Constructing the Net Primary Production and

Biomass accounts and Ecosystem Carbon Balance Index:

A Methodological Note

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Abstract

Understanding the relationships between key ecosystem functions, their products and related human uses at wide geographical scales remains a challenge for the scientific and policy communities. In this quest, the analysis of the relationships between ecosystems primary productivity and the human use in the form of food, fibre, timber etc., is a core issue for those concerned with the patterns on a continental scale. A novel method for mapping patterns in Europe is described here, that combines data from a range of national statistics for agriculture, forestry and livestock, with CORINE land-cover mapping, and information for net primary production, the Normalized Difference Vegetation Index

Key words – *primary production, human appropriation of primary production, ecosystem carbon balance, remote sensing, national statistics, land cover, GIS*

1. *Background and Aims*

This paper describes work done as part of the fast track implementation of simplified ecosystem capital accounts initiative led by the European Environmental Agency (EEA, 2011). It has resulted in the publication (EEA, 2011) of an experimental framework for ecosystem capital accounting, a key element of which is an estimate of the aggregate index, *Net Ecosystem Accessible Carbon Surplus*. The calculation is based on estimating the consumption or removal of Net Primary Productivity (NPP) via agriculture, forestry, and fisheries, which largely constitute the output of provisioning services from ecosystems. It builds on global studies such as those of Haberl et al. (2007) and Krausmann et al. (2008), which suggest that around 20% of Global Net Primary Productivity is appropriated by people. The aim of this study has been to develop an operational method for estimating the consumption of carbon by these sectors in a spatially explicit way for Europe at finer spatial and temporal scales than is available from these global studies. The goal has been to design an approach that is consistent with the spatially explicit Land and Ecosystem Accounting (LEAC) Framework that has been developed by the EEA (EEA, 2006; Weber, 2007); thus the work is based on the same 1 km^2 accounting grid for Europe that forms the basis of LEAC. It has also been designed to test the operational feasibility of the accounting framework, in terms of being able to update the information on an annual basis.

2. *Biomass/carbon in the experimental framework for simplified ecosystem capital account in Europe.*

In the framework for simplified ecosystem capital accounting in Europe, three groups of ecosystem services have been considered: accessible biomass/carbon, accessible water, and accessible regulating and cultural services. Accessible refers to the share of the 'total' or 'available' resource which can be used without damaging ecosystem capital capacity. All three groups of services are generally produced (in variable proportions) by all ecosystems. Accessible biomass/carbon and water together make up 99 per cent of all 'provisioning services' as described in the Millennium Ecosystem Assessment (MA, 2005) or Common International Classification of Ecosystem Services (CICES, Haines-Young and Potschin, 2010, 2011).

Biomass/carbon and water are recorded in formal balances while regulating and cultural services are measured indirectly on the basis of ecosystem capacity to deliver them (state of landscape green infrastructure and biodiversity). For each of these groups, the amount of services which can be used must be lower than the accessible surplus, which means that in terms of sustainable development there should not be significant trade-offs between these services. The primary ecosystem service is production of biomass which can be generated and withdrawn (by agriculture, forestry, fisheries, etc.) up to a surplus which takes into account nature's own reproductive needs. The surplus corresponds to the current 'food of biodiversity' and the maintenance of bio-carbon stocks in soil and perennial vegetation, and which is required if the ecosystem is to be self-sustaining. Production of biomass must also be compatible with the maintenance of accessible water resources (e.g. limits to irrigation) and the bundle of services supplied by the green landscape infrastructure.

Similarly, water can be abstracted only up to an accessible surplus, to ensure the good functioning of the water cycle, as well as biomass production, and the needs of landscapes and biodiversity; for example, a new reservoir destroys previous ecosystem functions, over-dimensioned irrigation infrastructures create risks of agricultural shortages in years with rainfall deficit. The development of landscape services may result in the reduction, for example, of biomass production because of subsequent falling yields — which will be recorded in the carbon/biomass account.

