Evaluating interactions between carbon sequestration and provisioning ecosystem services in Europe

By Emil Ivanov, June 2021

School of Geography, University of Nottingham, UK

Acknowledgements

I dedicate this thesis to a person who gave me knowledge of the plants and animals that are important in our lives, at my earliest age and in my mountain home, Stara planina, the mountains between Bulgaria and Serbia. My grandmother, she had studied really few years at schools and had never heard the word 'ecology', but she taught me the local names, properties and uses of most mountain species, which I learned formally about a decade later, at the University of Sofia. This is how I was educated in ecology and environmental science. I am extremely grateful to my family for teaching me how to be persistent, and for all their support so that I could pursue my study passion till the end which materialized in this thesis. I express my full gratitude to my supervisors from Nottingham: Doreen Boyd, Giles Foody, Roy Haines-Young and Bob Abrahart, for guiding me how to turn passionate ideas into critical and thorough research. Roy and Bob taught me how to start a research project, Doreen and Giles taught me how to finish it. Between the first and the second period of my PhD, I had an 18-month interruption to take part in a project on accounting ecosystem services, at the United Nations Statistics Division, which provided great inspiration and experience. Not least, I would like to express my full gratitude to my Nottingham friends for helping me in every way during the completion of my study.

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Definitions of terms and abbreviations

- **Aboveground Biomass** (AGB): includes all biomass in living vegetation, both woody and herbaceous
- **Carbon cycle**: bio-geo-chemical process of carbon transfers (in various forms, e.g. as carbon dioxide) between the atmosphere, ocean, terrestrial biosphere and lithosphere (called also carbon pools)
- **Carbon flows**: in this study the term comprises all fluxes and transfers of carbon between the atmosphere, ecosystems and economic systems
- **Carbon fluxes**: include the upward and downward exchange of carbon (included in CO_2) between the ecosystems to the atmosphere
- **Carbon stocks**: includes biomass (above-ground and below-ground) and soil organic carbon
- **Carbon-based ecosystem services**: ecosystem services related with the carbon cycle and expressed as mass of carbon
- **Ecosystem carbon accounts**: is the compilation of ecosystem stocks and flows expressed in terms of carbon
- **Ecosystem carbon budget**: includes carbon stocks within the ecosystems, carbon fluxes between ecosystems and the atmosphere, and transfers of carbon between ecosystems and economic systems
- **Ecosystem carbon sequestration**: in this study the term is applied as a measure of carbon capture into durable plant matter or soil organic carbon
- **Ecosystem Respiration** (RE): is the upward carbon flux (or release of CO_2) resulting from the respiration of all living organisms in an ecosystem. Excludes anthropogenic release of CO_2.
- **Ecosystem service** (ES): ecological characteristics, functions, or processes that directly or indirectly contribute to human wellbeing
- **Greenhouse gas** (GHG): gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth’s surface, the atmosphere itself, and by clouds (his property causes the greenhouse effect)
- **Gross Primary Production** (GPP): is the amount of carbon fixed during photosynthesis by all producers in the ecosystem

- **Natural capital** (NC): is the stock of renewable and non-renewable natural resources (e.g. plants, animals, air, water, soils, minerals) which contribute to human wellbeing
- **Net Ecosystem Carbon Balance** (NECB): is the difference between all inputs and outputs of (physical, biological and anthropogenic) carbon in an ecosystem
- **Net Ecosystem Production** (NEP): is the difference between gross primary production and ecosystem respiration
- **Net Primary Production** (NPP): is the difference between GPP and plant (autotrophic) respiration
- **Total carbon exports**: in this study the term comprises harvested crops, timber, hay and animal products, which when aggregated - define the total carbon export from the ecosystems
- **Total carbon returns**: in this study the term includes the sum of manure, seeds and animal feed

Abstract

This PhD study focused on research challenges associated with dependencies of human activities and wellbeing on the functioning of terrestrial ecosystems. It builds on the concepts of ecosystem services (ES) and natural capital accounting, applying a wider scope of actual or potential benefits to people but more specific recognition of the underlying ecological processes, expressed in a single measurement unit of carbon (gCm^{-2}).

The aim of the study is to evaluate how carbon sequestration and provisioning services interact and trade-off in spatially-explicit way across the European countries, applying carbon cycle and carbon budget approach. This was carried out through statistical analysis of ecosystems' carbon budget at ground level and spatial modelling at seamless grid-level. Data quality and accuracy issues were encountered at both ground and grid levels and addressed through remote sensing vegetation indices. Because of the high correlation between NDVI (from MODIS) and GPP (from Fluxnet), the former was applied to detect sites with abnormal (outlier) GPP values and inconsistencies with other carbon budget variables. This allowed to ensemble a high quality ground dataset, and consequently to enhance the grid GPP estimates produced with the Vegetation Photosynthesis Model (VPM) of Zhang et al. (2017). Then, the ground carbon budget data was applied to train and validate a new grid estimation method based on VPM-GPP, Corine land cover, soil organic carbon (SOC) and a map of European ecoregions. This method was applied to map comprehensively the key carbon budget components including fluxes, harvests and flows. Finally, consistent NEP and NECB were mapped at 250m x 250m and were assessed against independent ground data from the published studies, which produced statistically significant Pearson correlation r = 0.72 for NECB and r = 0.73 for NEP. Provisioning ESs, including harvests of crops and fodder were mapped and assessed at aggregate regional level against European official statistics from EUROSTAT. The sum of the provisioning services was compared with carbon sequestration in soil and biomass to assess the main ESs trade-offs. The results revealed synergistic supply of services in areas of south and east Europe occupied by forests and other natural vegetation, permanent crops and less productive croplands. Most of the intensively cultivated crops and forestry areas of west and north Europe showed high provisioning ES rates traded-off against carbon sequestration ESs. Highest carbon losses were assessed for crops and pastures on organic soils under intense cultivations.

Chapter 1: Introduction, background, aim and objectives

1.1 Introduction

This research addresses new sustainability challenges: how to assess trade-offs and impacts from ever-rising demands for food, energy, materials and living space. Meeting these demands exerts impacts on nature's ecosystems with their biodiversity structures and life-support functions. Moreover, the combined effect on the pursued benefits can be neutral, antagonistic or synergistic, which makes related research and policy challenges rather complex. Many examples of policy shifts took place after realization of such trade-offs, for example from REDD to REDD+[1]. A main motivation for this study is to seek ways for integrative and consistent supply of knowledge addressing such challenges in an interdisciplinary manner.

The UN System of Integrated Environmental-Economic Accounting (SEEA[2]) laid down broadly, globally agreed conceptual and methodological foundations for generating data and statistics to support consistently the above-pointed policies and challenges. Its Ecosystem Accounting (SEEA-EA, 2021)[3] component aims to address both benefits to people and impacts on ecosystems in a standardized framework, by defining ecosystem units (or assets) and ecosystem services, and quantifying their properties in a way consistent and comparable with standard economic accounting as practiced internationally according to the System of National Accounts (SNA)[4]. The SEEA approach to integration is driven by the established economic and traditional resource accounting principles, whereby ecological ones are still being developed. On the other hand ecology has sought integration with economics since its onset in the 1970s, including valuations of ecosystem services based on energetics (Odum and Odum 2000).

The concepts of natural capital, NC (Smith et al. 2017) and ecosystem services, ES (Millennium Ecosystem Assessment 2005, Costanza et al. 2017) were developed as a bridge between ecology and economics, so as to evaluate benefits and inter-dependencies between people and nature and assess the cost of their decrease or loss (TEEB[5]). In addition, ecosystem accounting included proper ecological measures, expressed as stocks or 'condition' metrics which ultimately aim to register impacts on the ecosystems, but fully

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1 http://redd.unfccc.int/
2 https://seea.un.org/
3 https://seea.un.org/ecosystem-accounting
4 https://unstats.un.org/unsd/nationalaccount/sna.asp
5 http://www.teebweb.org/

developed examples which illustrate the relation between ecosystem components stocks, ecosystems' condition and services are scarce. Moreover strict, precise and widely accepted definition of what is an ecosystem service or disservice is hard to apply uniformly (La Notte et al. 2017) across the multiple ways people benefit and suffer from nature. The IPBES[6] introduced a more inclusive concept termed Nature's Contributions to People (NCP, Diaz et al, 2018) which can be either positive or negative.

Important questions lie ahead to uncover, on the biophysical side - in what configuration does a service contribution change, stop or even become a disservice, and similarly on the socio-economic side, based on the preferences of the beneficiaries. Such questions require local level studies focused on specific processes. At the other end, international, continental and global level studies are left to rely on proxies for services, for which many examples exist but few are indeed consistent and comparable when multiple services are assessed (Jopke et al. 2015). ES are routinely addressed and assessed in a very broad spectrum of ways, methods (Dunford et al. 2018) and indicators (Spake et al. 2017) which prevents comparability and obstructs progress towards a standardized ES measurement method. Likely, one reason for this broad and scattered search of measurement ways, proxies and indicators throughout various academic disciplines and approaches, is the failure to recognize some of the key ecological mechanisms which supply ES. A main argument for this study is that ecological foundations and principles are not sufficiently incorporated into the integrated accounting approaches, and stronger geographic perspective is needed for improved comparability of ES measurement in an international studies context.

1.2 Defining ecosystem services

Costanza et al. 2017 provided the following ES definition:

> 'Ecosystem services' (ES) are the ecological characteristics, functions, or processes that directly or indirectly contribute to human wellbeing: that is, the benefits that people derive from functioning ecosystems'.

It is a broad conceptual definition, well accommodating the multitude of ES measurement ways mentioned above. ES are key to economy and human wellbeing, yet in an international perspective often remain difficult to define, assess and quantify in a fully meaningful and comparable way (Boerema et al. 2017). Structured approaches, contributing towards an international standard can be pictured as the ES supply cascade (Haines-Young and Potschin 2010) which is also followed by a number of academic studies (Burkhard et al. 2012, Dick et

[6] https://ipbes.net/

al. 2017, La Notte et al. 2016). They view a given service as part of several ecosystem and human use steps along the ‘production chain’: e.g. supply by biophysical structures in the form of ecosystem functions, use and consumption by people and related activities in the form of final products and benefits.

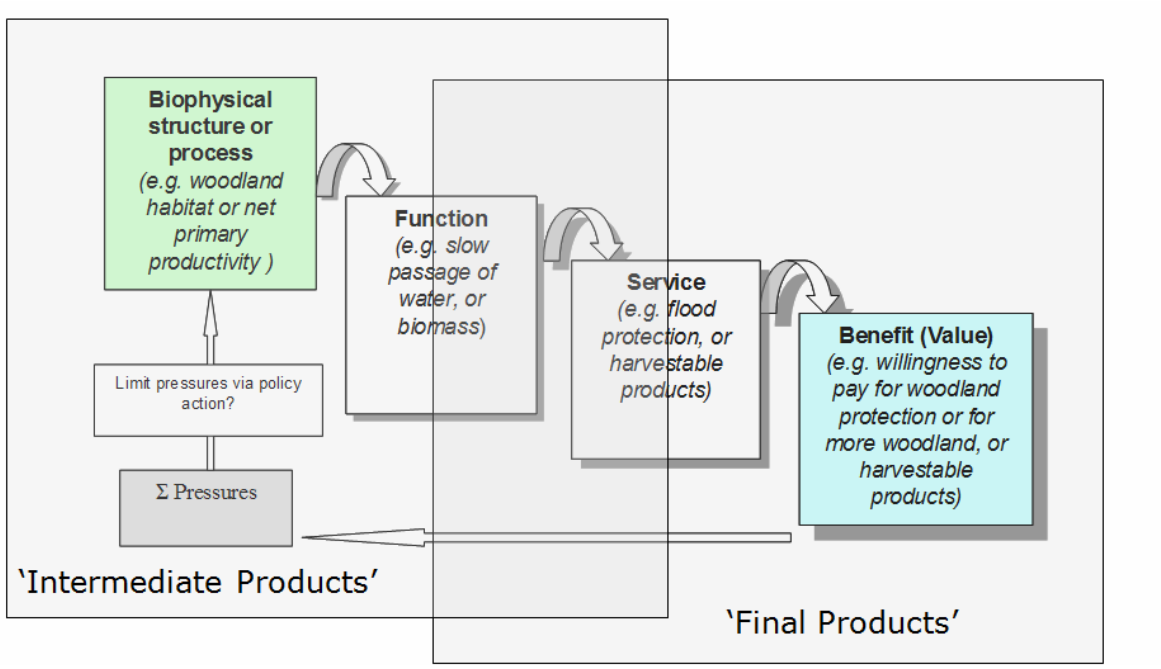


Figure 1.1: ‘Cascade’ view of the relationships between biodiversity, ecosystem services and human wellbeing, source: Haines-Young and Potschin (2010)

This ‘cascade’ view helps to clarify the nature and structure of ecosystem services but leaves the scope of defining them rather broad since virtually any ecological structure or process can be identified as beneficial to someone and at the same time can be obnoxious to someone else. SEEA-EA introduced a more formal delimitation of the ES supply scope, being what associates with production processes in the economy, whereby the difference between ecological functions and ESs is delimited by the ‘production boundary’. This approach directs the attention to some of the biggest ecological processes which feed into corresponding economic ones, such as growth of crops and timber, supply of clean water and air. While helpful for understanding the magnitude of the importance of such processes, this firmly utilitarian perspective is often criticized for implying that ESs can be managed and substituted by something else (e.g. by human structures/processes) or with other ESs (Arias-Arévalo et al. 2018). Another issue is that it forces ES values to be aligned and perceived in a more uniform way than their diversity implies, for example as food, or energy (provisioning ES), protection from storms and floods (regulatory ES) or cultural items (sacred mountains, animals). The biosphere, which is also sometimes considered the biggest ecosystem, holds values incommensurable with benefits to people. The ES concept is certainly not the only way to view connections between nature and humans. Other terms exist, for example in IPBES[7] discourses, groups from non-western country representatives preferred the term 'Gifts from nature' (Borie and Hulme 2015). Many stakeholders reject the ES concept as inadequate or even misleading. However, the objective of this study is not to develop further understanding of ES values or consolidate their acceptance, but to address measurement challenges of the rather well-known, fundamental ones which affect both human and ecological values (Farber, Costanza, and Wilson 2002).

This study uses the ES accounting concept of SEEA-EA, follows the above broad ES definition of Costanza et al. (2017) and the broad categorisation into provisioning, regulatory and cultural ES types according to CICES (Haines-Young and Potschin 2018). The accounting concepts of stocks and flows are used as defined in the SEEA Central Framework[8]: 'Physical flows are reflected in the movement and use of materials, water and energy' and 'stocks refer to the total quantity of assets at a given point in time'.

The focus is on final ESs which need to be distinguished from underlying ecological functions (also termed intermediate ESs), as well as from products and benefits which are accounted in the economy according to SNA. ESs are supplied by functioning ecosystem units and their measurement needs specific place and process to be defined at the point of their production or supply. At the other end, people benefit from ESs at various places, some at the very place of origin and others are used far away. According to the accounting rules in SEEA-EA, the supply of a given ES needs to equal its use, the entity (for example a timber product) and its quantity needs to be the same only changing place (where relevant) to make sure that 'transactions' between nature and economy are properly defined and recorded (UNSD, UNEP, and CBD 2017). This double-entry accounting principle is a key one in national accounting standards, needed to ensure a complete and balanced accounts compilation. Yet, definition problems arise where several steps in the supply chain are involved, e.g. with several transactions or transformations. A suitable example is a beef product from free-range grazing animals: the process starts with growth of grass, through consumed grass, growth of animals and finally meat produce, whereby confusions between an intermediate service, final service and a product are possible.

[7] https://www.ipbes.net/
[8] https://seea.un.org/content/seea-central-framework

The supply-use concept of SEEA-EA differs from demand and supply approaches that are broadly applied in the ES assessments literature (Burkhard et al. 2012; Palacios-Agundez et al. 2015; Sahle et al. 2018; etc.) namely, because of the requirement to have the supply equal to its use.

1.3 Ecological foundations for defining services

As stressed above, the existing ES definitions cannot fully articulate what is being transacted when an ES is used by people, and also often omit what ecological components are impacted in the processes, for example the loss of soil organic carbon (which if fully accounted should be reflected in the depletion of the corresponding stocks). Therefore, this study endeavours to develop the definition by extending the analyses further towards the ecological (biotic and abiotic) ends of the processes which entail services and benefits to people. In ecology, life-processes are studied to uncover their interaction with abiotic resources and other biotic processes. Any space on Earth has ecological conditions including solar radiation, water, nutrients and soil properties which drive best adaptations to sustain organisms' life optimally. When other forms of organisms are introduced for example new vegetation types, new crops, some part of this potential may be underused, while other species may even enhance it, for example nitrogen fixing plants or deeper root plants. If cultivations are selected and practiced with more consideration of 'ecological intensification' (Faucon, Houben, and Lambers 2017, Kovács-Hostyánszki et al. 2017) or optimization, ecosystem management would be more successful in delivering multiple benefits, also termed bundles of ecosystem services (Spake et al. 2017).

Considering such 'ecological optimum' ideas, the ES definition in this study sought to assess what happens to this optimum when under-used or enhanced (by irrigation for example) and hence how far towards the abiotic end should the ES production chain extend to assess a service and what would be the best measure for quantifying specific services and trade-offs with others. For example the growth of a crop can be assessed in terms of absorbed solar energy (in calories) from total available (light-use efficiency, LUE) (Running et al. 2004, Garbulsky et al. 2010); in terms of captured CO_2 (carbon use efficiency, CUE) (DeLucia et al. 2007, Kutsch and Kolari 2015), water resources (water use efficiency, WUE) (Jassal et al. 2009, Martín-Benito et al. 2010). In each of the three cases specific trade-offs can be assessed in relation to other crops or vegetation types, which ultimately will deliver different set of benefits to people, as well as different condition properties of the ecosystem components.

Yet, these efficiency measures have scarcely been applied in assessing ESs (Braun et al. 2017), which is indicative of a wider gap between carbon, water and nutrients cycles' studies and ecosystem services studies, as indicated in Fig.1.2. In fact, many of the functions and processes quantified in these studies can be identified as ESs, hence what is lacking is their proper identification. The need for such extensions has not been well recognized, while on the other hand ecosystem service studies often attempt to create alternative modelling, proxy estimations and valuations, without sufficiently relying on the existing ecological science. Carbon accounting in an ecosystem context is a strong example of this divide.

1.4 Integration of carbon and ecosystem accounting

Carbon is the basic element of all life (Odum and Barrett, 2005). Its content in living matter is rather stable, while the carbon content ratios with other main elements, primarily nitrogen (N) and phosphorus (P) vary substantially in terrestrial plants, according to the studies of ecological stoichiometry (Sterner and Elser, 2017). There are studies which track the movement of carbon through services and products from their ecosystem origin to their users, in a life-cycle assessment perspective (Hillier et al. 2009, Proietti et al. 2016), hence providing basis for defining and quantifying ES based on carbon. However, there is no generalized assessment of how carbon cycle processes match ES supply and their corresponding products. A broad review of carbon accounting practices, including national and corporate accounts with commonly applied definitions is provided by Stechemesser and Guenther (2012). While carbon sequestration, usually referred as 'removal of emissions' is a key component in these accounting practises, there is no mention of an ES in this overview.

Carbon accounting provides opportunities to define and measure a number of ES which can be expressed and quantified universally in terms of carbon. They are broadly based on vegetation primary production and include some of the most significant and sizeable provisioning ESs, e.g. the ecosystem contribution to growing crops, timber, fibre, animals, wild products, *etc.* as illustrated on *fig. 1.2.* Next, carbon accounting can help to define, delimit and assess the ecosystem units, called also ecosystem assets which supply the above services, for example by assessing agro-ecosystems' suitability for the production of (high-quality) crops, and at a lower cost; and similarly forest ecosystems for production of timber. Finally, the possibility to apply carbon balance indicators (NECB) helps to assess ecosystems' overall condition as affected directly by the rates of supplied ecosystem services and in relation to the state of the underlying stocks of biomass.

