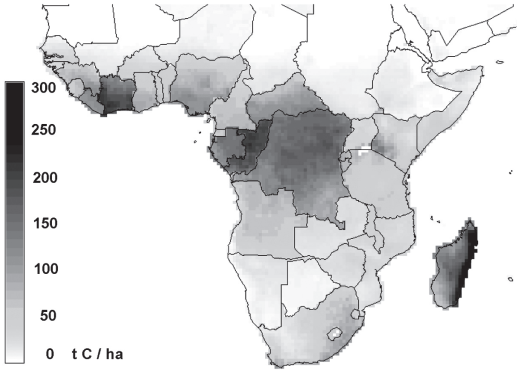


**Fig. 5.** Above ground Carbon Map – Central Africa (tC/ha in forests).

# 4 Discussion and Conclusion

The significance of forest area as a single indicator of forest development has often been overemphasized – growing stock and carbon storage may be considered equally important parameters (FAO, 2005). The results presented here represent one of the first attempts to produce a consistent global spatial database at half degree resolution containing forest growing stock, biomass and carbon stock values, based on the FRA2005. The approach makes some simple assumptions and will not be error free. However, this method will produce maps which are useful for current applications related to biomass burning emissions, carbon cycle or deforestation issues.

In some areas country borders can still be seen. This could have been reduced by using a smoothing function on the produced maps but this would also change the average country values so that they are not coincident with the FRA2005. The methods used here depend heavily on the accuracy of FAO stats. In Fig. 4, which shows carbon above ground, the country borders between USA, Canada and Mexico are not visible, whereas in Fig. 5 many country borders of Africa can be identified. This can be a realistic phenomena since in different countries, in particular in Europe, forest management differs and therefore carbon stocks vary. However in some countries within Africa the borders could also be artefacts and do not reflect different forest management.

Even though the FRA2005 database provides one of most consistent and current global datasets on forest parameters, many countries have difficulty providing data on biomass and carbon stocks, and the quality of the information provided is variable (FAO 2005). Large areas in some case have no value.

The presented methodology is a first attempt to downscale the FAO biomass data which is reported on a country level to a resolution of 0.5 degrees by using the relationship between biomass, NPP and human impact. Clearly there are shortcomings in the method due to a number of factors. The relationship between NPP and above-ground Biomass is not clear since it may be linear, quadratic or another relationship, depending on the region itself. The same applies for the other biomass and carbon fractions (i.e. biomass below ground, dead wood and total wood, carbon above, below ground, dead wood and litter) and soil carbon. Peat lands, for instance, store huge amounts of carbon in their soil as a result of long term accumulation and don't show high NPP rates. As we are only describing carbon pools in forest, the extremes of peat lands won't affect the results of this paper. Nevertheless it should be mentioned, that especially the soil values may not have such a tight relation to NPP as the above ground biomass has. Soil and litter values are based on few country values from FAO. This may indicate that these values are hard to gather and have not the quality like values of growing stock. The uncertainty of the estimated values for a grid depends on the quality of the FRA-values, the forest cover map, the linearity of NPP and human activity to the estimated values, the human activity map and the NPP map. The grid values summarized by country are similar to the FAO values and the quality will be in the same range.

This method is based on national FAO statistics which were derived from inventory data. Such a method has the advantage over dynamic vegetation models that it gives quite realistic estimates and is not prone to unrealistically high biomass accumulations – often the output of current global dynamic vegetation models, where the biomass module is still under development.

Techniques applied in this paper attempt to account for some of these inconsistencies and missing values in the data through a combination of other spatial datasets and regression analysis. This has resulted in a transparent methodology which delivers a suite of forest parameters in demand by the earth science community. These products could prove beneficial for comparison with biomass maps derived from future FRAs and results of DGVMs and biomass maps derived from future satellite missions.

Currently the datasets we could use to validate these results are sparse, but with sub-national statistics from FAO becoming available we could improve our methodology. Since the Earth science community is eager to use global higher resolution datasets, they are made available to be used in a number of applications. Users of these datasets do however have to be aware of the current limitations and shortcomings and the data should be used with care.

All resultant datasets (i.e. growing stock, biomass and carbon) from the methodology described in this paper are available online at www.iiasa.ac.at/Research/FOR/.

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