Simplified ecosystem capital accounts include tables in both physical and monetary units. Some of these tables are directly connected to SEEA volume 1 tables where breakdowns are mostly presented by economic sector and are, in that way, indirectly bridged to the SNA itself (in particular regarding supply and use and input-output tables). Other tables link back directly to the SNA.

The ecosystem capital carbon/biomass account measures the Net Ecosystem Accessible Carbon Surplus (NEACS) in soil, vegetation and fisheries and its use.

The account records, in tonnes of carbon, the stocks available in soil, below-ground and above-ground vegetation and in water (fish). It records the flows of Net Primary Production (NPP) by natural and cultivated vegetation, and its use by crops and timber harvests. In addition to inland ecosystems, the accounts covers sea (fisheries and sea regulating capacity) and the atmosphere's climate regulation capacity which is a measure of the amount of fossil carbon accessible without increasing mean global temperature beyond the stated target of a maximum of 2 degrees Celsius.

The characteristic indicators of ecosystem capital carbon/biomass accounts are:

- **NPP and its removal** by agriculture, forestry and fisheries, which indicates the availability of these provisioning ecosystem services;
- the **Net Ecosystem Carbon Balance (NECB)** which indicates the sustainability of carbon/ biomass use; in principle, NECB should be always greater than or equal to zero;
- **Net Ecosystem Accessible Carbon Surplus (NEACS)** which measures the share of available ecosystem production of carbon which meets the sustainability constraints of maintaining stocks in soils and vegetation (mostly in trees) and fisheries; in addition to inland and sea

ecosystems, NEACS includes the fossil carbon accessible under constraint of maintenance of the atmosphere's climate regulation functions.

- The Ecosystem Accessible Carbon Surplus index summarises the sustainability of total carbon use (removal of biological carbon plus use of fossil carbon) compared to the accessible resource (NEACS). The ratio NEACS/Use should be always greater than one.

Table 1: Provisional carbon/biomass account structure in the experimental framework of ecosystem capital accounts in Europe.

Table [B] Ecosystem Capital Carbon/biomass Account: Net Ecosystem Carbon Balance (NECB) & Net Ecosystem Accessible Carbon Surplus (NEACS)

Stock accounts

B1 Stock t1 (~1995), 10^6 tonnes of C

- b11 Stock t1 (~1995), 10^6 tonnes of C/Soil
- b12 Stock t1 (~1995), 10^6 tonnes of C/trees & shrubs

B2 Stock t10 (~ 2005), 10^6 tonnes of C

- b21 Stock t10 (~2005), 10^6 tonnes of C/soil
- b22 Stock t10 (~2005), 10^6 tonnes of C/trees & shrubs

B3 Change t10-t1, 10^6 tonnes of C

- b31 Change t10-t1, 10^6 tonnes of C/soil
- b32 Change t10-t1, 10^6 tonnes of C/trees & shrub
- *b33 Mean annual C increase %*

B4 Mean annual carbon/biomass flow account and NECB

- b41 GPP 10^6 tonnes of C
- b42 Rp = Respiration by Plants
- b43 NPP 10^6 tonnes of C
- b44 Rh = Respiration by Heterotrophs and Decomposers
- b45 NEP 10^6 tonnes of C
- b46 Leakages of carbon/biomass
    - b46a Leakages to water bodies/erosion, DOC
    - b46b Leakages to the atmosphere/fires, VOC
- b47 NEP Surplus 10^6 tonnes of C [b45-b46] (NB: includes effects of LUC)
- b48 Net removals
    - b481 Net removal/crops
        - b481a total harvest
        - b481b leftovers, returns
    - b482 Net removal/grazing
        - b482a total grazing
        - b482b animal excretion return to pasture
    - b483 Net removal/timber
        - b483a total harvest
        - b483b leftovers, returns
    - b484 Net removal/fish
        - b484a total catches
        - b484b leftovers, returns
    - b485 Removal/extraction of soil, peat
    - b486 Organic fertilisation
- b49 mean NECB (~1995–~2005), 10^6 tonnes of C, [b47-b481-b482-b483-b484-b485+b486]