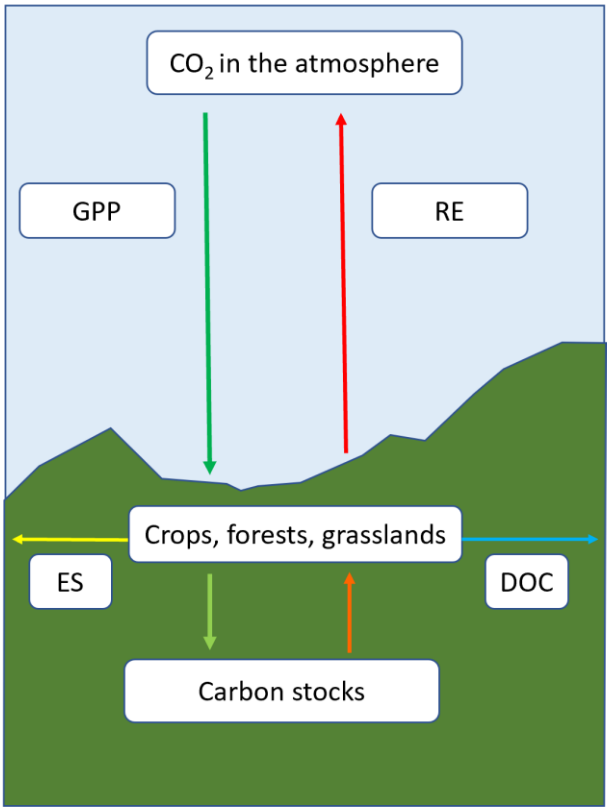


Figure 1.2*: Ecosystem carbon functions and related carbon-based services*

Fig. 1.2 illustrate the key variables which underpin carbon-based ecosystem services. Gross primary production (GPP) is the process which captures CO_2 from the atmosphere as shown by the green line and transforms it into crops, grass and trees biomass in the corresponding ecosystems. One portion of this CO_2 is released back into the atmosphere as a result of ecosystem respiration (RE) composed of autotrophic and heterotrophic respiration (indicated by the red line). Through provisioning ecosystem services (ES) a share of this biomass is exported (from the corresponding ecosystem units) in the form of harvested crops, timber and fodder (yellow line). On the other hand, other lateral transfers of carbon, such as leaching in the form of dissolved organic carbon (DOC) also export some the captured CO_2 into biomass (blue line). The residuals from harvests and lateral transfers feed into the carbon stocks contained in living and dead biomass and also in the soil (light green line). Certain amount of these stocks can also be exported through DOC and timber harvests (orange line). The sum of all the horizontal and lateral movements of carbon define the net ecosystem carbon balance (NECB).

As mentioned in section 1.2, in accordance with the double-entry accounting principle, the approach is to actually measure the service twice, first at the point of its supply and second at the point of its use (or purchase where applicable). The accounts can only be completed when the two sides match, which in the case of carbon means consistency with mass-balance preservation principles, even if certain adjustments may be needed, e.g. to account for accidental losses. This double measurement approach ensures consistency and reliability of the accounting information. If the two sides do not match then something substantial was left unaccounted, or something else was overestimated.

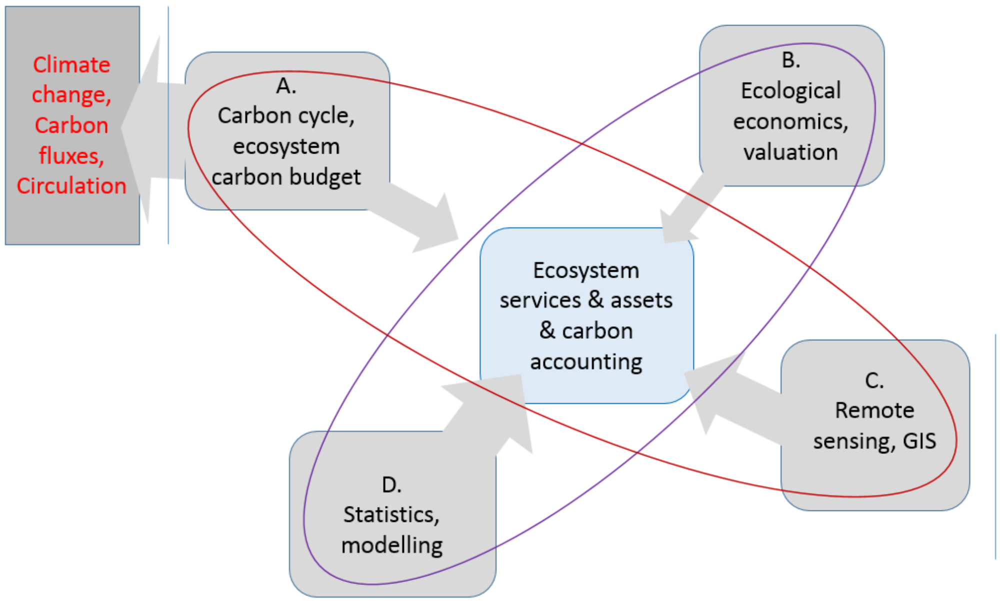


Figure 1.3: Integration of disciplinary inputs for assessing ecosystem services and assets in terms of carbon

Figure 1.3 illustrates the inputs from four distinct disciplinary areas needed to complete an account of ESs expressed in carbon, e.g. A. Carbon cycle science; B. Ecological economics, C. Remote sensing and GIS; and D. Statistics and modelling. Examples of inputs from these areas include land cover and vegetation indices from remote sensing; statistics on crops and timber quantifying the production quantities; carbon cycle variables such as net primary production (NPP), and CO_2 emissions; valuation of carbon sequestration benefits, *etc.* While advances suitable for ES accounting from all of these are abundant, they are driven further by research frontiers which ignore the need for their integration in view of ES accounting. Ultimately, the lack of integration impedes the assessment of multiple ESs, and especially the reliable assessment of their trade-offs. Ecosystem carbon accounting can advance as a field of research and practice by testing how the above building blocks can produce consistent results and knowledge. It contributes to better understanding of natural capital and its links to climate change discourses.

1.5 Research gaps, needs, thesis aim and objectives

Based on the above introduction and literature overviews the main research gaps identified are:

- Rare applications of advanced ecology and plant-physiology sciences to assess ESs, for example applying carbon cycle processes (Braun et al. 2017);
- Insufficiently developed geographical perspectives in ESs supply linked to these processes, since carbon budgets at regional scale has particular uncertainties (despite the relatively more certain estimates at local and global scales), which results in most national carbon budget inventories to be routinely done with default values established by IPCC (in Penman et al. 2003);
- Poorly understood and developed spatial configurations and dependencies in ESs supply, since most mapping methods for ES assessment rely solely on land-cover (Akujärvi, Lehtonen, and Liski 2016).

To address these gaps in a single study it needs to be internationally scoped, based on large-area spatial modelling of key ecological processes and with adequate spatial detail.

The thesis aim is to evaluate how carbon sequestration and provisioning services interact and trade-off in spatially-explicit way across the EU countries, applying carbon cycle and carbon budget approach.

The research hypothesis is that the more carbon is removed or exported from an ecosystem unit with provisioning ESs, the less sequestration takes place in that ecosystem unit, assuming that the exported carbon will eventually end up as additional carbon emissions in the atmosphere. Yet, it is known that for example forest thinning enhances radial growth, thus sequestration in above ground biomass (AGB), so a main research question is in which cases provisioning and sequestration impede- and which enhance each other. By focusing on the ecosystems as spatial units, it is possible to develop an improved understanding of the ES supply mechanisms at ecosystems scale, while the mechanisms of carbon retention and release in the domain of human activities are outside the scope of this study.

The following research objectives were defined:

1. Develop definitions on provisioning and sequestration services in a way that makes them comparable and scalable in biophysical terms, applying carbon as the metric or 'currency' for assessing ecosystem services;

2. Establish which measurement methods apply best for assessing provisioning and sequestration services and to what extent does optical remote sensing data correlate with these measurements in view of their mapping internationally;
3. Test if possible to map provisioning and sequestration services with readily available grid-data from carbon budget models;
4. Test and develop new mapping methods, if available grid-datasets are not sufficient;
5. Assess interactions and trade-offs between provisioning and carbon sequestration services.

These objectives were developed as separate research chapters.

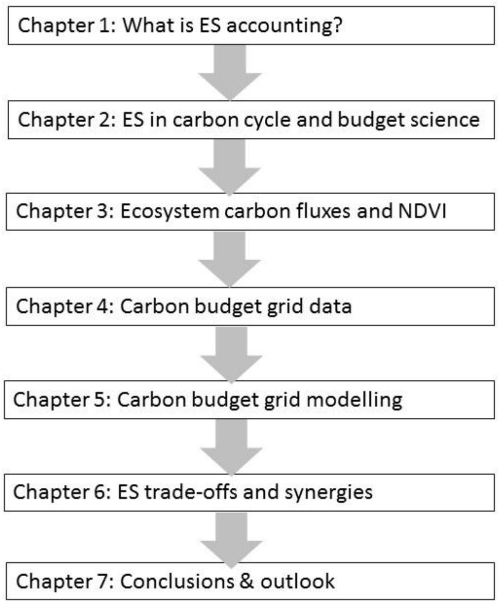


Figure 1.4: Thesis chapters

Chapter 2 explores comprehensively the carbon budget variables to which correspondence with ESs could be drawn. The study started with a review of the published literature on European ecosystems, the relevant values of carbon-measured variables were extracted and compiled in a database. Ecosystem services with their inputs and outputs were assessed through meta-analysis of the published values. Even though multiple observations were collected, the sample size of some key variables was not sufficient for further robust statistical analysis, therefore additional sources were explored for more representative data on the key processes.

Chapter 3 examines the applicability of carbon fluxes data to further inform ecosystem-specific functions (which supply ecosystem services) and also to perform quality control of all the collected ground data. Correlations between remote sensing vegetation indices and carbon fluxes were examined. NDVI was applied to detect possible quality issues of the collected ground-measured fluxes, based on its high correlation with GPP. The data with acceptable quality was then applied for assessment of grid-products on carbon fluxes in Europe.

Chapter 4 provides a review of the available grid products of the main carbon budget variables with European coverage. Further, it evaluates to what extent these products are applicable for mapping provisioning and carbon sequestration ESs considering thematic correspondence with the identified accounting categories in chapter 2 and other criteria, such as spatial detail, temporal coverage and accuracy assessed against the ground-data presented in chapters 2 and 3. Even though multiple grid products on the main carbon budget variables exist, only a single GPP grid product was found to be of acceptable quality.

Chapter 5 introduces a new method for grid-mapping of ecosystem carbon budget and balance, based on multivariate regression predictions with a minimized number of input variables. The method produced consistent grid-maps of provisioning ES, release of carbon to the atmosphere (ecosystem respiration), NEP and NECB. The latter two variables could be validated against the ground data presented in chapters 2 and 3.

Chapter 6 reviews examples of how ES interactions and trade-offs are assessed in the published literature. Trade-offs and synergetic supply of provisioning and carbon sequestration ES on grid-level (across the European countries) were assessed and contrasted trough cluster analysis.

Chapter 7 presents a synthesis of the research findings, followed by discussions on further research needs, on ecosystem carbon accounting in particular. The chapter also includes reflections on related ES definition and measurement issues. Further research needs addressing the role of earth observation and ground data production on the key carbon budget variables are discussed.

Chapter 2: Carbon cycle science for definition, measurement and assessment of ecosystem services

2.1 Introduction

The carbon cycle and carbon pools comprise ecosystem processes and structures in commonly measurable and universally comparable terms on land and water environments (e.g. in carbon derived as a percent of biomass and processes of biomass creation and destruction). Hundreds of ecosystem carbon budget studies have been published for Europe. These studies report directly comparable or convertible measurements [to gC m^{-2}] on the key budget components, including rates of primary production, storage of biomass, growth of crops, fodder and timber. The carbon budget approach makes it possible to identify three pathways for generating ecosystem services: primary production (photosynthesis), secondary production (animal growth) and decomposition-based (saprotrophic) production (e.g. mushrooms, bacteria, soil fauna). Nonetheless, the three pathways obtain organic matter created through photosynthesis, the 'natural' process which converts solar energy and atmospheric CO_2 into energy, raw materials and food for people (Tang et al. 2015, Verma et al. 2014).

Ecosystem services resulting from the process of photosynthesis and ecologically-defined functional traits that were enhanced through agronomic selection to perform carbon allocation into above-ground (seed, fruit, leaves, stems, branches) and below-ground (roots, tubers) biomass are among the most sizeable and most often valued ESs (Smith et al. 2017). Such services contribute to the production of all food, materials and bio-energy. Yet, the key life-enabling process is the capture of CO_2 from the atmosphere and concomitant release of oxygen (O_2) with consequent carbon storage in organic matter. The process is contributing to a balanced atmospheric composition, climate (Costanza et al. 2017) and hydrological regulation (Watanabe and Ortega 2011) functions based on vegetation structures, such as forests.

Figure 2.1 illustrates the main components of the ecosystems carbon cycle and carbon pools, and how they link with human benefits through ESs.

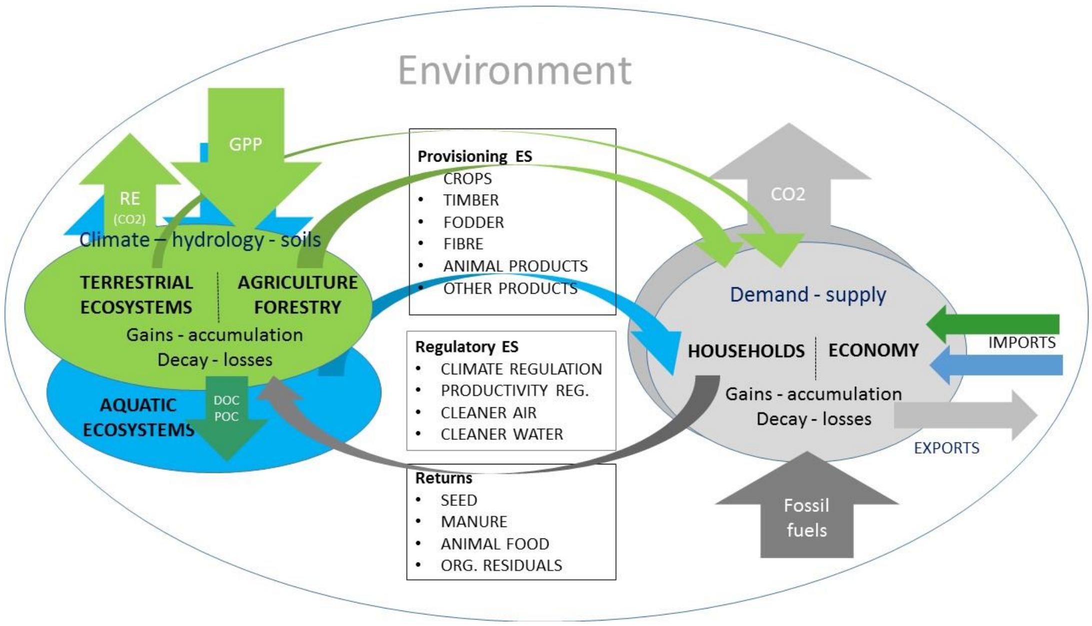


Figure 2.1: Carbon cycle, ecosystem services and their use in an ecosystem accounting context. This study addresses the flows listed as ecosystem services (provisioning and regulatory ES) and returns taking place in terrestrial ecosystems. The ecological functions supplying ES (left side) are explicitly addressed while the economic aspects (right side), only as means to identify the ES types. Other relevant management factors, such as application of mineral fertilizers and irrigation were not included in the figure since they do not transfer carbon in organic forms.

The accounting framework considers ecosystems (terrestrial and aquatic) as production systems (as depicted on the left side of fig. 2.1) which feed inputs into economic production systems (right side of fig 2.1) structured in various sectors. Processes of gain (or growth, production etc.) and accumulation (or storage) can be viewed in both ecological and economic systems, as well as processes of use, decay and losses. Main drivers of these processes in the ecosystems are climate, hydrology and soil fertility, while in economic systems the drivers are demand and supply which can be met either from (local) ecosystems are through imports. Provisioning ecosystem services feed directly (matter and energy) into economic processes, while regulatory ones feed indirectly, by affecting the overall environment (e.g. stabilizing climate, water flows, etc.). As stated in chapter 1 (section 1.5) one of the objectives of this study is to establish a measurement concept (or more specific definition) for the ES that can be expressed in terms of carbon, e.g. the provisioning and regulatory ES, namely climate regulation resulting from carbon sequestration. While multiple studies establish a numerical measure based on how ES supply meets ES demand (e.g. Burkhard et al. 2012; Palacios-Agundez et al. 2015; Sahle et al. 2018; etc.), here, in accordance with the accounting principles the focus is on the match between supply and use.

The use may be material and recorded in the SNA or non-material as in the case of climate regulation.

Many studies have addressed individual ES, for example: above-ground carbon storage at a city-wide scale (Davies et al. 2011); carbon stocks in Finnish Forests in Lapland (Mononen et al. 2017); or a bundle of services related to the carbon cycle, from global- to site-level:

- Climate regulation, food production, soil formation, water supply and flood control as driven by global geo-bio-chemical cycles (Watanabe and Ortega 2011);
- Provisioning and carbon sequestration services in Laegern mountain and its surroundings, in Switzerland (Braun et al. 2017);
- Sheep grazing, timber harvest, forest carbon sequestration and storage in Telemark, south Norway (Schröter et al. 2014);
- Crop and fodder production and carbon sequestration in Limburg province, the Netherlands (Remme, Schröter, and Hein 2014);
- Food (meat produced on site as live weight of animals), fibre (weight of wool produced by sheep or goats grazing on the site) and fuel (Weight of wood grown for fuel on the site) delivered by 11 long-term monitoring sites in the UK (Dick et al. 2011);
- Primary production (NPP, biomass growth), production of raw materials (harvested biomass), climate regulation (carbon stock in tree wood and SOC), Nutrient cycling, water quality control (dissolved organic carbon, DOC) in Västra Torup forest site in south Sweden (Zanchi et al. 2014).

These studies demonstrate much insight into the values and benefits which carbon budget components deliver to people and also much variation of definitions and measurements that obstruct comparability. The latter is cited as a profound problem of defining, measuring and classifying ecosystem services (Fisher, Turner, and Morling 2009, La Notte et al. 2016).

Recently, advanced classification systems on ES, including CICES version 5.1, (Haines-Young and Potschin 2018) and NESCS (US-EPA 2015) demonstrate convergence on what constitutes ESs and how to define them in a structured way which links explicitly ecological and human use processes, yet measurement issues remain. Therefore, the aim of this chapter is to examine the possibility to establish universally applicable definition and measure suitable for multiple and very sizable services. The study explores the possibility to define and measure ES in terms of carbon by following the nomenclature of CICES, where provisioning services are based on either 'biomass' or 'Genetic material from all biota (including seed, spore or gamete production)' and regulatory, based on 'Transformation of biochemical or physical inputs to ecosystems' or 'Regulation of physical, chemical, biological conditions'.

2.1.1 Concept for identifying carbon-based ecosystem services

Based on the reviewed literature and the ES definition of Costanza et al. (2017) cited in section 1.2, an additional conceptualization was developed to identify the ES which can be measured uniformly in terms of carbon. Because of ESs dual nature, with an ecological and human use components, identifying ESs require clear measurement boundary, a concept adapted from the 'economic production boundary' with which SNA operates. The 'ecological production space' in which ESs are generated is conceived according to the principles of classical ecology (Odum 1971) and includes abiotic resources: solar energy, temperature, water, minerals; and biotic components: species with their populations and interactions. The species may be wild or domestic, in which case they are considered part of the economic system (an economic asset), yet their growth and reproduction rely on the same ecological resources and eco-physiological processes as the wild ones when raised in open environment. Hence the ES production boundary delimits the ecological space in which either wild or domestic organisms reproduce and grow to supply benefits to people and the economy. This space excludes the organisms growing in artificial environments (laboratories, greenhouses).

Since not all ecological processes are identifiable as 'services', it is likely that the ecological space produces more than what an ES takes for a recognizable benefit to people and the economy. Hence the measurement boundary needs to delimit, or partition the processes in this space in a way that the ecological component matches quantitatively a used component. The used component may be a product or commodity already included in the SNA (e.g. caught fish, felled timber, or harvested crops). If not so, it may be a subject of novel valuation approaches, such as inquiries of willingness to pay to preserve valuable nature assets (Farber, Costanza, and Wilson 2002), or avoided costs of damage, for example from a storm-surge, prevented by preserved mangroves (Das and Vincent 2009). However, this study does not address such valuation issues, it merely considers products or commodities as means to help identify the services and the ecological functions that generate them. The process of ES generation is also termed an ecological production function (Jonsson et al. 2014).

The proposed concept of 'ecological production space' may be illustrated as a crop field, with suitable topology, soil, minerals, water and solar radiation resources. The more abundant these resources are, up to an optimum, the more ecologically profitable this field will be, which trades-off with the need for agricultural inputs, such as irrigation and fertilizers. Hence the strength of the ecological production process reduces economic production costs. This optimum configuration of ecological resources defines the size of a potential ecosystem process, in this case - for plant biomass growth and may be reflected in the field's price as an agricultural production asset.