- b491 mean NECB (~1995–~2005), 10_6 tonnes of C_soil
- b492 mean NECB (~1995–~2005), 10_6 tonnes of C_trees & shrubs

Net Ecosystem Accessible Carbon Surplus

B5 Carbon stress coefficient t1 (~1995) ([b81+b82)/100)
- b51 A = Total area% WHERE NECB_Soil < or = 0
- b52 B = area% of SELU WHERE NECB_Trees & shrubs < NEP surplus

B6 Carbon stress coefficient t10 (~2005)
- b61 A = Total area% WHERE NECB_Soil < or = 0
- b62 B = area% of SELU WHERE NECB_Trees & shrubs < NEP surplus

B7 Net Ecosystem Accessible Carbon Surplus: NEACS t1 (~1995), weighted 106 tonnes of C [proxy b47*B8]
B8 Net Ecosystem Accessible Carbon Surplus: NEACS t10 (~2005), weighted 106 tonnes of C [proxy b47*B9]
- *B8-B7 Change in NEACS*

B9 Use of biological carbon (removals) t1 (~1995), weighted 106 tonnes of C [b481+b482+b483-b484]
B10 Use of biological carbon (removals) t10 (~2005), weighted 106 tonnes of C [b481+b482+b483-b484]
B11 Use of fossil carbon, t1 (~1995), 106 tonnes
B12 Use of fossil carbon, t1 (~2005), 106 tonnes

*B13 Ecosystem Accessible Carbon Surplus index t1 (~1995), [B7/B9*100)] [NB should be > 100]*
*B14 Ecosystem Accessible Carbon Surplus index t10 (~2005), [B8/B10*100)] [NB should be > 100]*

3. *Designing a method of broad-scale assessment and mapping of NPP and biomass accounts*

The Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1973) has been widely used to map photosynthetic activity using remotely sensed data. It has been shown to be closely correlated with the abundance of plant green biomass, as well as with the rate of photosynthetic activity, or NPP. Although the calculation of the index is sensitive to atmospheric effects (e.g. cloud cover), soil wetness and sensor design, it remains the most widely used input for high-resolution mapping and assessment of vegetation at continental scales, including for modelling and quantification of the Net primary production (NPP). NPP data calculated using different algorithms are now available from several sources. Two were considered as a potential input for this study:

- MODIS, estimating NPP applying additional parameters such as land-cover vegetation type, precipitation and temperature (Running et al,, 2004)
- GEOSUCCESS, applying C-fix model, with soil and temperature coefficients

The significance of such data in relation to the construction of ecosystem accounts is that while estimates of the consumption of biomass are available at national level scales, the fine spatial resolution of NDVI data offers a means for analysing patterns of supply and use in greater geographical detail.

The current work has involved the development of a spatially explicit mapping technique that uses a *downscaling procedure* to spatially redistribute aggregated national statistical data on biomass use using geographically continuous information for land cover and NDVI. The procedure involves two key data processing steps, namely identifying the volumes of biomass consumed at national levels that needs to be ‘redistributed’ and the production of a base map that enables the units of consumption to be allocated to each cell of the European accounting grid based on its characteristics of land cover and NDVI.

For the base mapping, the extent of standing forest, intensive cropland, mixed cropland and pasture has been expressed as a percentage of the area of a 1 km^2 grid cell in the accounting grid. Each cell has also been assigned an index value based on the available NDVI data, to record its potential contribution to the total national stock of NPP. Various indices were tested, including the mean value for a particular year, the 11 year time-series mean, or the difference between two consecutive years. The NDVI data derived from SPOT Vegetation instrument was applied as it retains more explicit spatial patterns at landscape level.

To calculate the probability map one of the inputs was used as a proxy and the other applied as a correction factor or weight. Finally, the downscaled product was calculated by dividing the sum of the volume (of crop or timber) for a country over the sum of the probabilities from all grid-cells calculated for the same country. In this way a downscaling coefficient was derived for each country, which was consequently multiplied by the probability map to produce the final downscaled product for each parameter. The downscaling procedure was applied to calculate the annual use of NPP and biomass through crops harvest, timber extraction, and grazed biomass (consumed by grazing livestock). Further because of the difficulty to calculate biomass stock accumulation, it was approach in a similar way, by downscaling available estimations of biomass in forests reported by FAO’s Forest Resource Assessments.

4. *First results and examples of European NPP and Biomass accounts*

Four accounting elements have been produced: carbon stock, carbon resource, carbon use and carbon balance. All outputs are reported as tons of carbon per km^2 and per year (where relevant). Only exchanges related to living processes are considered at this stage, carbon sequestration in the ocean or processes related to fossil fuels are not considered. An overview of the four accounting categories is presented below.

a. Carbon stocks

This account addresses the ecosystem processes of carbon stock accumulation and storage in the living and dead biomass (mostly woody) and in the soil during an extended period of time. A harmonized map for the EU countries was made by downscaling country level estimates from the FAO’s Forest Resources Assessment Reports, which was added to the estimates for the carbon stock in soil produced by the EC’s Joint Research Centre (OCTOP, reference) and the EEA. It is recognised that this is probably an underestimate of the real stocks since no associated vegetation biomass was be included at this stage. Moreover, carbon stocks deeper than 30 cm subsoil, including peat were not included, given the nature of the OCTOP data.