The crop species are not considered an ecosystem asset, yet their growth is driven by the availability and suitability of the above resources, hence their growth in the field can be defined as the product of an ecosystem service. The corresponding eco-physiological processes are photosynthesis, generation of organic matter (biomass) and its allocation into plant organs. Photosynthesis and biomass growth are the inputs (or intermediate services) for many ESs, hence what constitutes a specific and final ES is the biomass allocation into plant organs with distinct qualities, such as palatability, nutrition value, energy content etc. Consequently, the outputs of the ESs form part of the different crops. The quantitative output from the ESs depends on the plants functional traits, such as growing season length, biomass allocation mechanisms (in roots, leaves, stems or seeds), root depth, C4 or C3 photosynthesis mechanism, nitrogen fixing structures (Faucon, Houben, and Lambers 2017), all of which are specific adaptations of the plant species to utilize optimally the ecological resources and produce a maximum amount of a given crop.

Further on, if cultivations are ecologically optimized, a bundle of services can be supplied, such as (i) carbon sequestration in the soil, (ii) livestock grazing of crop residues and (iii) habitat for species associated with croplands (farmland birds). The birds may be recognised as a supplier of an additional service to the farmer, by (iv) preventing outbreaks of pest insects. Scale considerations are relevant along with abiotic resources and species for the complete measure of an ES, for example (i) and (ii) might be sufficiently assessed at a single field scale, while (iii) needs a wider landscape assessment, e.g. single field in a large forest matrix would not support a population of farmland birds. This measurement concept implies that most plant growth may incur ESs, including weeds and natural vegetation among the crops, not only the harvestable crop growth, and understanding the additional ones, is a matter of comprehensive measurements and assessments, e.g. to uncover interactions and trade-offs between multiple services and each with likely district value to people which may be popularly recognised at present or not (Costanza et al. 2017).

In accordance with the previously discussed accounting convention, the service supply equals its use which may be identified at the same or at a different scale and place. Consequently, the use links to a product, benefit or good (public or private) which can be commercially traded or otherwise beneficial for people and economic activities. So, in the case of crops, the amount of crop harvest, which equals the corresponding growth of usable plant organs that took place in the field, is the measure of the final service, and the actual use is expressed as the harvested crop. Therefore, supply and use occur at the same ‘production space’, and similarly would be assessed the use of grazing services, with corresponding edible plant growth as a final service, and grazed biomass as the product. Consequently, the ecosystem service supply is to be identified among the ecological processes taking place in a given ecosystem, while the related products may be used within or outside this ecosystem.

In the case of carbon sequestration (because of weeds and crop-leftovers incorporation in the soil), the use aspect would be associated with regional or global public good (e.g. contribution to climate change mitigation) hence supply and use mismatch in scale, yet a biophysical measure is only meaningful at the field level. The use of habitat-service for sustaining farmland bird populations may incur benefits to a national government agency in charge of their conservation, as well as birdwatchers and hunters, and correspondingly the scale of use would be either national or local, while the measure of the service might be defined as the bird reproduction success at the field.

In this measurement concept the key items are defining (i) ecological production space or ecosystem unit (ii) the ecosystem function, (iii) the final service, and (iv) the products. The measurement is done by quantifying a biophysical value of each service, while the assessment involves revealing the weight of the benefit from each service within the bundle. Assessing trade-offs is relevant in both measurement and assessment context. The measurement of a final service will likely need input variables which define the potential processes, as well as physiological processes, such as ecosystem respiration, intermediate production steps, for example the growth of insects which farmland birds consume. The main purpose of the introduced ES measurement concept is to help understand an ecosystem as an ecological production space, which needs to be partitioned into distinct intermediate and final services for a complete assessment of the ESs (with their supply and use) and to help evaluate the interactions and trade-offs between the different ESs.

2.1.2 Research objectives

Measuring the very ecological processes which supply ES is rarely a research novelty, however the novelty here is their identification and recognition as such, and especially - assessing their interactions and trade-offs. A key requirement for such assessments is ensuring comparability and consistency, for which a uniform, or readily convertible measurement units are needed. Studies focused on the carbon budget offer untested opportunities for establishing such an ES measurement system since practically all ecosystems and most ecological processes involve a carbon component. This leads to the need for extensive reviews of published studies and meta-analysis of published data as a first research step.

The research objectives in this chapter are:

1. review space- and time- explicit carbon budget studies in Europe and extract the variables which may be applied as a measure of an ES, (including proxies) and its inputs (ecosystem processes) and outputs (products);
2. develop a carbon based ESs accounting structure for identification and aggregation of the ESs with their inputs and outputs;
3. establish supply pathways, interactions and trade-offs between ESs, with their inputs and outputs.

The outcomes if this study, besides advancing bio-physical comparability of services, can support monetary valuation provided that definitions match concrete products with monetary values; can feed in models for ecosystem services quantification and mapping (where carbon budget variables are applicable); and can be further linked to assessing stocks and ecosystem condition in relation to the used services.

2.2 Methods

The research started with extensive reviews of published studies, followed by meta-analysis and statistical analysis of the extracted data, according to recommendations from Fox et al. (2015).

2.2.1 Literature review for collecting time and space-explicit carbon budget measurements

Several literature searches were performed in Scopus[9] and GoogleScholar, first with the commonly applicable key words 'carbon budget' and 'carbon balance', and additional searches with key words for specific products and services – 'forest thinning', 'forest harvest', 'grassland grazing', 'crop harvest', 'urban carbon exchange'.

The following criteria for selection of studies were followed:

[9] https://www.scopus.com/

- Carbon budget variables: any variable which relates to the ecosystem carbon cycle and pools, expressed in convertible and scalable way to [gCm^{-2}] and [$gCm^{-2}yr^{-1}$] (further referred as '*carbon*').
- Temporal detail: annual, or time periods specific to crop-rotations, and forest-management cycles which span the last 30 years, but more detailed for the period 2000 – 2015.
- Spatial detail: individual ecosystems, defined by specific vegetation and management type, including natural, agricultural or forestry property (management) units which can be considered homogenous in terms of main carbon cycle processes.

Retained were the studies which include carbon records in the current EU countries, plus Switzerland and the UK. Each site has a unique identifier (name), geographic coordinates, dominant land cover type (one of five broad ones: grass, shrub, forest, crop, wetland; and IGBP land cover class) and time for each identified carbon budget component. For consequent meta-analysis the following details were extracted wherever possible: site area (ha), site management, dominant species (of crop, fodder or tree) or species association, altitude, cultivation history, leaf-area index (LAI). Stand inventory data was collected for the forest sites, including age [years], basal area [$m^{-2}ha^{-1}$], number of trees, tree height [m], volume of timber [$m^{-3}ha^{-1}$], diameter [cm] as shown in table 2.1.

Site code	BE-Bra
Site name	Brasschaat (De Inslag Forest)
IGBP land cover	ENF (evergreen needle-leaf forest)
Dom. land cover	Forest
Year (of the record)	2002
Species/association	Scots pine (Pinus sylvestris L.)
Management / use	thinning in February 2002
area (ha)	2
Height (m)	21.4
Age (yr)	80
Number trees	374.5
Diameter (cm)	30
Basal area (m2 ha-1)	27.9
Source	Gielen, et al. 2013

Table 2.1 Descriptive details for forest site Brasschaat, source Gielen, et al. 2013

The different carbon budget components had to be compiled in separate blocks of data, because often one was derived from one source and the next one from a different source, and often for a different period of time. Consequently, the following data blocks (table 2.2) were extracted, each with its own time- and source- reference, but linked to the same site:

A. Ecosystem identification and characteristics, B. Stocks, C. Fluxes, D. Harvests, E. Other fluxes, transfers and NECB.

A. Ecosystem identification and characteristics	**B. Stocks**	**C. Fluxes, growth, mortality**	**D. Harvests**	**E. Other flows, transfers, and NECB**
1.Site name 2.Land cover (IGBP class) 3.Vegetation type (species) 4.Land use / management 5.Geographic coordinates 6.Bio-climatic region	1.Biomass (AGB, with forest inventories) 2.Soil type, SOC, SOC content 3.Livestock	1.GPP, RE, NEP 2.NPP, Wood growth 3.Mortality and residues 4.Soil respiration	1.Fodder (hay, grazed) 2.Animal products (meat, milk) 3.Crops (food, industrial, fodder-crops, energy-crops, crops by-products) 4.Timber and wood	1.CH_4, DOC 2.Returns (manure, seed, feed) 3.NECB

Table 2.2: Site information and variables extracted from the published studies, organized in 5 data blocks within a single database

If not expressed in [$gCm^{-2}yr^{-1}$] at source (but rather often in $tCha^{-1}$), the records were transformed to the former unit. Where biomass was reported as dry matter of either wood, crops or fodder, this was converted to carbon content by applying a uniform weight of 0.5, assuming 50% carbon content as a default value (Penman et al. 2003). Where timber was recorder as volume, it was converted first to wood density using species-specific coefficients from 'the wood database' (www.wood-database.com) and then to 50% carbon content. Live animal biomass was converted to carbon by assuming 30% dry matter content and 50% carbon content from the dry matter.

2.2.2 Analytical framework to structure carbon variables into accounting categories

The objective of this part of the study was to introduce specifications for defining carbon-based ecosystem services and their inputs and outputs.

Once the blocks of data were compiled and linked to specific ecosystem units (sites) and time units, the next step was to interpret the role of the carbon budget components in producing ESs. Specifically, the ESs generation pathways from primary, secondary and saprotrophic production and biomass accumulation were examined. The ecosystem service and product generation process was approached as suggested by the 'cascade model' (Haines-Young and Potschin 2010) and the 'transaction ideas' included in the technical recommendations for SEEA-EEA. Whereby, the generation of an ecosystem service is depicted as a chain of components and events, starting with a biophysical structure (an ecosystem with its stocks) which generates a process, called an 'intermediate service' that entails a final service. The final service contributes to a benefit and further production processes in the economy.

The 'transaction concept' applies specifically in an accounting context, it views the ecosystem as a production unit able to generate something equivalent to a commodity which is then used by people, so an ecosystem service is measured and recorded in two sided form: 'ecosystem service supply' and 'ecosystem service use'. In the present work supply is considered to be the natural process and further referred as the 'ecosystem service', while the use is actually reflecting what people already valued, used or consumed, and most often human inputs were applied to get it, so it is further referred to as a 'product'. The final ecosystem service (supply) and product (use) are same in entity and quantity but may differ in location and 'owner' in accordance with the transaction logic. Thus, in an accounting context the two should be distinguished. The main focus of this study is to advance the services definitions for measurement purpose, so products are further considered only in view of their role to identify services. In addition, because of the difficulty to readily identify the service with its corresponding product, 'proxy services' are considered too. The difference between proxy and intermediate services may also be obscure, in this study an intermediate process is identified when the variable feeds into several final services, while a proxy service is rather a variable that is correlated with an ES that cannot be measured directly.

Based on the above considerations the following accounting categories were defined to advance the identification of ES with their inputs and outputs in a measurement context:

a) Ecosystem components, defined and quantified as stocks in carbon (biomass) are the structures which produce ESs (could be populations of organisms e.g. reindeer; or parts of organisms e.g. standing trees, grass).

b) Ecological functions, called also intermediate ESs are the processes which initiate an ES supply chain, for example photosynthesis (expressed as total amount of CO_2 captured by plants). There can be several distinct processes before identifying an ES.

c) Potential services linked to processes which entail ESs and products, for example the growth of crop plants, which is larger than the actual crop harvest, or that can be divided into several final ESs. For example, positive NEP implies that carbon was captured and retained in biomass, soil or both.

d) Final services are the parts (quantities) of the above processes which match exactly the quantity of the products being harvested or otherwise used or valued.

e) Products are the known ones already included in national accounts (in SNA), such as timber and harvested crops, or yet unaccounted at present, but with clear value to people, for example carbon sequestered in biomass.

The following principles and rules were followed to judge the place each carbon budget component in the ecosystem service generation chain:

- If human activities are needed to access, collect, consume or otherwise use the carbon budget component then it is most likely to be a product. In addition, these items are included in existing official statistics, such as agricultural and forestry year-books.
- If a direct link between the product and either primary, secondary or saprotrophic productivity can be drawn then these processes entail an ecosystem service and the actual value of the service can be expressed as a function of productivity or biomass. The productivity measure in itself is considered an intermediate service (or an ecosystem function), because not all of it will yield a product, only the part that is allocated to either crop product, harvestable fodder or timber, etc. and at certain efficiency rate (Braun et al. 2017).
- If the carbon budget component could be interpreted as a proxy service it was also included in this accounting category.

Consequently, all the reviewed carbon budget components were placed in the most likely accounting category along the service production chain. The judgement was based on recognizing first the product with accountable value. In addition, the transaction logic helped to identify other actual or potential services/products which an owner may use or sell, for example meadow for grazing someone else's animals, which may affect the carbon budget negligibly but effectively sells an ecosystem product (grazed grass).

2.2.3 Analysis of relations between ESs with their inputs and outputs

Once the carbon budget components were allocated into accounting categories, their interlinkages were analysed to further determine and explain the pathways of ESs supply.

The main eco-physiological processes in full relevance to carbon accounting are primary production (PP), secondary- (SP) and saprotrophic production (StP). These processes depend on the quantity and performance of initial stocks, for example 'growing stock' of timber trees or young animals, and a rate of biomass growth depending on the source of the captured carbon. For primary production, it is the atmosphere which is an unlimited source, but elevated CO_2 concentrations are found to have a fertilization effect (Nösberger et al. 2006) on plant growth. For secondary, SP, it is the rate of PP and for saprotrophic it is both PP and SP. In addition, SP and StP can source carbon from other ecosystems, for example inflows of particulate organic carbon through run-off, therefore at a wider spatial scale (or more holistic view) all production processes depend on PP.

The initial production processes are followed by different mechanisms of carbon allocation, e.g. for plants in seed, fruit, tubers (crops), herbal stems and leaves (grass), woody stems and branched (above 6 cm diameter - timber); belowground, etc. which result in identifiable products. These mechanisms depend on species' functional traits. Therefore, the product of the rate of primary production and the allocation mechanism for a given time, is expected to define and measure most carbon-based ecosystem services, and in addition to develop product-specific functions.

As mentioned before, since not all the primary production is used to generate the product, the amount that is actually used can be expressed as a productivity use efficiency [PUE_{ES}], by dividing the accounted product value [AP_{ES}] over the primary production value [PP].

$$PUE_{ES} = AP_{ES} / PP$$

In this way the PP and allocation mechanism can be taken into account for specific classes of products (grown wood, harvested timber, crops, fodder, animal products) that can be further detailed according to the share of this allocation as part of NPP or GPP, to define the growth as a production function of the ES. The values of the ES and the product are the same when expressed in carbon, hence these values can be referred to interchangeably. This rule was applied to estimate [PUE_{ES}] for every studied site where both [PP] and [AP] records were available, as shown on the following example.

Site code	Ecosystem	Years	NPP	PUE_{ES}	AP Crops	Source
BE-Lon	Crop rotation Lonzee (BE)	2004-2007	864	0.47	405	Ceschia, et al., 2010
DE-Geb	Crop rotation Gebesee (DE)	2004-2007	770	0.60	465	Ceschia, et al., 2011
DE-Kli	Crop rotation Klingenberg (DE)	2004-2008	645	0.44	281	Ceschia, et al., 2012
DK-Ris	Crop rotation Risbyholm (DK)	2004-2008	610	0.42	256	Ceschia, et al., 2013
ES-ES3	Rice polder El Saler-Sueca (ES)	2005-2008	928	0.43	402	Ceschia, et al., 2014

Table 2.3: NPP, crop products and PUE applied as definition of the ES of crop growth

Consequently, the product-specific PUE from PP was applied as a production function which enables the estimation of ESs from PP. The efficiency concept applies for assessing potential services too, for example NEP, which can be assessed as a share of GPP, and when positive, interpreted that carbon sequestration took place either in the biomass or the soil.

2.2.4 Statistical analysis

Descriptive statistics of sample size and means with standard errors were calculated for ecosystem processes, services and products. Relations between them were analysed on scatterplots and assessed on the basis of their significance (at either 95% or 99% level) and Pearson correlation coefficients (*r*). As mentioned above, PUE was estimated wherever the corresponding records match for PUE from NPP and GPP. PUE from NPP was examined first since NEP and GPP include respiration which obscures the relationship with AP values.

2.3. Results

Collection and meta-analysis of the carbon budget studies in Europe are shown in this section.

2.3.1 Time and space-explicit carbon budget studies in Europe

The number of sites with retrieved carbon budget measurements across Europe is 242. On five sites land cover changed, and these where counted as different ecosystems, so 247 were considered in total, with the following counts per IGBP class.

IGBP class	Class abbreviation	N sites
Croplands	CRO	54
Closed shrublands	CSH	5
Deciduous broadleaf forest	DBF	38
Evergreen broadleaf forest	EBF	6
Evergreen needleleaf forest	ENF	47
Grasslands	GRA	53
Mixed forest	MF	6
Open shrublands	OSH	9
Savana	SAV	1
Urban areas	URB	4
Wetlands	WET	24
Total		247

Table 2.4: Counts of sites with carbon studies per ecosystem type according to the IGBP nomenclature

These counts are indicative of the breadth of vegetation variability that the meta-study has addressed, and also that only studies on croplands, forests and grasslands can be studied with statistical rigour. The location of the sites is illustrated on fig. 2.3.

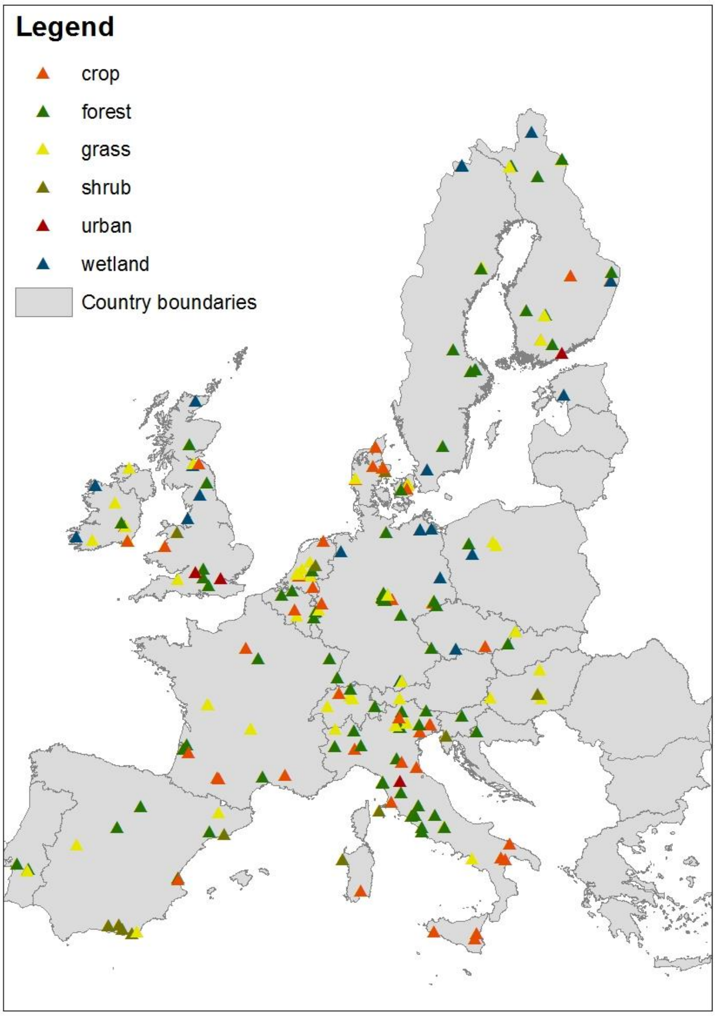


Figure 2.3: Location of sites with carbon budget data in Europe

By dominant land cover type, the sites are well spaced across the European countries, with the exception of south-east Europe. The carbon budget components are reported in comparable way in the reviewed studies and this allowed all the reviewed measurements (shown in Annex 1 and 2) to be summarized into 42 component variables, listed in table 2.3. Most of these studies include an estimate of NEP and GPP and fewer NPP, wood-, and crops growth, AGB, soil carbon stocks and NECB. NECB and Net Biome Productivity (NBP) are considered synonyms and used interchangeably. Only a few studies address and quantify the amount of animal products from grazing animals in time and space explicit way. The latter are also harder to express in a common unit, since grazing times vary in length and intensity. A single study reported the amount of biomass from collected wild mushrooms. While some of the above measurements are produced in standardized way, for example forest biomass growth calculated from forest biomass inventory data, others result from various methods, e.g. NPP and carbon fluxes, or from differing measurement parameters as in the case of SOC. SOC is mostly reported for the topsoil with 30 cm depth but many studied did it at other depts (60 cm or 1 m). These differences affected the number of comparable records shown in the next section, in table 2.5. In addition, not all the variables are independently measured, for example NEP (the inverse of net ecosystem exchange, NEE) is measured by eddy-covariance flux towers, while GPP and RE are estimated by partitioning NEE, hence certain errors are introduced for those estimated variables. Moreover, some of the variables are measured applying different methods, for example NPP, which results in additional quality issues. The quality of the key variables, as affected by differing methods of measurement and modelling methods, is addressed in chapter 3 (on fluxes, NEP, GPP and RE) and chapter 4 (addressing harvests).