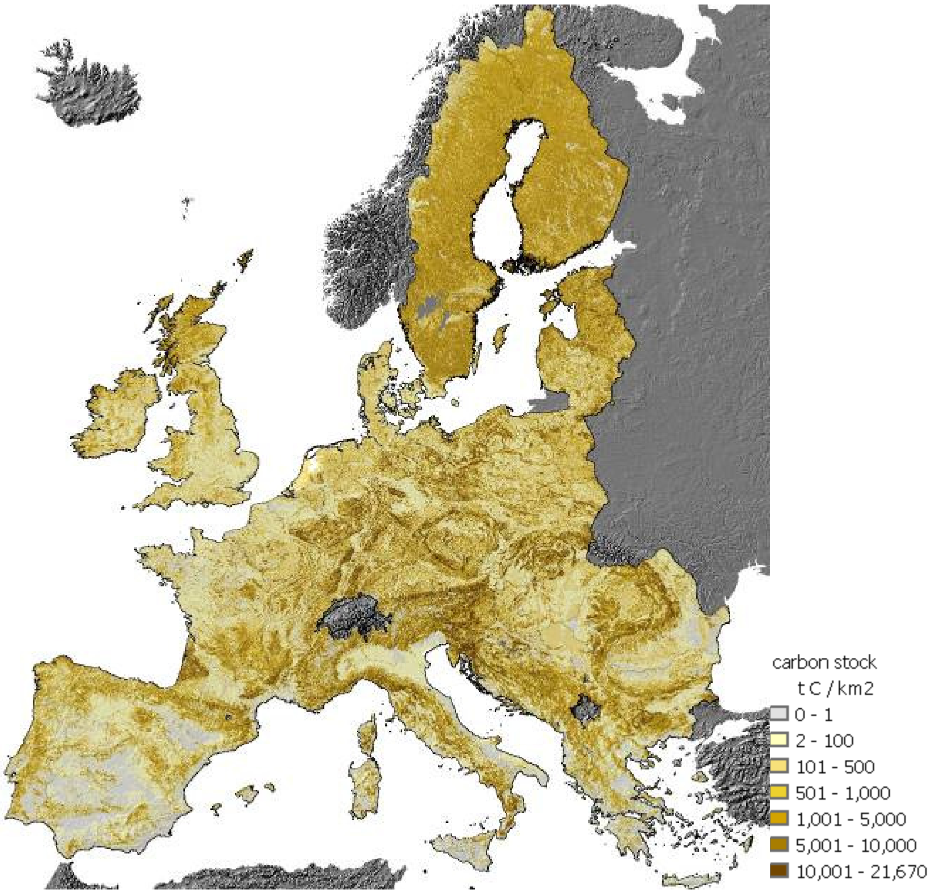

Figure 1: Biomass/Carbon stock of Europe

The Carbon stock accumulated in the woody biomass is a downscaled estimate of total carbon in living biomass represented by forest; it is estimated in tons of carbon per km^2. For its estimation the *above ground* and *below ground* living biomass amounts for all the EU countries were considered, other estimations such as *dead wood material*, *littler*, *soil carbon* etc which were available only for some countries, therefore had to be excluded from the total stock forest calculations. The source of data is: MCPFE/ECE/FAO quantitative indicators enquiry (http://live.unece.org/)

The country level statistics were downscaled to 1 km^2 grid using the 11 year mean NDVI as a proxi of productivity. It was weighted by the extent of standing forest extracted from CORINE Land Cover data, by summing the classes Broadleaf, Coniferous and Mixed forest. The final map of carbon stock is calculated by summing the stock accumulated in woody biomass and the organic carbon accumulated in the top-soil.

b. *Annual production of Carbon resource: Ecosystem productivity and returns from harvest*

The total resource of Bio-carbon is the sum of net ecosystem production and the residuals and returns from crop harvesting, grazing and tree clearing. The estimate is in tons of carbon per km^2, calculated annually for a time-series 2000-6. The annual resource refers to the ecosystem's primary production function. For Europe, the GEOSUCCESS NPP product was used after being adjusted for general heterotrophic respiration rates using the night temperature estimation. GEOSUCCESS has produced 10-day estimation of NPP by applying C-fix model on SPOT vegetation NDVI imagery, in 1 km grid. The data was downloaded from http://www.geosuccess.net/ and annual sums calculated. A night temperature coefficient was applied on the annual NPP maps to approximate an annual rate of Net Ecosystem productivity (NEP). Residuals from crops (10 % from 'wet crops' and 20 % from 'dry crops', see below); and timber (10 % from the tree fell) and manure (30% of the grazed biomass) we summed up and consequently added to the adjusted NPP to produce a map of the total resource.

A harmonized EU map is thus produced. It should be noted, however, that this is probably an underestimation since no production under plastic or under forest canopy is captured using these optical remote sensing approaches.

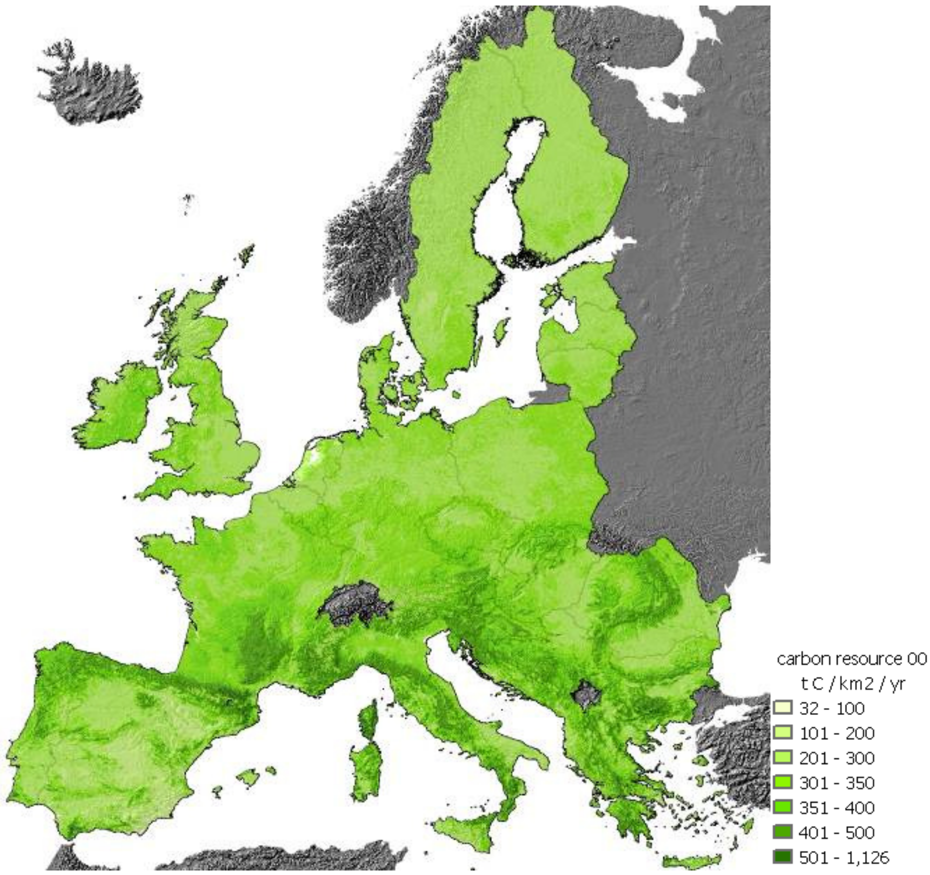

Figure 2: Biomass/Carbon resource annual production

c. *Human use of carbon*

The total use of Bio-carbon is the sum of withdrawals by agriculture crops, grazing of grasslands and clearing of forests. The values are gross, in the sense that the residuals and leftovers are not deducted at this stage.

This account addresses what people take from the ecosystem as renewable resources, and includes both annual production and accumulated stock for products such as food, fibre, materials and bio-fuels, but not fossil fuels. FAO statistics were downscaled for the purpose of this calculation, using the percentage land-cover estimates and NDVI. A harmonized map for the EU countries has therefore been produced for each of the three components, as well as their sum, to represent the total use of Bio-C.

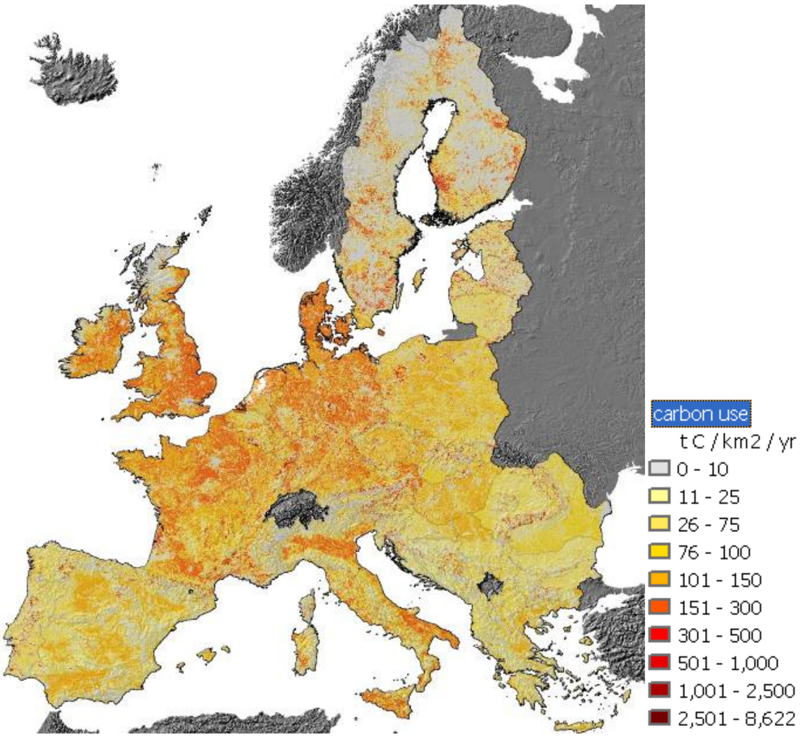

Figure 3: Human use of biomass/carbon

d. *Crop downscaling*

This parameter expresses the intensity of crop cultivation in Europe for years 2000 through 2006. It approximates how much carbon was extracted from the ecosystems through cropping. It is the result of both natural productivity and the human enhancement of it through irrigation and artificial inputs to agriculture.