2.3.2 Correspondence between carbon budget components and ecosystem services

The carbon budget variables were allocated into accounting categories based on the identification concept introduced in section 2.1.1, their representativeness was judged based on the number of comparable measurements expressed as counts in table 2.5.

Table 2.5 lists 42 carbon budget variables organized in six accounting categories: (1) ecosystem processes (shortly labelled as ‘processes’ in the table); (2) proxy ecosystem services (‘proxies’); (3) final ecosystem services; (4) products; (5) other transfers and fluxes of carbon (labelled as ‘other flows’) and (6) carbon stocks. The counts of site/year number of records (annual records counted as separate observations for each site) is also shown. However, for few of the variables comparable records could not be compiled, such as grazing animals and their excretions (mainly because of the varying periods of grazing). Heterotrophic and autotrophic respiration were included as separate variables but without counts because those are already reflected in the total ecosystem respiration.

Key relations between the different accounting categories (e.g. stocks and flows) are also indicated in the table. With a plus [+] are shown cases where ESs or other flows have a positive contribution to the carbon stocks and the ecosystem carbon balance and a minus [-] negative. The measure for provisioning services is expressed as productivity use efficiency based on the rate of primary production, marked with one star [PUE*] for growth of crops, which corresponds to the harvested crop products. The PUE* for growth of woody biomass is defined as the measure for ES supplying the product of carbon sequestration in woody biomass, if not harvested during the accounting year. PUE** measure ESs resulting from secondary production which equal the amount of animal products (milk, meat), and PUE*** from saprotrophic equalling the amount of collected mushrooms. Multiple years of PUE* for wood-growth (equivalent to the accumulated AGB) need to be considered to quantify the growth which equals the timber harvest. Carbon sequestration (****) in the soil results from combination of processes, starting with breakdown of particulate organic matter (POM, formed of mostly dead plant parts), humification and growth of soil organisms.

	Ecosystem carbon budget component, abbreviation	**N records**	**Process**	**Proxy**	**Final ES**	**Product**	**Other flows**	**Stocks**
1	Gross primary production (GPP)	**370**	**√**					
2	Net primary production (NPP)	**159**	**√**					
3	Ecosystem respiration (RE)	**366**					**√ (-)**	
4	Autotrophic respiration	NA					**√ (-)**	
5	Heterotrophic respiration	NA					**√ (-)**	
6	Animal respiration	NA					**√ (-)**	
7	Soil respiration	**83**					**√ (-)**	
8	Methane, (CH_4)	**64**					**√ (-)**	
9	Grazing animals excretions	NA					**√ (-)**	
10	Net ecosystem production (NEP)	**412**		**√ (+)**				
11	Net Ecosys. Carbon balance (NECB)	**134**		**√ (+)**				
12	Growth of woody biomass	**83**			**PUE* (+)**	**√ (reg.)**		
13	Aboveground biomass (AGB)	**133**						**√**
14	Biomass in stems	**39**						**√**
15	Biomass in branches	**35**						**√**
16	Biomass in herbs/leaves	**28**						**√**
17	Belowground biomass	**54**						**√**
18	Total crops	**104**						
19	Harvested crops	**58**			**PUE* (-)**	**√**		
20	Harvest by-products	**22**			**PUE* (-)**	**√**		
21	Harvest energy crops	**14**			**PUE* (-)**	**√**		
22	Fodder	**74**						
23	Mowed grass	**65**			**PUE* (-)**	**√**		
24	Grazed grass	**21**			**PUE* (-)**	**√**		
25	Grazing animals	NA						**√**
26	Grazing animals products	**29**						
27	Milk	**5**			**PUE**(-)**	**√**		
28	Meet	**19**			**PUE**(-)**	**√**		
29	Sheep wool	**9**			**PUE**(-)**	**√**		
30	Mushrooms	**3**			**PUE***(-**	**√**		
31	Harvested wood/ timber	**24**			**PUE* (-)**	**√**		
32	Harvest residues	**16**			**PUE* (+)**	**√ (reg.)**		
33	Dissolved org. carbon (DOC)	**61**					**√ (-)**	
34	Dissolved inorg. carbon (DIC)	NC					**√ (-)**	
35	Soil org. carbon	**92**						**√**
36	Peat	**14**						**√**
37	Returns (seed, feed)	**45**						
38	Manure/sludge	**97**					**√ (+)**	
39	Seed/seedlings	**40**					**√ (+)**	
40	Animal feed	**5**					**√ (+)**	
41	C sequestration in soil	NA			****** (+)**	**√ (reg.)**		
42	Biomass of soil fauna & bacteria	NA						**√**

Table 2.5 Correspondence between carbon budget components and ecosystem accounting categories. The checked boxes [√] indicate the likely role of each carbon budget component in the ES's production chain. The following abbreviations and signs are used in the table: [NA] means not counted; [+] indicates positive contribution to the carbon stocks and the ecosystem carbon balance and [-] negative. PUE is indicated as a measure of all ES types which can be quantified on the basis of carbon use efficiency, with one star (*) indicating ES supplied through primary production, (**) through secondary, (***) through saprotrophic and (****) a combination of the former. With [prov.] are marked the products resulting from provisioning services and with [reg.] those resulting from regulatory.

The carbon budget records allocated into accounting categories revealed 13 ES with corresponding products, of which eight originate from primary production (crops with by-products and residues, timber, fodder and sequestration in AGB); three from secondary (animal products); one from saprotrophic production (mushrooms) and one from combined production processes and humification (sequestration in the soil). Consequently, 11 out of 13 ESs can be defined as eco-physiological functions, namely growth of organisms and specific organs or tissues, expressed as PUE which is based on and constrained by primary or secondary production.

In addition, NEP, NECB were identified as suitable proxies for the above and other services. NEP and NECB are balance estimates, which when positive can be applied as a measure of carbon sequestration. Positive NEP also indicates biomass growth. Stocks in biomass and soil organic carbon can also be applied as proxies for other, for example regulatory services e.g. hydrological and micro-climate regulation, but these were not further analysed in this study.

These counts show that a wide spectrum of carbon-measured ecosystem services can be identified, but mostly those related to primary production can be further assessed in statistically rigorous way, secondary production processes and products can be assessed to a limited extent and saprotrophic production cannot be analysed further (on the basis of a single study).

2.3.3 Values of the identified ecosystem processes, services and products

Since measurements of the ES of carbon sequestration in the soil could not be identified with uniformly reported values in the carbon budget studies, nor the role of harvest residues feeding into this ES, 11 out of the above 13 ESs and associated ecosystem functions were analysed as shown on figure 2.4. The boxplots show the size (with medians) and variation of the identified intermediate ES (GPP and NPP) and final ES (grown wood, crops, fodder and animal products). Timber harvest is a result of multi-annual timber growth, so the records extracted from the published studies are shown here as an average of a rotation assumed to last 10 years. The letters placed with the variable names indicate the order along the ES production chain, e.g. A. and B. are the rates of gross and net primary production, C. are ES resulting from different carbon allocation mechanisms of it, D. are products resulting from secondary productivity and E. from saprotrophic processes.

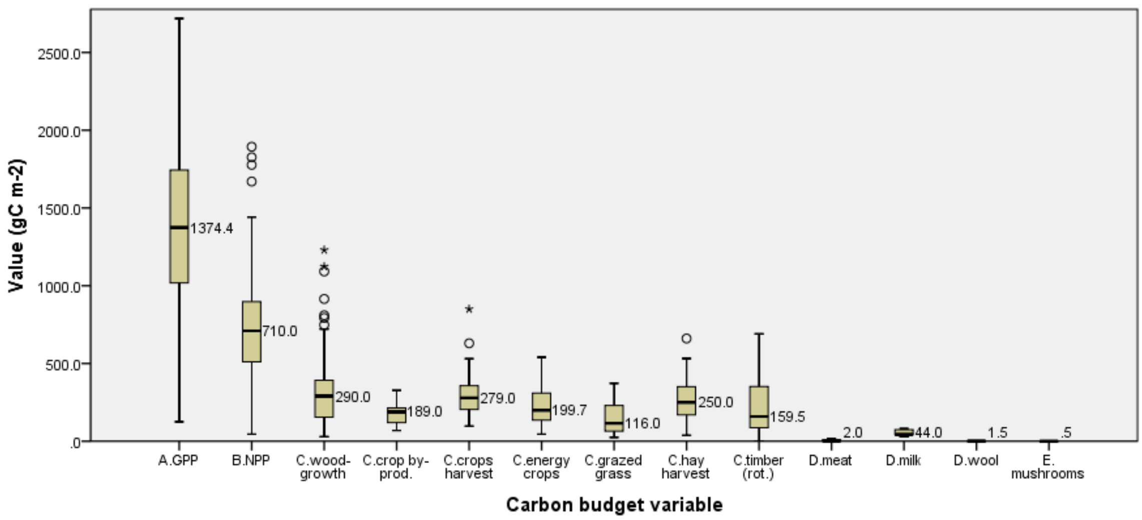
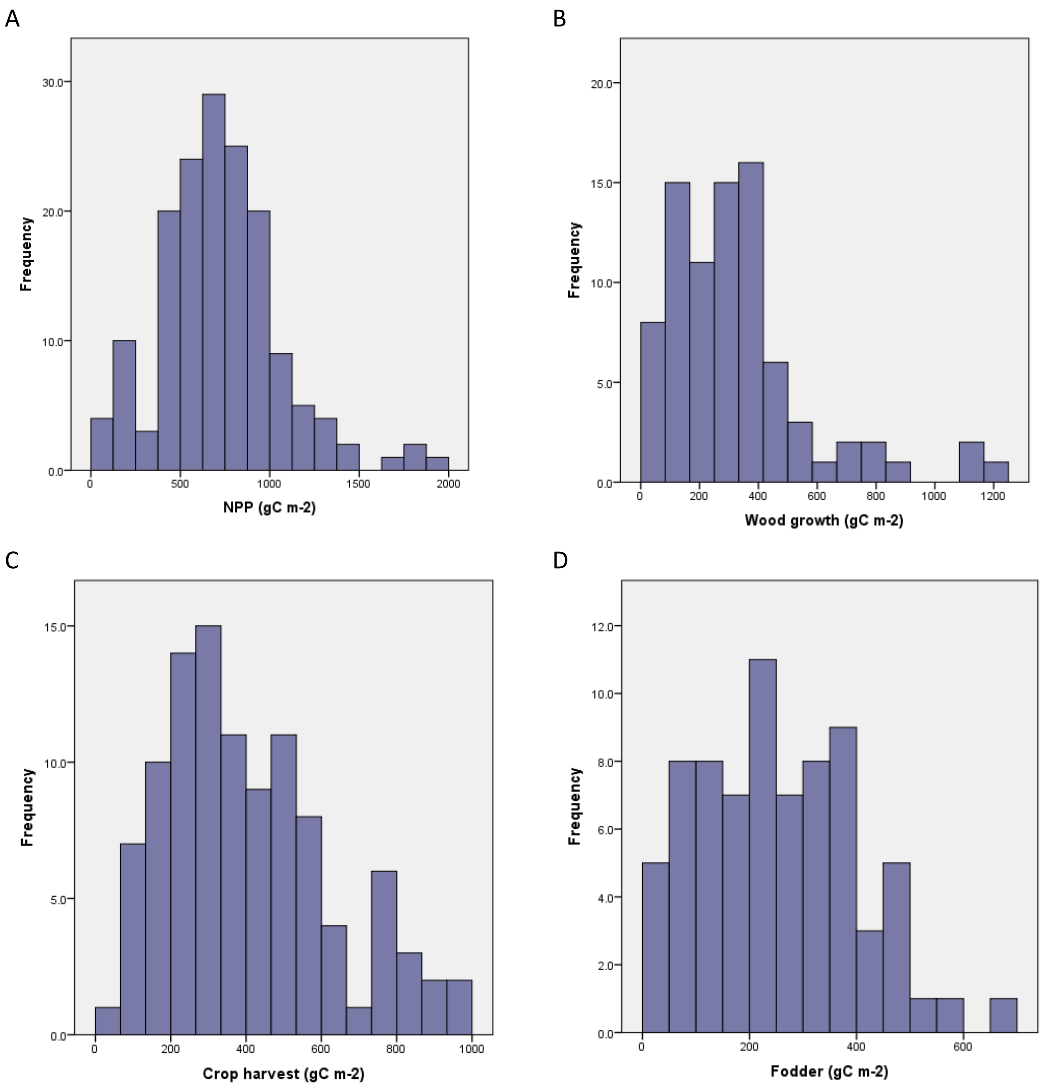


Figure 2.4: Boxplots of carbon budget components from meta-analysis of the studies in Europe

The figure (2.4) summarises the carbon values of the key accounting categories and variables. GPP has the largest median value (1374 gC m^{-2}), NPP is about half of it. Despite the very broad stretch of variability of all primary production components, their medians are similar, between 200 and 300 gC m^{-2}. Animal products of milk and wool and wild mushrooms harvests (0.5 gC m^{-2}) have the smallest values, hence they play negligible role in the carbon budget and balance. Besides the wide variation of the carbon variables, multiple strong outliers can be seen on harvests of crops and hay, wood growth and NPP. The median values of ES's contributing to crops, fodder and wood-growth are likely well representative since these apply to particular ecosystem types (e.g. croplands, grasslands and forests) and because of their larger sample sizes, shown in table 2.3. However, several boxplots are asymmetrical and affected by outliers (wood-growth, harvests of timber, crop by-products and energy crops, grazed grass) hence their suitability for applying parametric statistics to their further analysis is questionable. On the other hand, the smaller sample size of several classes such as milk, meat, wool, energy crops and timber indicate that no robust statistics can be estimated and further data collection is needed.

For further analyses and for estimating more robust statistics, crops, their by-products and energy crops were merged in a single category (total crops), similarly hay and grazed grass (fodder), and milk and meat into total animal products. Timber was assessed in both individual year harvests, and as 10-year mean rotation harvest value. This increased the sample sizes of the ESs grouped in a way that links with the dominating land cover types in Europe: croplands, grasslands and forests. Rates of carbon sequestration in the soil were estimated in very few studies and in different ways, mostly based on stocks-differencing methods, so not explicitly revealing the mechanism of the corresponding ES generation.

While the positive records of NECB can be applied as a measure of sequestered carbon (Braun et al. 2017) considering both biomass and soil (with possible trade-offs between the two), here NECB was analysed as it is, considering also the case when ecosystems act as carbon sources. Histograms of the five consolidated classes of provisioning ES (growth of crops, fodder, timber, animal products and wood-growth), NPP, NEP and NECB are shown on figure 2.5.



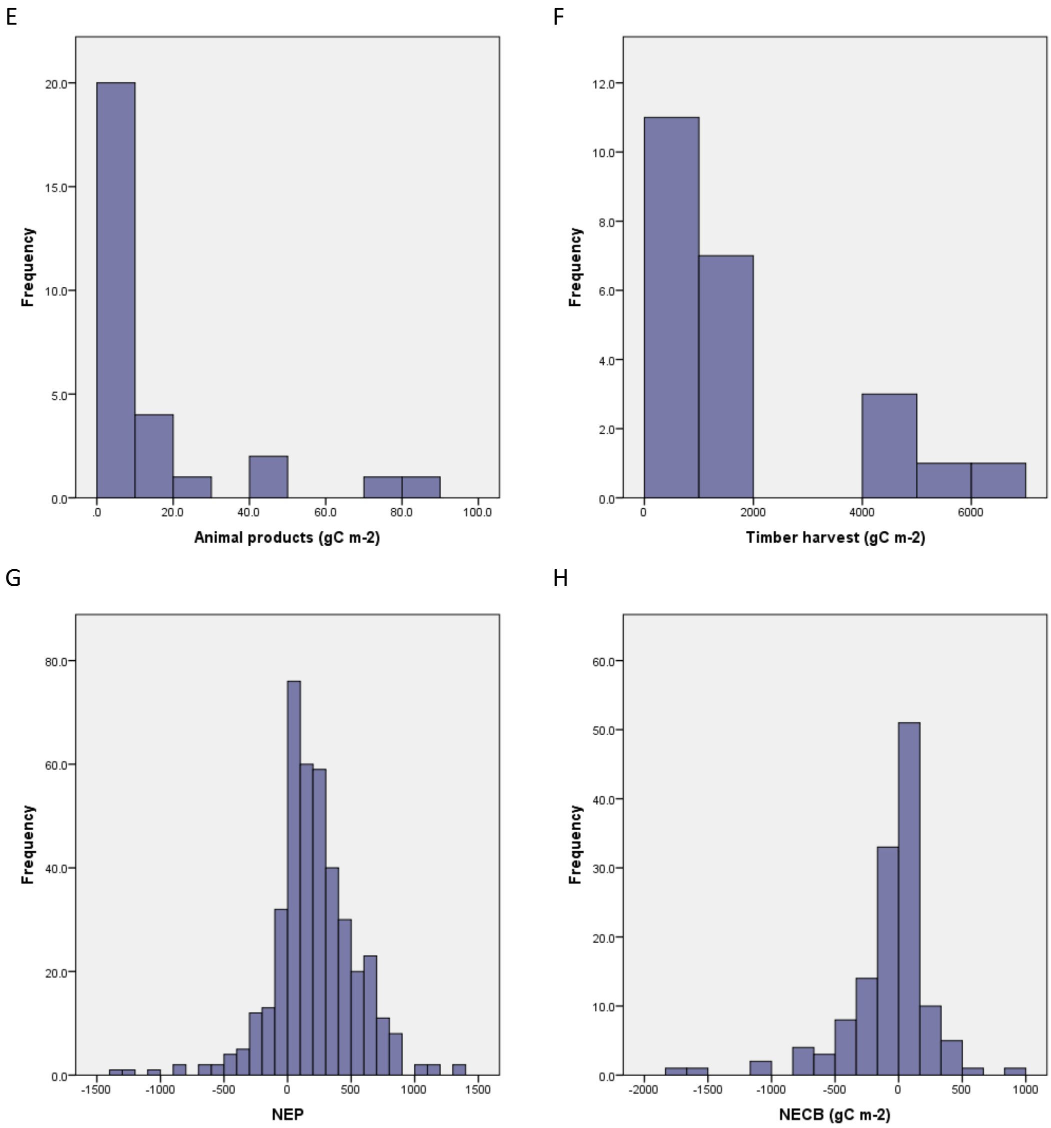


Figure 2.5: Histograms of final and intermediate ES values from published studies in Europe: (A) NPP, n=159; (B) wood-growth, n=83; (C) crops, n=104; (D) fodder, n=74; (E) animal products, n=29; (F) timber harvest, n=24; (G) NEP, n= 412 and (H) NECB, n=134

The histograms of intermediate and final ES values (on figure 2.5) demonstrate substantial variation of their distributions by class. Only fodder values do not differ significantly from a normal distribution according to Shapiro-Wilk test for normality, with test statistic of 0.98 and significance 0.165. All the other distributions differ significantly from normal. Harvests of timber and animal products are most skewed towards the highest values, while wood-growth and crops harvests are slightly less skewed. NEP and NPP have relatively symmetric distributions (skewness for NEP is -0.338 and for NPP is 0.724). GPP values (not shown above) are also symmetrically distributed (skewness -0.111). NECB is skewed towards the lowest (negative) values (skewness -1.804). These distributions indicate that parametric statistics can be used for analysing the intermediate ES (GPP, NPP, NEP) while the final ones need non-parametric analysis.

Table 2.6 shows descriptive statistics for the main carbon variables extracted per six dominating land cover classes (croplands, forests, grasslands, shrublands, wetlands and urban areas) derived by grouping corresponding IGBP land cover types. The statistics include sample size (after the above-mentioned consolidation), median value (to reduce the effect of the outliers in comparisons with means) and range. The values for the consolidated ES types (crops, fodder, animal products, wood-growth and timber harvests) are shown next to values of the primary productivity processes (GPP and NPP) for these ecosystems, as well as losses through ecosystem respiration, DOC flows and methane emissions, and finally NECB.

		GPP	RE	NEP	NPP	Wood growth	Fodder	Animal products	Total crops	Timber	Methane	DOC	NECB
Croplands	N	76	74	90	62	5	4		100		9	7	61
	Median	**1305**	**-970**	**298**	**780**	**98**	**253**		**360**		**0.1**	**13**	**-93**
	Range	2625	3100	2710	1234	83	256		944		28	10	2082
Forests	N	154	153	162	66	73		3	2	23	2	16	7
	Median	**1433**	**-1101**	**289**	**655**	**320**		**0.5**	**176**	**1384**	**15**	**9**	**171**
	Range	2180	1699	1744	1522	1200		1	148	6905	4	25	886
Grasslands	N	108	105	111	21		69	26			38	29	53
	Median	**1556**	**-1433**	**82**	**721**		**232**	**5**			**6**	**7**	**68**
	Range	2518	2675	1696	968		661	81			34	45	1628
Shrublands	N	6	6	6	6	5				1		5	5
	Median	**1337**	**-1174**	**207**	**211**	**61**				**1652**		**5**	**-2**
	Range	1430	1255	274	432	176						20	199
Wetlands	N	24	26	36	2		1				15	4	8
	Median	**449**	**-281**	**56**	**374**		**23**				**5**	**6**	**22**
	Range	1139	1032	754	259						17	8	260
Urban	N			4									
	Median			**-5015**									
	Range			10975									

Table 2.6: Statistics of medians and ranges per dominating land cover types in Europe for the carbon budget items (in gC m^{-2}).

Establishing the correspondences between broad ecosystem types and ES types reveals first a few inconsistencies, for example two records for crops harvested in forests, as well as four records for fodder harvested in croplands and one record of timber harvested from shrublands. The latter is actually a burned forest site, where logs were collected and the site description was defined as open shrubland. The crops in forests are short-rotation-coppice (SRC) sites which were labelled as deciduous forest, whereas the harvested output was labelled as energy crop. These mismatches require further work on defining ecosystem units and services to ensure complete consistency, nevertheless the majority of records are located in their correct place.

Despite being broken by dominating land cover classes the variation of the productivity processes and ESs is still very wide. GPP however does show some differences by class, being highest for grasslands and lowest for wetlands (because most of the latter are sedge-dominated peat bogs). NPP on the other hand is highest for crops and lower for natural vegetation. Because of the rather few counts of NPP for wetlands and shrublands the median values are unlikely to be representative and are clearly inconsistent with GPP which has higher number of counts for most land cover types. The variation of carbon losses through RE, and consequently NEP is the widest. For example urban areas being the largest carbon sources, emit around 5 kg of carbon per square meter as indicated by their median NEP, with maximum value of 12.7 kg for a flux measurement site in central London (Ward et al. 2015), while forest and croplands capture around a quarter of a kg annually. Grasslands and wetlands have NEP medians slightly above zero. Wood-growth in croplands is calculated for permanent crops and is lower in comparison to forests (98 versus 320 gC m^{-2} yr^{-1}). Fodder and crop harvest have similar median values, only the single assessment of grazed fodder on a sedge wetland is much lower (23 gC m^{-2} yr^{-1}). Timber harvests are shown here with their actual quantities at the time of logging, hence they have much higher values up to almost 7 kg per square meter. DOC and methane emissions have very small values when compared with the gross carbon fluxes (GPP and RE) but they are not negligible when compared with NECB. NECB has large sample size for crops and grasslands, and small for forests, shrublands and wetlands. The distinguished values (negative for crops, positive for forests and near-neutral for grasslands) are more contrasting than earlier continental assessments for Europe: e.g. cropland NBP -13 ± 33 gCm^{-2} yr^{-1} (Ciais et al. 2010); 75±20 gCm^{-2} yr^{-1} for forests (Luyssaert et al. 2010) and 15±7 gCm^{-2} yr^{-1} for grasslands (Chang et al. 2015), but still the balances are of the same sign.

2.3.4 Relation between provisioning and sequestration services

The site-values of total provisioning ESs were plotted against NEP and NECB to explore overall relation and likely trade-offs between provisioning and carbon sequestration ESs.

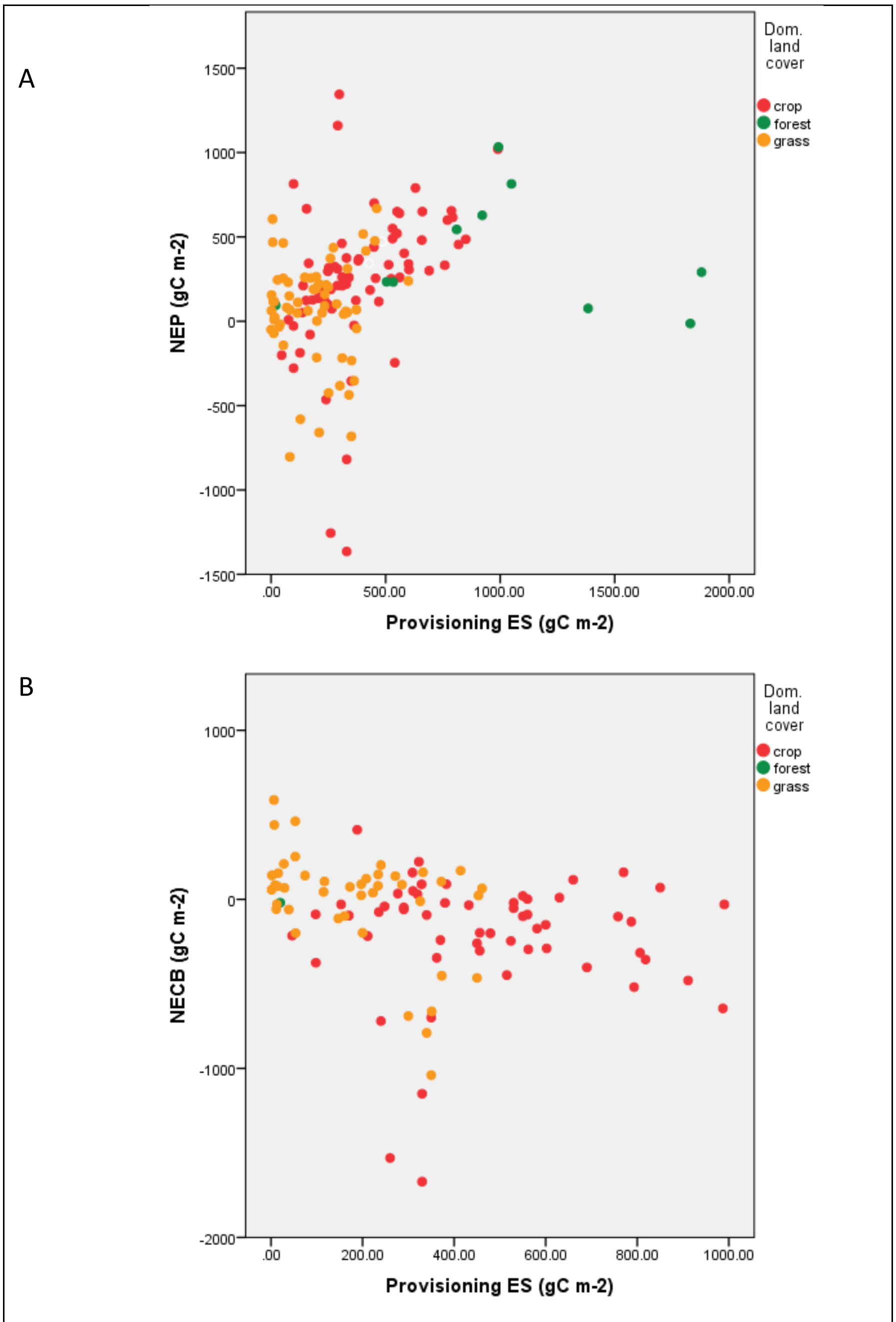


Figure 2.6: Relation between provisioning services and (A) NEP and (B) NECB

The relation explored on a scatterplot between total provisioning ESs against NEP and NECB shows certain negative Pearson correlation with NECB (r = -0.26, significant at 0.01 level) and similar but positive with NEP (r = 0.31, also significant at 0.01 level). The positive relation between NEP and provisioning ESs affirms the suitability of NEP as proxy for multiple ESs. The negative correlation between provisioning ESs and NECB imply an overall trade-off, but the sample size per dominant class is not sufficient for a more detailed assessment. The two scatterplots illustrate the importance of analysing the complete carbon budget and balance for a thorough trade-off assessment.

2.3.5 Relations between primary production and ESs' products

Figure 2.7 illustrates the relations between the provisioning ES products and primary production on scatterplots with GPP (A) and NPP (B). GPP and NPP records are highly correlated (Pearson correlation coefficient, r = 0.76, n=93), so the differences between the two plots arise because of the way the studies reported matches either with NPP or GPP, and rarely with both. The plots include a total of the provisioning values which are calculated as a sum of all crops (with by-products), fodder, animal products, wood-growth and harvested timber, however where harvested timber is reported, the wood-growth was not included as separate ES to avoid double counting.

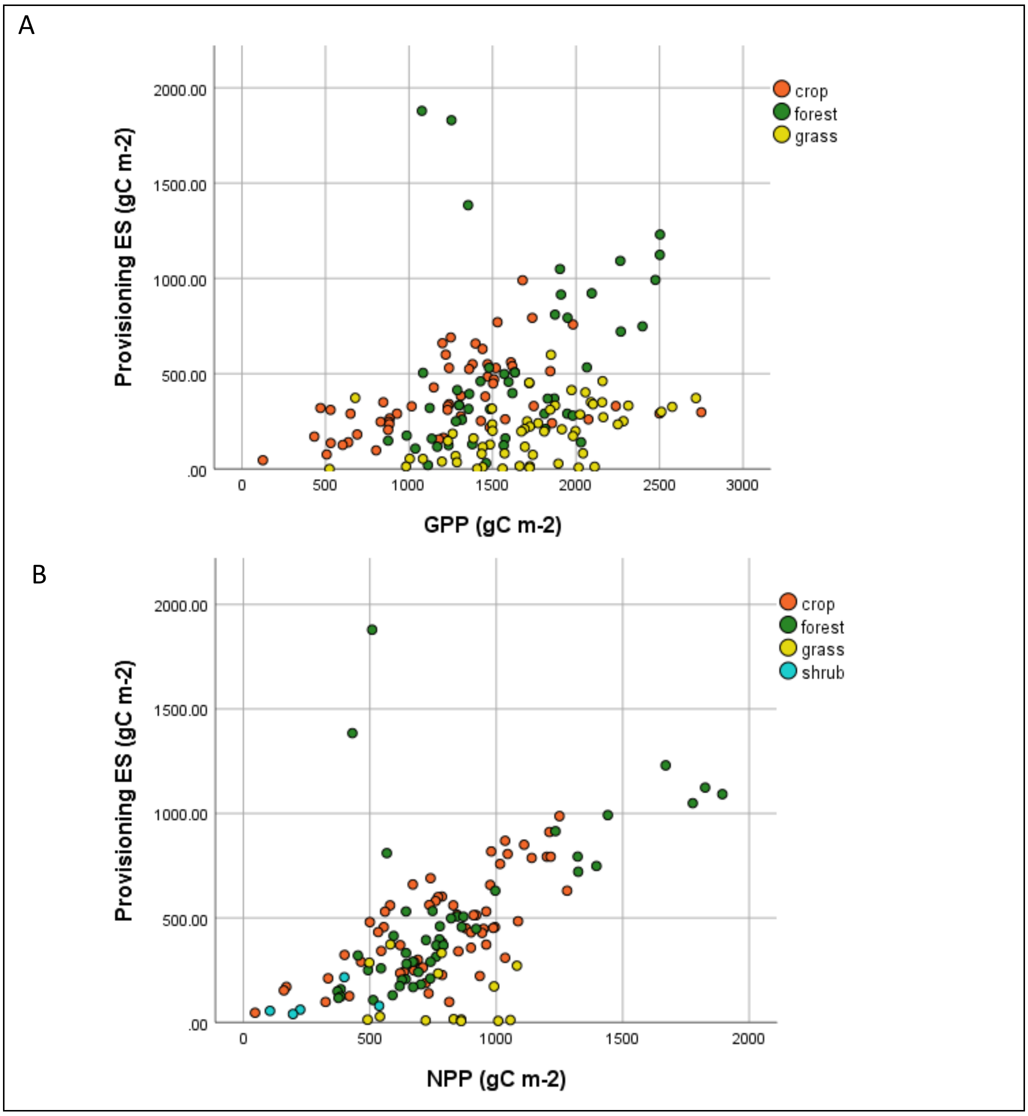
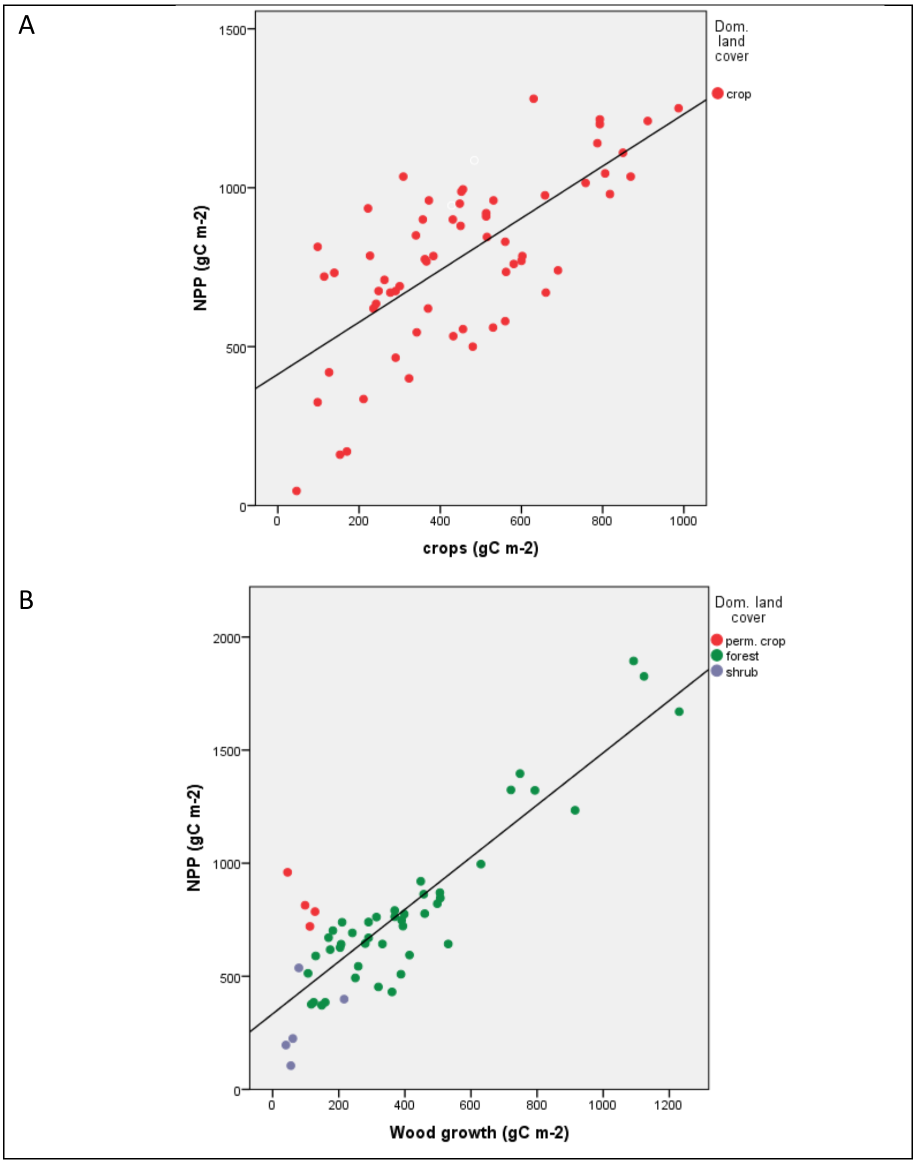


Figure 2.7: Scatterplot of total provisioning ecosystem service values against GPP

The figure indicates that there are linear relationships between some of the ES categories and primary production and with varying steepness of the slopes visible on the scatterplot with GPP. For grasslands (in yellow) there are rather few cases where both NPP and the ES product (fodder) are reported. Overall, a prevailing linear relation is apparent on the NPP plot. Because of the skewed distributions of the final ES, their correlation with NPP was further assessed using Spearman rank correlation coefficient (ρ). Significant and positive correlations between primary production and ES products were found for the three most sizeable ESs: growth of wood, crops and fodder shown on figure 2.8.



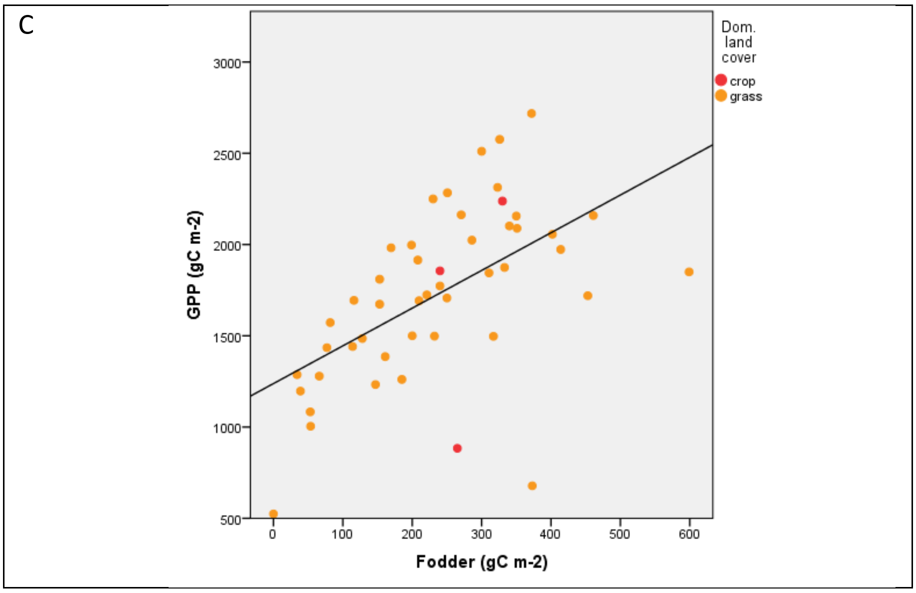


Figure 2.8: Association between ecosystems' primary production and ES products: A crops, B wood-growth and C fodder

The Spearman correlation between crops and NPP is ρ =0.644 (n=64), significant at 0.01 level; between NPP and wood growth is ρ =0.691, (n=53) also significant at 0.01 level. The wood-growth of permanent crops (in red) has distinctively smaller values than forest' wood growth. Fodder was compared with GPP because too few studies reported NPP, but the correlation is almost as for crops, ρ =0.633 (n=48) and also significant at 0.01 level. The two fodder points with high harvest and low GPP values are functionally impossible, since this would mean that nearly all the annual GPP was incorporated in harvestable biomass (without autotrophic respiration). GPP has low and non-significant correlation with animal products (ρ =0.318) which implies limited applicability to predict such products on the basis of GPP or NPP alone. Timber/wood products have no correlation with annual GPP neither with AGB, therefore such products need other information, even though the AGB can be applied as a constraint of maximum possible harvest.

Table 2.7 summarizes the average product-specific PUEs estimated from NPP.

	Croplands			Forests			Grasslands		
CUE from NPP	N	**Mean**	Std. Error of Mean	N	**Mean**	Std. Error of Mean	N	**Mean**	Std. Error of Mean
wood growth	4	**0.12**	0.03	47	**0.48**	0.02			
grass fodder	3	**0.03**	0.03				6	**0.39**	0.08
animal products							10	**0.02**	0.005
main crops	40	**0.41**	0.03						
crop by-products	16	**0.27**	0.02						
energy crops	57	**0.59**	0.03						
timber % AGB				16	**0.24**	0.06			
NECB	42	**-0.30**	0.12	5	**0.40**	0.08	17	**0.14**	0.07

Table 2.7: Average NPP-PUE for ES's products

The growth of crops, fodder and woody biomass display highest shares of NPP in the studied ecosystems (between 40 and 60%) and products from grazing animals the lowest, about 2%. In croplands, the high share of provision PUE is associated with negative NECB, representing about 30% of NPP. In forests these PUEs indicate that provisioning and sequestration ES are supplied synergistically. Wood-growth and grass mowed in croplands (estimated in a few permanent crop cultivations) show much smaller shares from NPP, since these are diminished because of the carbon allocated in fruit-growth, as well as carbon sequestered in the soil often after deliberate deposition of pruning and other plant materials. The large sample size and small standard errors for growth of crops and woody biomass indicates that these have the most representative PUE values and can be applied for estimating ES from NPP. Similar estimates for the remaining categories (based on NPP) would be rather uncertain.