The main input is FAO's crop statistics downloaded from http://faostat.fao.org/ for the EU27 countries. The following categories were downloaded and subdivided into 'wet crop' in blue and 'dry crops' on yellow background:

Cereals,Total + (Total)
Fibre Crops Primary + (Total)
Fruit excl Melons,Total + (Total)
Oilcrops Primary + (Total)
Pulses,Total + (Total)
Roots and Tubers,Total + (Total)
Treenuts,Total + (Total)
Vegetables&Melons, Total + (Total)

In making the calculations an 80% dry matter content of the live weight was assumed for 'dry crops'; 20% was assumed for wet ones. For both, the carbon content was assumed to be 50 % of the dry matter content. A further spatial adjustment was applied for crop cultivation intensity. For the latter two filters were produced by summing up the following land-cover classes, expressed as percentages, to distinguish between intensively (fully) used lands (these are the categories on green background in the table below; the more extensively used areas are shown in orange).

12	211	Non-irrigated arable land
13	212	Permanently irrigated land
14	213	Rice fields
15	221	Vineyards
16	222	Fruit trees and berry plantations
17	223	Olive groves
18	231	Pastures
19	241	Annual crops associated with permanent crops
20	242	Complex cultivation patterns
21	243	Land principally occupied by agriculture, with significant areas of natural vegetation
22	244	Agro-forestry areas

A weight of 1.25 was then applied to the intensive cropland and of 0.66 over the extensive ones (why?). Finally an index of cropland cultivation intensity was calculated by summing up the two maps and applied as a weight on the 'wet and dry' downscaled crop maps.

e. *Timber downscaling*

This parameter expresses the intensity of timber extraction, expressed as "roundwood removal" in Europe for years 2000 through 2006. It approximates how much carbon was extracted from the ecosystems through timber. It is the result of both natural productivity and the human enhancement of it through forest management practices.

As a main input were applied the round wood extraction statistics from ForeSTAT, downloaded for the EU27 countries and downscaled on the basis of detected decreasing NDVI between the year of the reported statistics and the previous one. Because of the pronounced climatic influences on the variability of NDVI, a correction was applied to one of the images, following a simple method. First a coefficient of '*regional climate influence*' was calculated by extracting a sum of NDVI for landscape units (defined by the combination of a map of the Dominant Landscape types in Europe (EEA product) and the administrative divisions, NUTS2) calculating a coefficient as the ratio between the reference year over the year to be corrected and then multiplying the NDVI of the year to be corrected by this coefficient. Then a simple NDVI difference was calculated, the negative part extracted and filtered by the percentage of forest cover (as expressed by the domination of standing forest), so that the more forest occurs, the more NDVI difference is retained. The resulting map was applied to define where most probably trees were cut and removed. The country round wood extraction statistics were downscaled using the negative NDVI difference map.

f. *Grazed biomass mapping*

The grazed biomass by livestock was approached in a different way. A product by FAO on downscaled stocks of grazing animals for year 2000 (cows, buffaloes, goats and sheep) in 1 km^2 maps was applied but with a correction for a maximum grazing activity according to the percentage of available pasture land ($C0_{grazed}$), derived by aggregating the following CORINE LC maps:

18	231	Pastures	100%
22	244	Agro-forestry areas	70%
26	321	Natural grasslands	100%
29	324	Transitional woodland-shrub	50%

Then, the livestock distribution numbers from FAO were truncated to the maximum of available grazing land (if FAO livestock ≤ $C0_{grazed}$, then FAO livestock, else $C0_{grazed}$) assuming that the remaining number of animals would be kept under closer and fed by biomass that is not grazed, but harvested from croplands.

g. *Carbon balance*

Finally, an index called Net Ecosystem Carbon Balance (NECB) was calculated, as the difference between the biomass that the ecosystems produce and the biomass that people take away or in other words an approximation of how much ecosystem production people used and how much they shared with the rest of the living organisms to sustain the ecosystems. It summarizes all inputs and outputs for a given ecosystem as a numerical value. This first calculation is limited to agriculture crops, pasture and natural grassland and forest.