2.4 Discussions and conclusions

The study found that a dozen of ecosystem services can be identified and quantified in terms of carbon, and that the most sizeable ones, such as carbon sequestration, crop and timber provisioning play a key role in the ecosystem carbon budget and balance. The collected ground data from published studies in Europe is suitable for assessing the relations between these ESs with associated ecosystem processes, including primary production and carbon losses through respiration and DOC flows for the dominating land cover types: crops, forests and grasslands. These are the ecosystems with highest values of either provisioning or sequestration ESs, or both in the case of forests. Their ES carbon values are likely well representative because of larger sample sizes with well-matched values along most carbon budget variables. Wetlands and shrublands have much lower ES values, smaller sample sizes of the carbon budget variables and with certain inconsistencies between them, which indicates that more data is needed before clear statements about their ES values can be made.

The provisioning ES for growing crops, wood and fodder are clearly dependant of the rates of NPP, so the latter can be applied as a reliable predictor of their distribution. Carbon sequestration in AGB can be considered equal to annual wood-growth after accounting exports through timber harvests. Sequestration in the soil could not be assessed on the basis of the published data, because the collected records were found to be incomparable. NECB can be applied for assessing the overall sequestration of carbon but only crops and grasslands have large sample size for estimating reliable statistics. Nevertheless, the meta-analysis results on NECB do not contradict previous studies on crops, forests and grasslands. Ciais et al. (2010) reported that croplands NPP from various sources ranged between 490 and 846 $gCm^{-2}yr^{-1}$, and the mean NBP (equivalent to NECB) was -13±33 $gCm^{-2}yr^{-1}$. Similarly, Luyssaert, et al (2010) reported certain convergence between several methods of calculating carbon fluxes of the forests in the EU-25 countries. For example, mean NPP derived from forest inventories was 447, from site studies 544 and from modelling between 439 and 638 $gCm^{-2}yr^{-1}$. Mean forest NBP was 89 according to the national forest inventories, 75 according to site studies and 63 $gCm^{-2}yr^{-1}$according to modelling.

The carbon values of the assessed ESs are only applicable in the context of ecosystem service generation and its impact on the underlying stocks and condition, and not in monetary valuation context. Fresh or dry-weight biomass values would be need to apply in monetary valuation context (e.g. live crop, timber of animal product weight). Yet the carbon equivalent is readily convertible to dry-matter (IPCC 2003) and dry matter of most products can be converted to live weight, hence reporting in carbon does not obstruct valuation in monetary terms.

The overview of the terrestrial carbon budget studies in Europe revealed several pathways of generating ecosystem services which constitute different allocation mechanisms of the CO_2 captured from the atmosphere (expressed in GPP or NPP) and which can be directly measured in carbon. They are based on primary, secondary and saprotrophic productivity or a combination (e.g. for carbon sequestration in the soil). In addition, the following pathway details can be summarized:

(1) Starting with NPP, retention of part of the captured carbon in growing biomass (providing food, materials, bio-energy) and biomass storage (carbon sequestration, timber, habitats). The two processes are performed by different organisms, organs and tissues e.g. growth taking place in plant meristem and cambium; storage in various durable woody plant tissues – heartwood, sapwood, bark;
(2) Biological retention of part of the carbon in soil organic (humus, plant material) and inorganic matter through humification and mineralization (sustaining soil fertility; recycling nutrients) following food-webs and decomposition;
(3) Physical retaining of particulate/dissolved carbon from run-off, excretions and other lateral transfers with consequent decomposition or deposition and sedimentation into durable sequestration forms.

The available studies provide large sample size for meta-analyses of the ESs originating from the first and to a lesser extent of the second pathway. The third pathway was not analysed further in this study. The meta-analysis revealed consistent and robust relations between NPP and ES products which allows to have the latter quantified and mapped on the basis of NPP values.

The definition and identification logic and rules applied are consistent with similar ones from published studies. La Notte et al. (2017) proposed a framework where ecosystem services are conceptualized on the theoretical grounds of systems ecology, suggesting that each service can be tracked in either biomass, interaction or information. Information here is understood as genetic one, e.g. species, and biomass is again the results of allocation and accumulation of NPP. The 13 ESs identified in this study are readily identifiable in 7 classes of ESs in CICES v5.1. Provisioning ESs match at the same level of detail, while regulating services are defined in CICES in broader sense. For example, carbon sequestration is part of general chemical composition regulation of the atmosphere and oceans.

Overall, the carbon budget studies can contribute substantially to the measurement of intermediate, potential and final ecosystem services and their corresponding products in terms of carbon. For further analysis of the ESs, including for their valuation in monetary terms the carbon budget components are not adequately detailed. For example, the timber in tree stems and branches would not be of the same quality and price, also the timber from different tree species will have different quality, hence further identification and definition would be needed in valuation context.

The next steps in this research focus on assessment of ground and grid data applicable for mapping the defined ES in terms of carbon.

Chapter 3: Eddy-covariance and biometric methods for measuring carbon fluxes

3.1 Introduction

The previous chapter revealed that about a dozen ecosystem services (ES) can be identified and their values extracted from the existing carbon budget studies in Europe. These final ES were grouped into two aggregate-level categories: provisioning and carbon sequestration (or regulatory) services as suggested by CICES (Haines-Young and Potschin 2018) and other classifications of ESs. The trade-offs between provisioning and carbon sequestration ESs could be partially assessed at this aggregate level on the basis of a negative and statistically significant correlation between the two. Carbon sequestration and provisioning services display large variation across the continent's ecosystems, mainly as a result of annual GPP and cultivation patterns on mineral and organic soils, which lead to contrasting NEP values. Issues of variable sample size of the ES values collected from the published literature (and associated uncertainties) obstructed their assessment in a statistically rigorous way, in particular for timber and animal products provision. The intermediate services of GPP and NEP on the other hand have much larger sample sizes and broader representability across the continent, therefore their variation needs to be studied further, to understand better their spatial patterns, the quality of the measured flux values, and also to increase the confidence of the final ES assessment.

3.1.1 Ground-data needs for carbon budgets in ecosystem accounting context

Ground data on the main carbon fluxes: GPP, RE and NEP have been scarcely used in ecosystem services accounting, with a single example of Braun et al. (2017) who addressed provisioning and sequestration ESs. On the other hand these fluxes are the most used variables to construct carbon budgets in carbon accounting context (Hutley et al. 2005) which does not address final ESs. Ecosystem accounting requires broad representativeness of the fluxes across biomes and national boundaries hence the data have to be geographically comprehensive - covering all biomes, and ecologically exhaustive – addressing the key carbon budget components. Published sources of carbon budget data are abundant but on specific ecosystems and limited geographical coverage. Recent advances such as Fluxnet (Baldocchi et al. 2001) based on eddy-covariance (EC) techniques to measure carbon fluxes, opened unprecedented opportunities for broad (continental and global), comprehensive (all biomes) and ecologically complex (GPP, RE and NEP) assessments.

The previous chapter (section 2.3.1) revealed that 242 sites across Europe recorded space- and time-explicit carbon budget data, of which 194 include NEP and 158 GPP estimates. Such data are needed on one hand to evaluate the intermediate services on ground level, and on the other to assess the quality of grid-products for mapping ESs at continental level which is the subject of the next chapters. However, the carbon budget includes multiple variables from heterogeneous sources and the first data explorations here, showed rather often inconsistent or even contradictory carbon values for specific sites when the different sources were collated. Thus, ground-level data quality issues can obstruct both site-level assessments and consequent mapping and validation steps at continental scale.

3.1.2 Eddy-covariance versus biometric measurements

Eddy-covariance is the most applied method for measuring high-temporal frequency carbon fluxes for entire ecosystems, since the flux-towers' footprints span hundreds of meters (Baldocchi 2014). The Euroflux network[10] includes hundreds of towers across the continent. Soil chambers are also commonly applied for estimating carbon fluxes, although measurements are typically done at weekly or monthly intervals and the representability of the estimated fluxes might be compromised by vegetation heterogeneity and choice of location (e.g. if not spaced in a homogenous vegetation patch). A number of studies used soil chambers to assess carbon emissions from multiple sites in Europe, including peat wetlands (Wilson et al. 2016), crops on organic soils (Elsgaard et al. 2012), shrublands (Beier et al. 2009). Differences derived from repeated carbon stocks inventories are also applied to assess fluxes, including annual net carbon storage in the soil and biomass pools, as an approximation of NEP (Gielen et al. 2005); and for estimating both GPP and NEP of a short-rotation coppice (SRC) site with artificial CO_2 fertilization. Similarly, De Simon et al. (2012) applied detailed AGB, litter and SOC inventories to evaluate NPP and NEP in two Alpine forest sites. With flux data derived from three measurement approaches, there is an opportunity to test if summary statistics are coherent and consequently - to analyse the impact of the choice of method on the resulting data quality.

Campioli et al. (2016) assessed convergence between eddy covariance and biometric estimates of forest carbon budget. The considered biometric measurement methods included the above-mentioned soil chambers, plant growth assessments and repeated stock inventories. The authors discussed that while eddy-covariance measurements are informed by the vertical air movements, their quality is often affected by advection (horizontal air

[10] http://www.europe-fluxdata.eu/home/sites-list

movements, breeze at varied topography), in particular night-time respiration which gets underestimated (Campioli et al., 2016). Surface energy budgets cannot be closed, so it is likely that underestimated energy may be correlated with underestimated carbon fluxes. In addition, only NEE is measured, GPP and RE are estimates derived by partitioning the NEE. Despite these deficiencies the authors concluded that eddy-covariance is more consistent than biometric methods for carbon budget assessments (Campioli et al., 2016), based on a globally representative study. Day-time partitioned GPP and RE decreased the divergence with biometric estimates for forests. Differences between eddy covariance and biometric estimates did not correlate with environmental factors such as elevation, slope, mean temperature and precipitation (Campioli et al. 2016).

3.1.3 Relations between remote sensing products and carbon fluxes

Multiple site-level studies have revealed high correlation between timeseries of remote sensing products and carbon fluxes, in particular for ecosystems with strong phenological changes. For example, Tang et al. (2013) found very high correlation between LSWI/EVI and fluxes (GPP, NEP and RE) during the growing season of a temperate forest, while during non-grow periods the fluxes were mostly correlated with LST (and more with LSWI than EVI); Yan et al. (2015) did similarly for an alpine grassland.

In terms of spatial variation, the corresponding correlations are less strong and less studied. Chen et al. (2015) performed a comprehensive analysis of correlations between mean EVI and fluxes' (NEP, GPP and RE) values for the global biomes and found high correlations between EVI and GPP/RE for forests and grasslands and low for croplands and wetlands. Correlations between EVI and NEP were lacking or very low for all classes. Nevertheless, other studies (Verma et al. 2014) found higher predictive skill of regressions with vegetation indices and meteorology to predict biome-specific GPP compared to several models, including the MODIS NPP/GPP algorithm (Running et al. 2004).

In addition to fluxes, mapping AGB is widely based upon the NDVI (Zhu and Liu 2015; González-Alonso et al. 2006); changes in NDVI (Gideon Neba et al. 2014), different vegetation indices (Foody, Boyd, and Cutler 2003) and spectral bands in Europe (Gallaun et al. 2010) and the US (Blackard et al. 2008). Because of the indicated consistent relations between vegetation indices and carbon fluxes (and biomass) in the above studies, the potential to apply indices like NDVI for additional quality assessment of the fluxes need to be examined.

3.1.4 Study objectives

A comprehensive carbon flux dataset was collected for Europe from the available sources which cover the period 1995-2016. Many sites contain up to 20-year time-series. The available sources include the published records discussed in the previous chapter and several collections and databases: La Thuile [11], Fluxnet2015[12], DAAC Forest carbon budget (Luyssaert, Inglima, and Jung 2009) and the study of Chen et al. (2015). The data contains multiple observations on GPP, RE and NEP, which reveal broad variations both within and between the ecosystem types alternating from south-to-north and west-to-east of Europe. This variation introduces certain gradients of the flux sizes as shown by Luyssaert et al. (2007) on humid evergreen forests increasing from Boreal with GPP of 973 gC m^{-2}, temperate GPP 1762 gC m^{-2} to tropical GPP 3551 gC m^{-2}.

Direct comparability between measured fluxes over a given site can be obstructed because of the influence of varying conditions, measurement instruments and partitioning methods for GPP and RE estimation (Mauder et al. 2013). Annual and seasonal flux values are sensitive to meteorological extremes (Ciais et al. 2005) which cause large temporal variations, for example two-fold decrease of GPP and NEP during a dry year in comparison to a normal year. Land management and crop selection also cause substantial variation of the fluxes (Gilmanov et al. 2014) because of differences in crop-growth periods and leaf-area index (LAI). Application of manure can also affect the fluxes, by increasing substantially RE in certain conditions that favour accelerated decomposition, and consequently decrease the value of NEP. The flux responses to the above factors are not fully understood and quantified in spatially explicit manner for Europe. Given the highly fragmented nature of European landscapes, there could be 'stable' ecosystem-specific variations of the fluxes, abnormal or extreme values resulting from management or extreme weather factors and measurement or data processing biases. All of these raise data quality issues which may affect strongly the ecosystems' class-specific statistics. Therefore, possible outliers and biases need to be examined and distinguished, if caused as a result of measurement issues or from distinct environmental factors. In the former case the outliers need to be separated as errors or 'bad values' and in the latter as unique ecosystems or 'good outliers'.

The aim of this chapter is to assess the quality of the carbon fluxes data in an ecosystem-explicit way. The quality assessment is based on defining typical carbon fluxes profiles of

[11] https://fluxnet.fluxdata.org/data/la-thuile-dataset/
[12] http://fluxnet.fluxdata.org/data/fluxnet2015-dataset/

European ecosystems and distinguish the 'good outliers' which represent specific ecosystems in Europe from the 'bad ones' resulting from measurement/estimation problems, and 'irregular outliers' from erratic conditions (e.g. too dry, hot or old year). The latter are expected to show up only if cases have single year-observations and are still realistic, but they are less likely to be captured by grid-mapping methods/models (to be evaluated in the next chapter) and therefore need to be marked (tagged).

The objectives of this chapter are to:

1. Compile a comprehensive and exhaustive ground dataset on carbon fluxes of the main biomes in Europe in space- and time- explicit manner from existing data-sources following published quality rules;
2. Analyse how geographic gradients, variation and sample size apply to define class-specific flux profiles of European ecosystems;
3. Analyse relations between the fluxes and remote sensing vegetation indices (NDVI) since strong relationships could help to define outliers resulting from possible measurement issues;
4. Test methods for assessing outliers and establish consistent quality control of the carbon fluxes data derived from different measurement methods.

The expected outcome of this study is a contribution to an improved understanding of data quality issues of the ecosystem fluxes (GPP, RE and NEP) which will be helpful to perform reliable European continental-level validation studies.

3.2. Methods

3.2.1 Database compilation

The ground data compilation for this study built on and expanded the descriptive variables explained in the previous chapter, including vegetation species and land use, to which all the carbon variables were collated with site-explicit annual values.

Geographic coordinates and other site information

The geographic coordinates of the sites were defined to a higher detail e.g. four digit decimal degrees, since most of the published sources reported coordinates only in degrees and minutes. The precise coordinates were defined and quality issues tagged as follows:

- For all sites included in ICOS[13] the precise coordinates were directly applied and tagged with 0 as a quality flag.
- For sites from the published literature which are not included in ICOS, but with coordinates reported in geographic degrees, minutes and seconds, the latter were converted to decimal degrees and tagged with 0 as a quality flag.
- For sites with coordinates specified only in degrees and minutes, a more precise location could be defined in cases where the location was shown also on aerial images, the latter could be recognized in GoogleEarth with more detailed coordinates extracted from there, and tagged with a quality flag 1.
- Sites with no precise coordinates were still retained but tagged with a quality flag 2.
- A few sites with most likely erroneous coordinates were retrieved too and tagged with a quality flag 3.

Since each site was inspected on GoogleEarth, the homogeneity around the study site (plotted as a point) was visually assessed and labelled in a binary form as homogenous or heterogeneous. In addition, possible land cover issues were noted, for example likely confusions between a wetland and forest, if the site was recorded as a wetland but numerous trees could be observed. Information on vegetation species and land use was extracted from the sites' description in the published articles and/or other sources, including fluxnet[14] and various national sources, for example the Italian flux network (Papale et al. 2015). The specific information source for each site was recorded, only a few sites were left with general land cover description according to the IGBP nomenclature (shown in section 2.3.1). Age records were included for sites with forests, permanent and perennial vegetation wherever applicable.

Carbon stocks

Multiple records of stocks in biomass and soil were compiled as shown in section 2.3.2. For this chapter, the values of soil organic carbon (SOC) were further reviewed and some could be harmonized. As mentioned in chapter 2, SOC measurements are reported at varying soil depth (e.g. 20, 30, 60cm) which renders the values incomparable. Also, some studies reported SOC as mass (in tons per ha), others as percent in the topsoil and others as gC contained in a kg of dry soil. The latter could be converted to a percent (divided by a thousand

[13] http://gaia.agraria.unitus.it/home/sites-list
[14] http://www.fluxdata.org

and multiplied by 100). For further analysis, the values expressed as %SOC at 30 cm depth were retained.

Flux data sources

Five sources of spatially distributed carbon flux data were identified: 1. Fluxnet2015, with NEP (the inverse of NEE), day-time and night-time partitioned GPP and RE; 2. La Thuile with NEP, night-time partitioned GPP and RE; 3. DAAC Forest carbon budget (Luyssaert, Inglima, and Jung 2009) with NEP, GPP and RE as produced by various measurement methods; 4. NEP, GPP and RE site-measured data published in peer-reviewed literature; 5. The study of Chen et al. (2015) which contains a very exhaustive compilation of the published data, but does not cover all the sources identified in this study.

The sites and flux data records from the study of Chen et al. (2015) addressed all eddy-covariance measured fluxes globally, and overlapped considerably with the published data for Europe, (source 4 above). There is also a considerable overlap with the forest sites fluxes included in the DAAC database, as well as with fluxnet sites. Consequently, the flux data records were organized in three blocks: Fluxnet2015; La Thuile; and the other 3 sources merged in a single block, called 'published data'. In the latter case, DAAC and the compilation of Chen et al. (2015) were used as complementary sources to the published data collected in chapter two (very few additional items were added).

Flux data quality assessment

Organizing the flux data into three blocks, with large overlap of site/year records provided basis for an initial inspection to find discrepancies between the three blocks and further comparative data quality assessment.

Fluxnet2015 contains advanced data quality information, whereby annually-aggregated NEE values have an overall indicator of completeness, expressed as percent measured (versus gap-filled) half-hourly records which were used to estimate the annual one. Based on this completeness indicator, all annual site/year NEE records with less than 90% completeness were flagged and removed from the database (37% of all records). GPP and RE records estimated from the incomplete NEE were removed too.

The published data-block contains values from eddy-covariance, with GPP and RE mostly partitioned with the night-time method; and also fluxes estimated with soil-chambers and biomass measurement methods. The measurement method was specified for each site/year flux record.

La Thuile contains only a few site/year records which are not covered by the other two data-blocks and was only screened for values largely differing with the other two blocks. Fluxnet2015 and the published data-block were compared by estimating a difference between the two for each of the variables: GPP, RE and NEP. Values which differed by more than 10% were assessed as divergent, with likely measurement errors or bias.

Construction of a combined flux dataset

After initial data quality assessment, removing the incomplete Fluxnet2015 records and flagging the divergent ones, the three data-blocks, Fluxnet2015, La Thuile and published data were merged into a single dataset. This was done to ensure a most comprehensive coverage of the European ecosystems and with largest sample size for each ecosystem and flux type. Flux data from La Thuile was applied for 11 sites, from Fluxnet2015 – for 49 sites and from published sources – for 171 sites.

Based on the comparative assessment of the fluxes from the three data blocks, and literature recommendations (Campioli et al. 2016) eddy-covariance data were given preference over biometric and soil chambers measured fluxes, where site/year records overlapped, provided that the following quality criteria were satisfied:

- Annual NEP (inverse NEE) with over 90% measured data for each year, e.g. up-to a maximum 10% gap-filled estimates used for annual NEP estimation
- GPP and RE with night-time partitioning were retained to ensure agreement with the other sources.

If GPP and RE from published or La Thuile were collated for the same site and the values differed substantially (by more than a third) the GPP from the different sources was assessed additionally against NDVI (see next section), and the source with closer agreement with NDVI was retained.

In addition to the readily available data, the following records could be estimated for this study, from the published records:

- NEP was estimated for sites where biometric data on NPP and heterotrophic respiration (HRE) was reported by the authors, e.g. for six shrubland sites (Beier et al. 2009), based on the same relation (NEP = NPP-HRE);
- GPP was estimated from NPP for the six shrubland sites from Beier et al. (2009) applying CUE coefficient of 0.4.

- NPP was estimated in a few cases by subtracting heterotrophic respiration from NEP (Alberti et al. 2010).

After completing the flux data assessment and compiling a single combined dataset, two versions of flux data were retained: annual data from variable sources per site; and multi-annually averaged values per site, which were estimated from the best source, according to the above criteria.

The distribution of the values in the combined fluxes dataset are shown on figure 3.1.

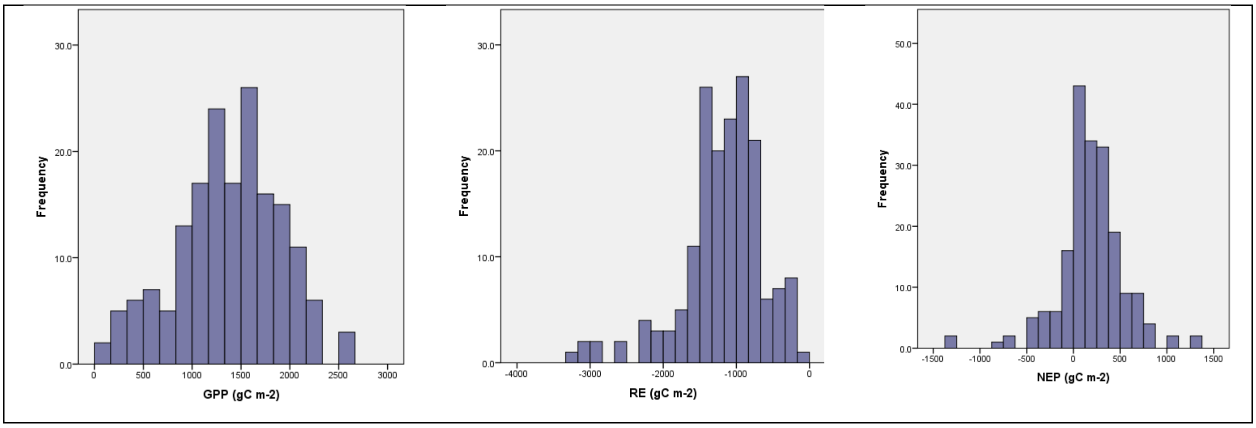


Figure 3.1: Histograms of enlarged datasets of carbon fluxes in Europe

The enlarged data on GPP has symmetric (skewness -0.263) and normally distributed values (Shapiro-Wilk test statistic 0.985, significance 0.065) with no outliers detected on the overall distribution, which makes it suitable for parametric statistical analysis. On the other hand, RE is strongly skewed (-1.159) and NEP- slightly skewed (-0.59) towards the negative values, with multiple outliers, therefore parametric statistics can only be applied with caution.

3.2.2 Scatterplot analysis of geographic gradients and factors affecting the variation of fluxes

Exploratory data analyses were undertaken using the site-average values of the fluxes GPP, RE and NEP against several factors affecting their variability: geographic position, biome, carbon stocks and forest age.

Data exploration started with establishing the broad geographic gradients of variation of the fluxes before analysing the biome-specific variability. If properly detected such gradients will affirm consequent relations between the analysed fluxes GPP, RE and NEP. The gradients were examined by plotting geographic latitude/longitude against the mean value of GPP estimated for each site where multi-annual data exists. The plots helped to uncover overall patterns of variation from south-to-north and from west-to-east and also patterns influenced by vegetation type (crops, grass, forest, shrublands).

The three fluxes were also plotted as single values against the biome types as defined by the IGBP nomenclature to explore if biomes can distinguish flux patterns. This allowed to assess overall spread of values per biome and to distinguish class-patterns where most values lie in close proximity, possible outliers, as well as possible sub-classes within an IGBP class.

Next, the relations between fluxes and carbon stocks were explored similarly, by plotting them against above ground biomass (AGB) and percent organic carbon in the soil (% SOC). Finally, specifically on forest and other woody vegetation, the influence of age on the size of fluxes was assessed too.

3.2.3 Analysis of ecosystem fluxes variation

Biome and ecoregion fluxes

The variation of fluxes per IGBP biomes and European ecoregions were examined on boxplots applying the site-averaged GPP, RE and NEP values per class. In this way the influence of single year climate extremes was expected to be reduced, while real outliers resulting from persistent measurement issues would be revealed when assessing extreme outlier values detected on the boxplots.

Customized ecosystem classification

Because of the rather wide within-class variation of the fluxes, additional classification categories were introduced to partition the IGBP classes into more homogeneous flux classes. For this purpose, a more detailed ecosystem classification was constructed by splitting the IGBP classes to address larger differences (for the same IGBP class) that could be observed within the other three input categories shown in table 3.1: European ecoregions, organic carbon stocks in the soil and forest age classes.

Ecoregion	**IGBP class**	**Soil organic carbon**	**Forest age**
ALP – Alpine	CRO - Annual crop	below 6% - mineral	Clear-cut (0 years)
BOR - Boreal	DBF - Deciduous broadleaf	6 - 11% - low organic	Planted (1 year)
CON- Continental	EBF - Evergreen broadleaf	12 - 18% - high organic	Seedlings (2 – 4 years)
ATL – Atlantic	ENF- Evergreen needleleaf	Above 18 % - very high	Young (5 – 30 years)
MED- Mediterranean	MF - Mixed forest		Mid-age (30 – 100)
PAN – Pannonian	GRA – Grass		Old forest (100 – 400)
	CSH - Closed shrub		
	OSH - Open shrub		
	SAV - Savana		
	WET – Wetland		
	URB – Urban		

Table 3.1 Input variables with main categories used to define a new ecosystem classification

Mean values of the carbon fluxes (GPP, RE and NEP) were inspected first for all the above input classifications separately and then in a merged classification where each IGBP class was subdivided first into 'Ecoregions', then 'SOC classes' and finally 'Forest age'. Consequently, where large differences within a single IGBP class were detected because of any of the other 3 inputs, the class was accordingly split. As a result, the following 21 ecosystem classes were defined and labelled as shown in table 3.2.

Ecosystem code and label	
19.URB	Urban and artificial cover
21.CRO	Annual and perennial crops
22.CRO_org	Annual and perennial crops on organic soils
23.CRO_rice	Rice
24.CRO_perm	Permanent crops
34.FOR_young	Young forest (4 - 24 years)
35.FOR_dist	Clear-cut, disturbed and first year plantations (0 – 3 years unless species is fast-growing)
36.ENF	Evergreen needleleaf forest (Mid- and old-age)
37.ENF_org	Evergreen needleleaf forest on org. soils (Mid- and old-age)
38.ENF_BOR	Boreal evergreen needleleaf forest (Mid- and old-age)
39.DBF_EBF	Deciduous and evergreen broadleaf forests (Mid- and old-age)
40.GRA	Grazed and mowed grasslands
41.GRA_org	Grazed and mowed grasslands on org. soils
43.GRA_ext	Natural and extensively used grasslands
45.OSH	Temperate shrublands
46.CSH_moor	Moors
47.SH_MED	Mediterranean shrublands
48.sparce	Sparse vegetation (Alpine, Tundra and Mediterranean)
51.WET_reed	Wetlands with reed
52.WET_sedge.peat	Wetlands with sage and peat moss
70.peat	Bared peat (peat excavations with no vegetation)

Table 3.2: Classification of ecosystems for discriminating carbon fluxes

The classes were consolidated and labelled taking into account the key ecological, geographical and land use/management factors as explained in section 3.2.2 and 3.2.3.

3.2.5 Analysis of correlation between carbon fluxes and NDVI

The combined set of fluxes: GPP, RE and NEP were plotted against NDVI from MODIS, version six, where annual values were estimated by averaging all bi-weekly ones. The time period included data from 2000 through 2011. First, overall relations were examined by plotting annual NDVI values against GPP, RE and NEP. Next, mean values of GPP and NDVI were assessed per ecosystem types to distinguish ecosystems where mean GPP and NDVI match closely and ecosystems where they do not.

The flux measurement method influence on the relation between GPP, RE and NEP with NDVI was analysed by sub-group trend analysis, where the subgroups distinguished if fluxes were measured through eddy-covariance towers (EC) or biometric methods (BM). The latter include soil chambers and biomass-based estimates.

Outliers were assessed and analysed on scatterplots applying the site-average and annual NDVI and GPP values. Linear correlation between NDVI and GPP were plotted and all values lying outside the 95% confidence interval were marked as outliers. The coefficient of determination (R^2) was compared before and after outlier removal.

3.3 Results

This section includes results from analysis of the European flux data, with class-specific variation and outliers on boxplots and correlations between fluxes and NDVI. The plots of fluxes against NDVI include annual data which for GPP has a sample size of 304, RE – 299 and NEP – 323. The plots against the carbon stocks and other factors are done with either annual or site-averaged values (to ensure consistent match) in which case the sample size is much lower as specified in each case.

3.3.1 Geographic gradients and factors affecting the size of carbon fluxes

Geographic gradients

A scatter plot of site-average GPP values (sample size of 167 records) against latitude and longitude (fig. 3.2) illustrates gradients of decreasing GPP values for forest, crop and grassland sites. GPP decreases from around 50 degrees latitude north-wards and also from about 10 degrees longitude to eastwards. Overall, these gradients are driven by the temperature and precipitation patterns in Europe, however land use legacies also play a role.

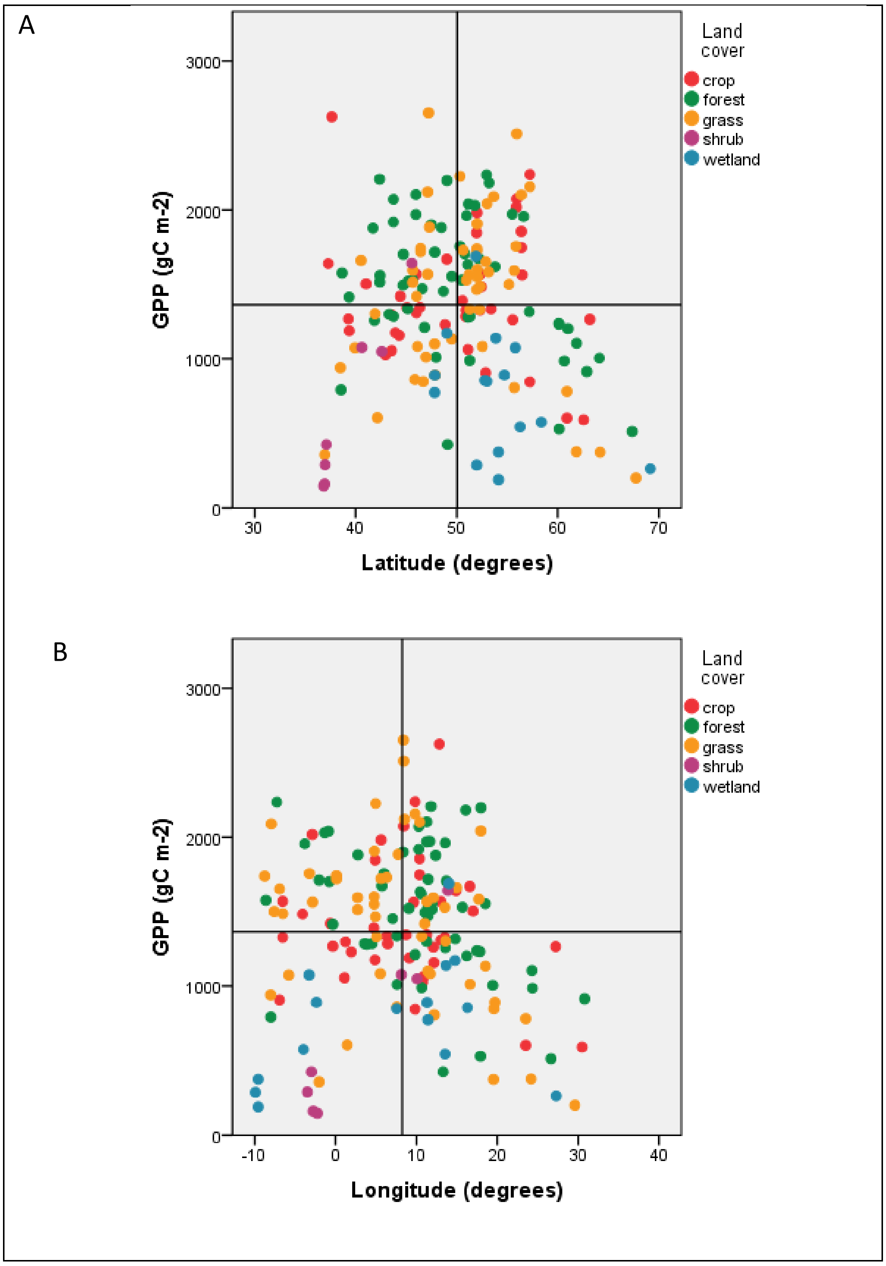


Figure 3.2: Scatterplots of GPP and geographic latitude (A) and longitude (B)

The variation of GPP values is much wider in the west and south of Europe due to the interaction of multiple factors affecting GPP and narrows down towards north and east, where temperature and precipitation become the main limiting factors on the size of the carbon fluxes. These gradients need to be taken into accounts for analysing ecosystem-specific variation of the fluxes. Wetlands and the arid shrub- and grass- sites of Spain (low-left points) do not conform to the overall geographic gradients.

Relations between carbon fluxes and carbon stocks in above ground biomass and soil

Mostly forest sites had corresponding values of fluxes and above ground biomass, but a few permanent and perennial crops too. GPP, RE and NEP fluxes and AGB values were matched at either single years or as an average of several years. Scatterplots of association between carbon fluxes and stocks were examined separately. The one between NEP and AGB (n = 57) is shown on figures 3.2 and then scatterplots of GPP and NEP against percent SOC on figure 3.3 (n = 88 and n = 86 respectively). The rest are not shown because of having shapes rather similar to the ones mentioned.

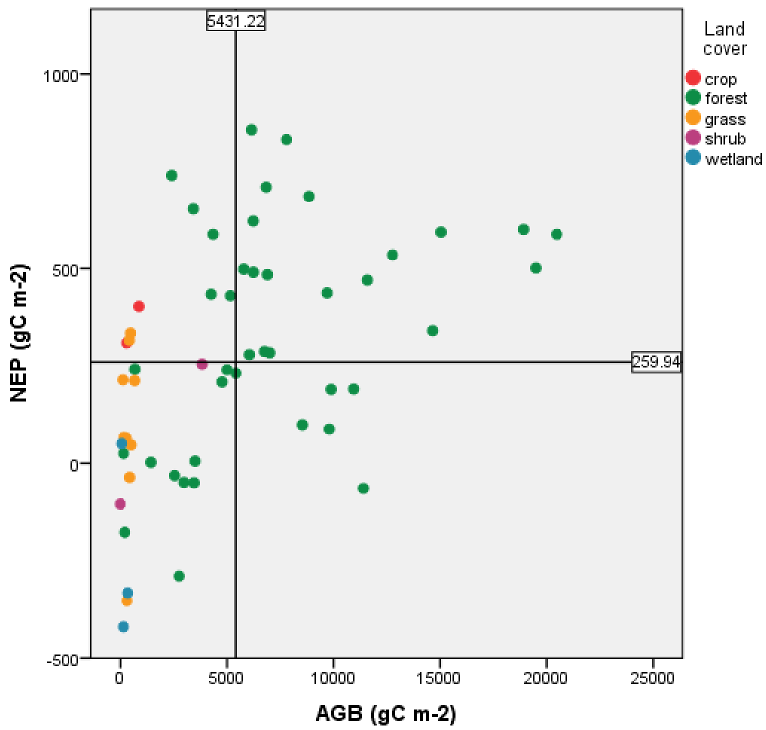


Figure 3.3: Association between AGB and NEP

All fluxes have a pattern of wide dispersion for biomass below 5000 gC m^{-2}, which narrows down at high AGB values as shown for NEP against AGB (figure 3.3). The plot indicates that forests with lower biomass have highest NEP values. NEP then declines with increasing biomass, yet most high biomass forest sites maintain also positive NEP, only one is below 0, which indicates that these sites continue accumulating carbon stocks, as documented before (Knohl et al. 2003), but contrary to common carbon accounting assertions that old forests are carbon-neutral.

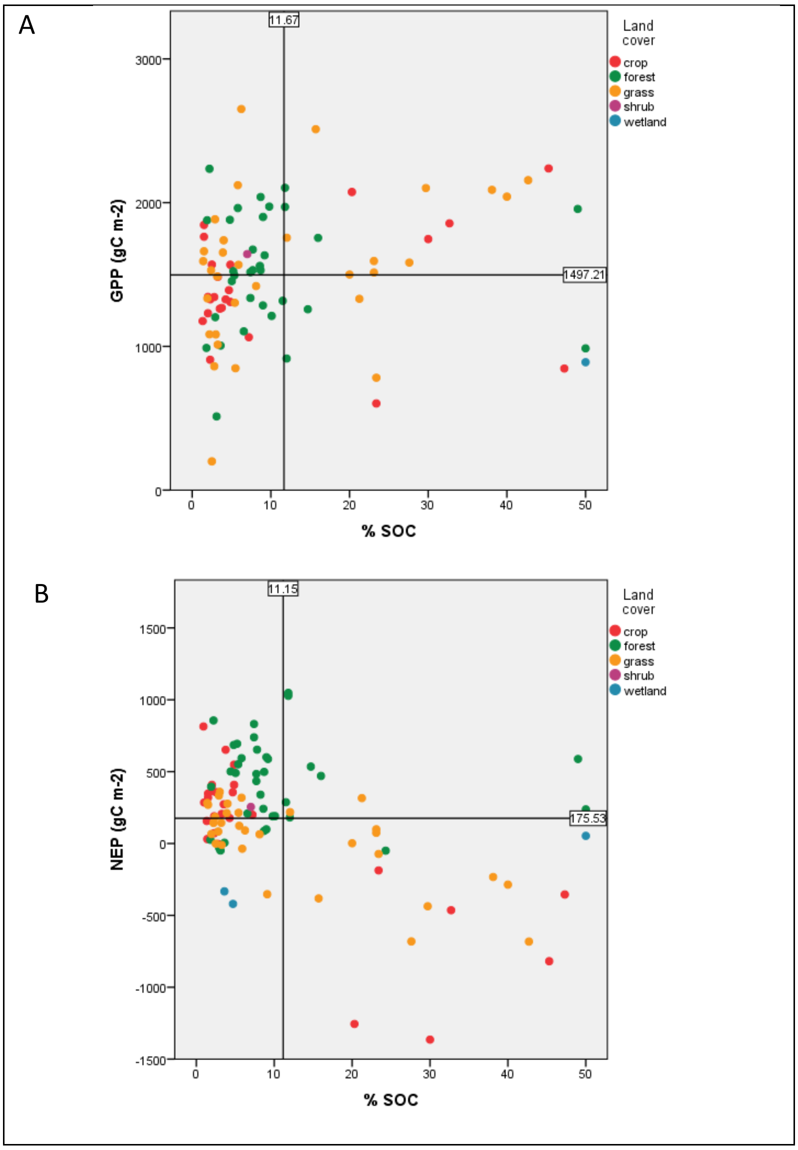


Figure 3.4: Association between organic carbon content in soil and (A) GPP, (B) NEP

GPP does not show a relation with % SOC but NEP (and similarly RE) display a clear pattern of large negative values above the mean % SOC of about 11%, and this value is an appropriate distinction point for most organic soil types. All these negative NEP values are from crop and grass sites, while the few forest sites on organic soils maintain NEP above 0. In conclusion, SOC might be of little relevance to provisioning services (originating from GPP), but of great relevance to carbon sequestration.

Biome-specific carbon fluxes variation

Site-averaged fluxes of GPP, RE and NEP were plotted per biome type (as dash symbols) on fig. 3.5.