Exploring the patterns depicted by the NECB has allowed outlining five categories of state of the ecosystem in respect of the interaction between human and natural controlling factors:

- The dark green areas are those where biggest surplus, between the amount of biomass the ecosystems produce and the amount of biomass people harvest, is observed. These may be defined as the areas of highest and increasing potential for the ecosystem to maintain primary production vigorously and therefore these areas were labelled as areas of intensive carbon sequestration. Several of these areas are also outstanding in terms of having their own micro-climate of humid conditions in semi-arid areas, such as West Crete and South-West Spain.
- The light green shows areas of not very intensive production where a lot of biomass is left available to maintain essential ecosystem functions, such as food-webs, bio-degradation and soil fertility.
- The light yellow areas indicate either very intensive production, mainly croplands, or very poor net primary production as in the semi-desertic areas of South-East Spain. In the first case this situation may imply that land is left with no biomass during certain seasons during which no consumers food-webs can be maintained and therefore a pronounced impact on biodiversity can be expected as a major issue.
- The areas in orange indicate a situation where all annual biomass production is extracted, which if continuous may be expected to cause long-term depletion of the environmental resources. It is not surprising to see such areas in the most intensively cultivated regions of Europe, and supposedly these may be still ‘productive’ only due to the amount of human input such as pesticides, fertilizers and water.
- In red are shown the areas where major deforestations occurred, mainly due to very intensive forestry, but also because of wide-scale storm effects, such as in South-West France in year 2000.

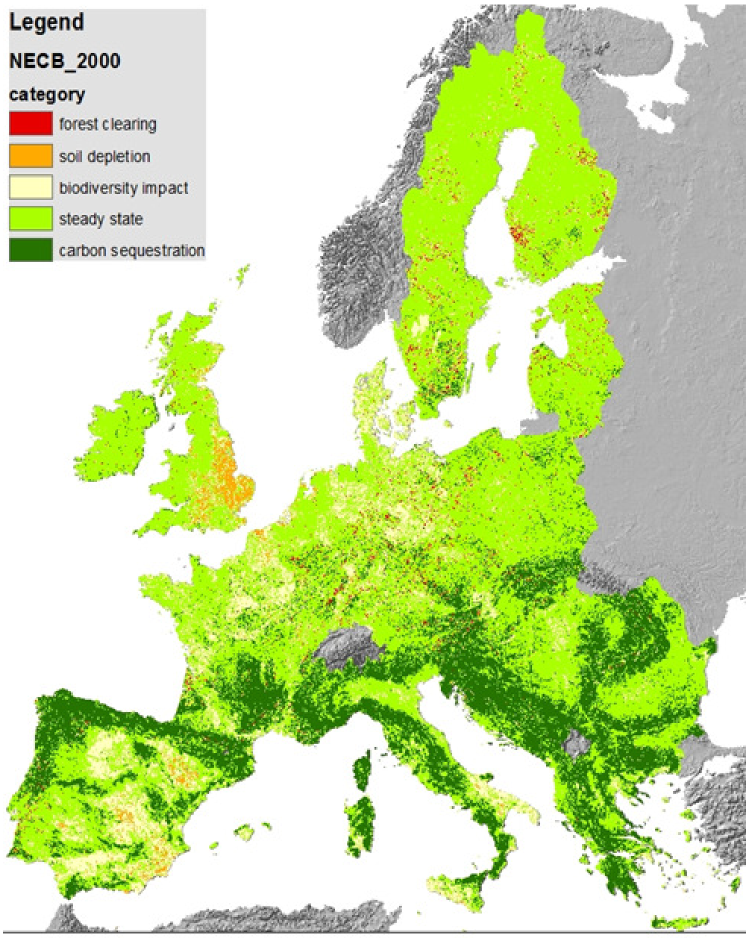

Figure 4: Net Ecosystem Carbon Balance and Figure 5 Interpretation of the NECB

These five categories have been defined and described on the basis of expert interpretation and recognition of known patterns and events in Europe.

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