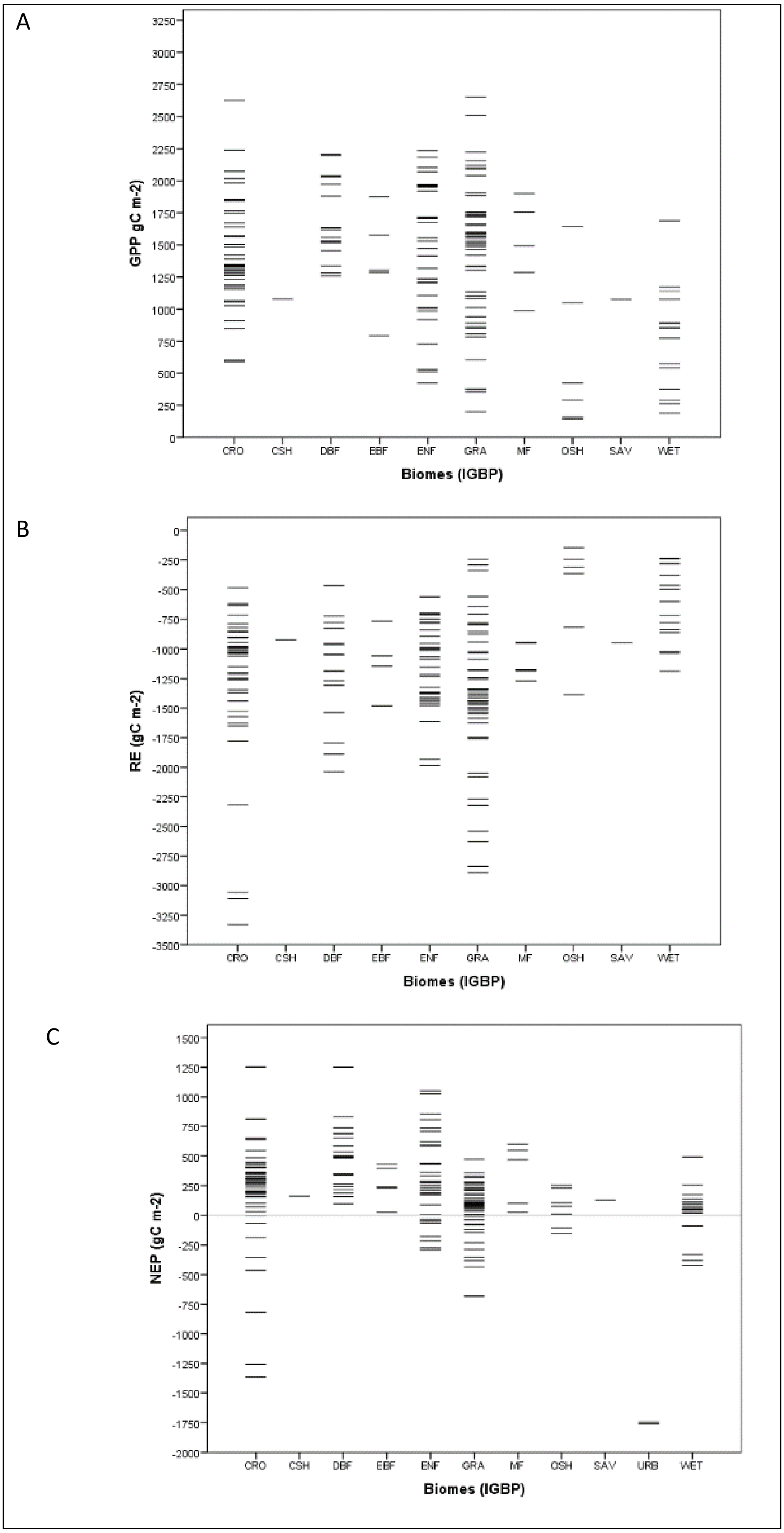


Figure 3.5: Values of (A) GPP, (B) RE and (C) NEP per IGBP biome

All biomes with multiple observations show wide variation on the GPP and RE plots, with crops, grasslands and ENF having particularly wide stretch of values. Groups (or clusters) of closer GPP and RE values can be observed within the crops, broad-leaf and needle-leaf forests and the grass sites, suggesting that there are essentially different ecosystems to be distinguished in these IGBP classes. NEP has similarly wide spread for crops and more narrow variation for the other biomes, with a number of single-value outliers, but sub-groups can be distinguished on this graph too.

Influence of woody vegetation age on GPP and NEP

The scatterplots on figure 3.6 show relations between the size of fluxes of woody and perennial vegetation and their age.

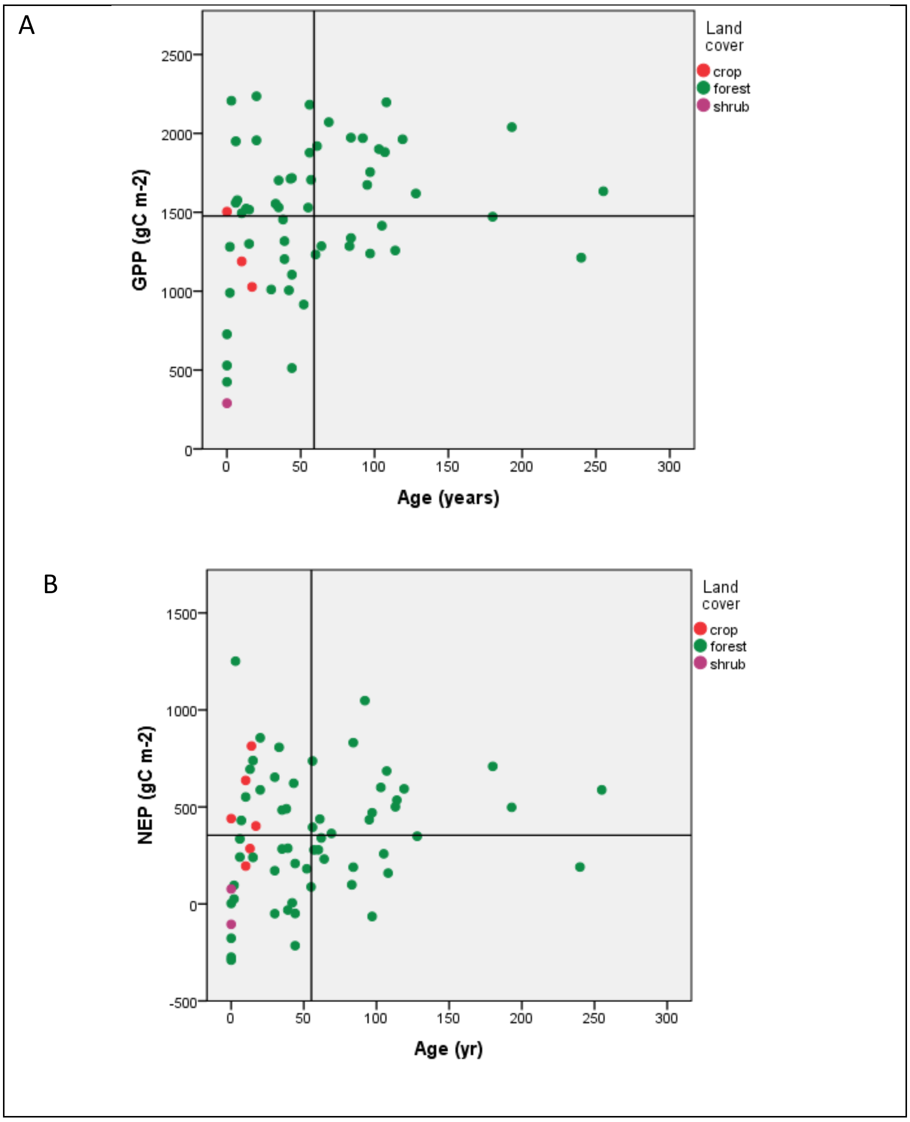


Figure 3.6: Dependence of GPP and NEP on the age of woody and perennial vegetation

The fluxes of woody vegetation, which is mainly forests and a few permanent or perennial crops do not correlate clearly with age but do show patterns. GPP and NEP are increasing until mid-age (around 50 years) where they level off and slightly decrease towards old-ages. The crop sites shown on the graph are either perennial or permanent crops where age was reported. NEP of these crops increases with age, which was also emphasized in the studies from which the data was extracted (Ní Choncubhair et al. 2017 and Sabbatini et al. 2016).

3.3.2 Class patterns of the carbon fluxes and outliers

Biomes and ecoregions fluxes

The gradients of decreasing flux sizes northwards and eastwards were expected to cause distinguishable flux patterns when summarised by biome and ecoregion. However, the medians and interquartile ranges did not show clear differences when inspected on the boxplots of figure 3.7. The dominant land cover types of grass, crop and conifer forest ecosystems have particularly similar medians and variations of GPP as shown on the IGBP plot (left), while clearer differences can be observed on the ecoregions plot (right) which reflect better the geographic gradients discussed above.

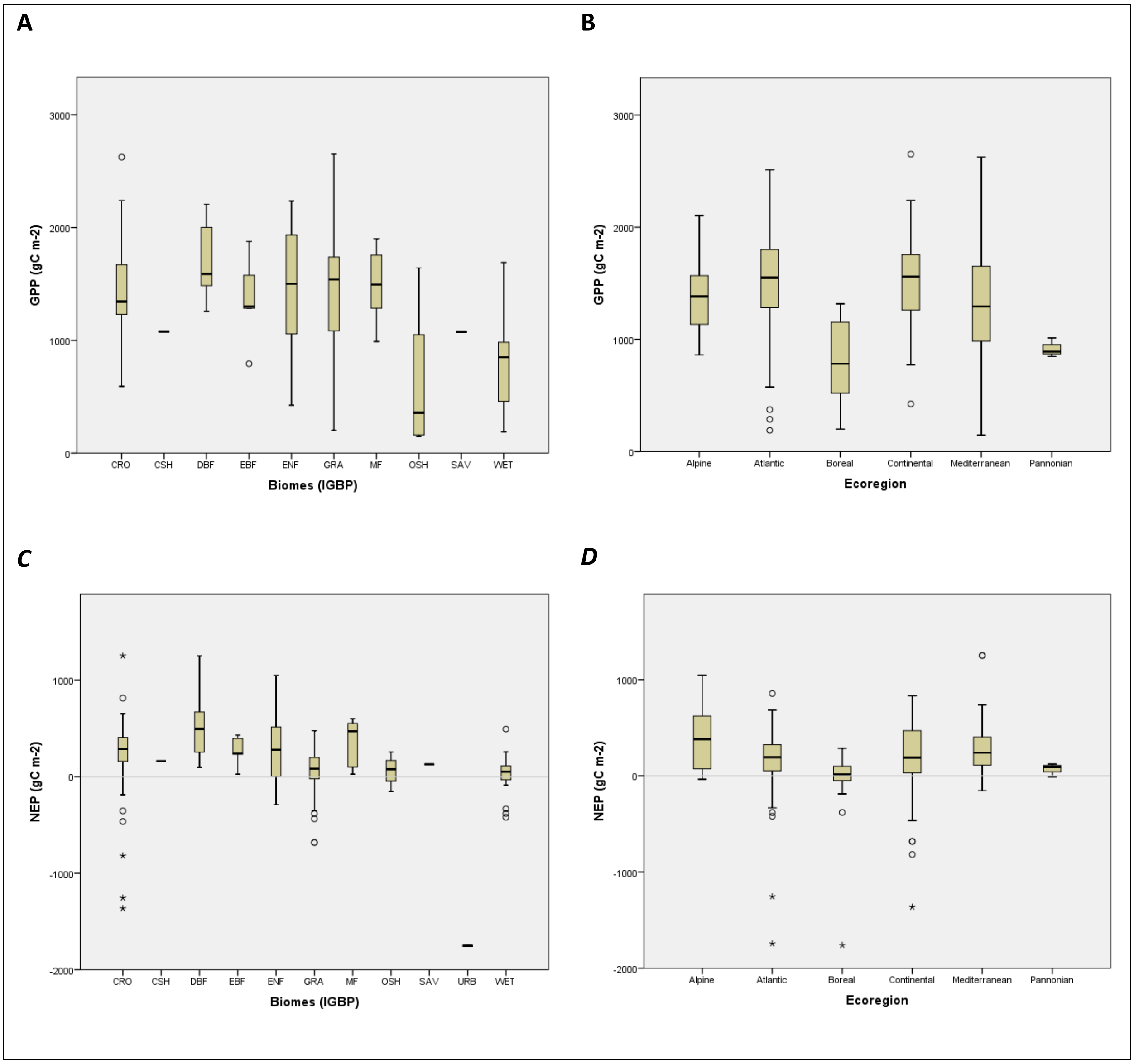


Figure 3.7: Boxplots of GPP and NEP by biome (A and C) and ecoregion (B and D)

NEP medians differ more than GPP, with grasslands, shrublands and wetlands close to 0, higher for croplands and highest for broadleaf forest. Ecosystems in the Boreal and Pannonian ecoregions have NEP close to 0 on average, while Alpine ones appear with highest NEP.

A number of outliers could be detected on the above boxplots. An olive orchard (IT-Ctv) and a grassland (PT-Mi1) are detected as outliers on the IGBP plot of GPP; the same orchard (IT-Ctv) also on the NEP plot affirming it as an outlier. A number of cultivated sites (crops and grass) are also identified as outliers on the NEP plot. These sites with large negative NEP values, were identified as cultivations on organic soils which should be defined as a distinct ecosystem rather than outliers. On the ecoregions' plot of GPP, different sites appeared as outliers: moors in Ireland with lowest GPP (IE-Kil, IE-Bellacorick); and a grassland in

Switzerland with highest GPP (CH-Cha). However, on the NEP plot the same sites as on the GPP plot are detected as outliers, namely those on organic soils, and also the urban ecosystems because of the very high CO_2 release there.

The above figures illustrate that the existing classification cannot distinguish the carbon flux profiles of European ecosystems, therefore the customized ecosystem classification was applied.

Custom ecosystem classes

A boxplot of GPP per customized ecosystem types is shown on fig. 3.8. Urban and peat sites did not have GPP values and were excluded from this plot. These boxplots demonstrate much narrowed within-class variation, exceptions are the classes of cultivated grass and crops on organic soils, which vary widely because they contain sites from all the biomes (Boreal, Atlantic, Continental and Mediterranean). The organic grass sites have highest GPP; followed by very high in young, needle-leaf and broadleaf forests, cultivated grasslands on mineral soils. Sparse vegetation has the lowest GPP, sedge/peat-moss wetlands, moors and disturbed forests have slightly higher.

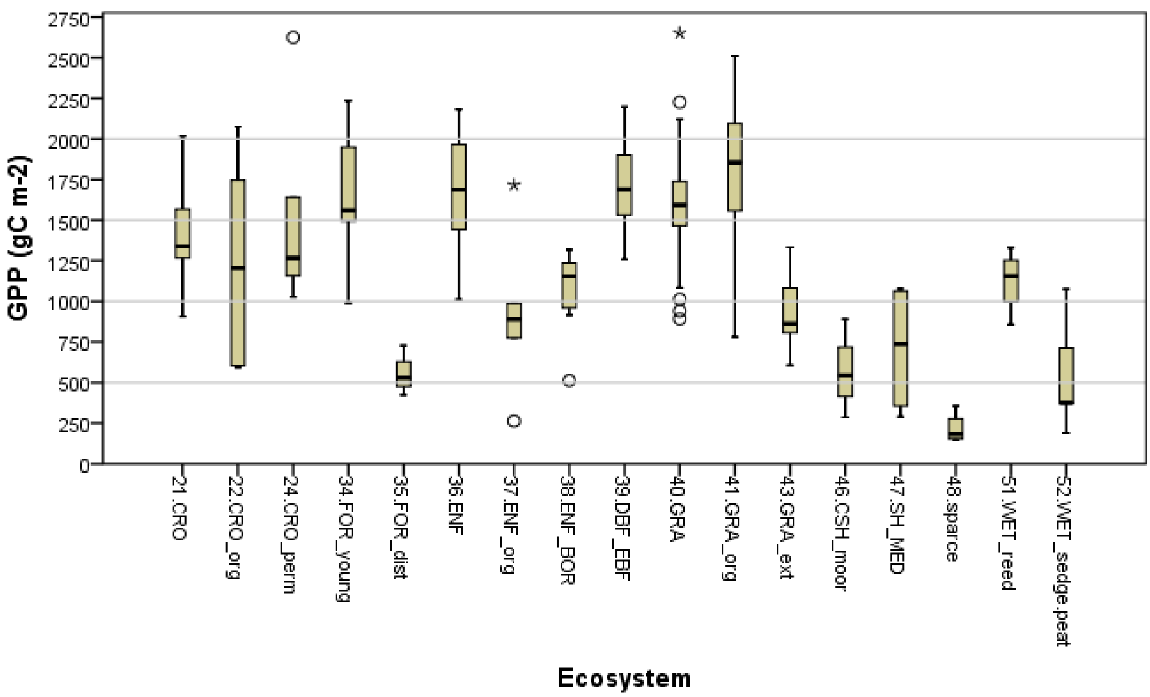


Figure 3.8: GPP of European ecosystems with interquartile ranges, outliers (dots) and extreme outliers (stars)

A few outliers can be seen on the plot of figure 3.8: extreme ones (marked with a star) in grasslands (CH-Cha), and needle-leaf forest on organic soils. The latter is actually a 'good outlier', DE-Mooseurach is a temperate forest site which differs from the rest that are all in the Boreal ecoregion with distinctly smaller fluxes. The rest of the outliers, IT-Ctv, (also detected in the previous section), FI-Kaa, FI-Sod, HU-He1, BE-Dor, HU-Mat, PT-Mi2 need further examination to be assessed as outliers.

The next boxplot on figure 3.9 shows RE per ecosystem types. Most of the medians and interquartile ranges have similar patterns as for GPP, however the grass and crop cultivations on organic soils show very large carbon sources, up to 3 kg C m^{-2} and with vary wide variation.

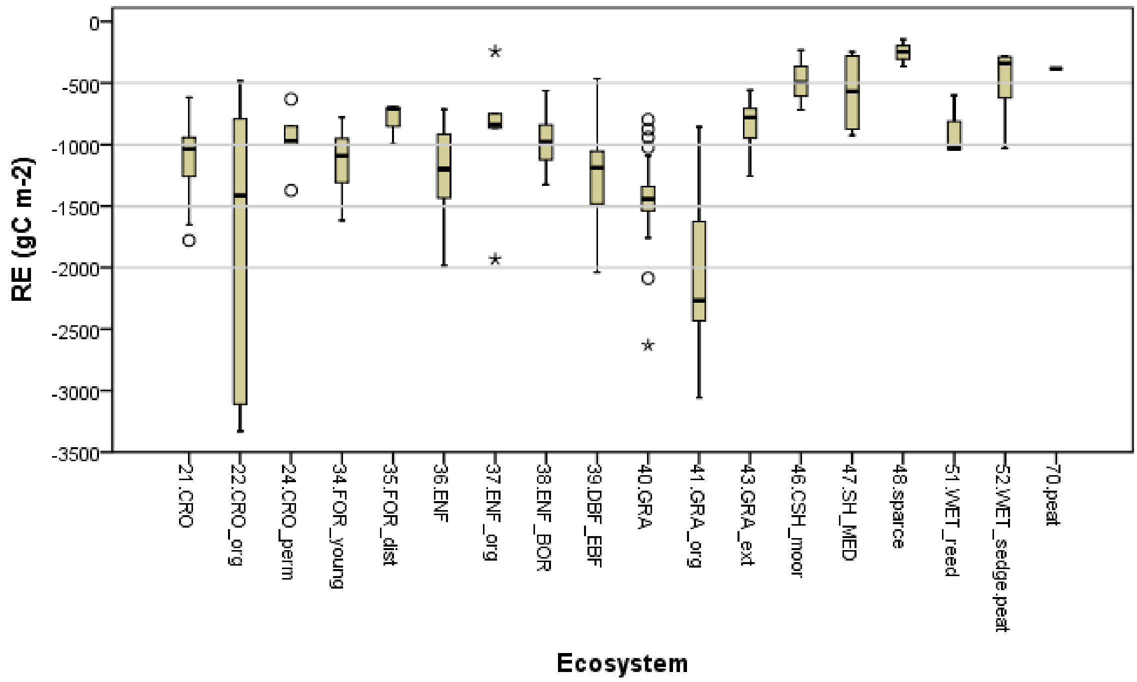


Figure 3.9: RE of European ecosystems with interquartile ranges, outliers (dots) and extreme outliers (stars)

The ecosystem boxplots of RE detected 3 extreme outliers: DE-Mooseurach (as on the GPP boxplots), FI-Kaa and CH-Cha. The non-extreme outliers are the same sites as on the GPP graph.

The boxplot of NEP variation per ecosystem classes is shown on figure 3.10. It helps to distinguish clearly ecosystems with positive NEP (permanent crops, grass and crops on mineral soils, deciduous and needle-leaf forests and reed-wetlands), near-neutral (Boreal and needle-leaf forest on organic soils, natural grasslands, moors and sparse vegetation) and negative NEP (disturbed forest, crops and grass cultivations on organic soils, peat and urban ecosystems).

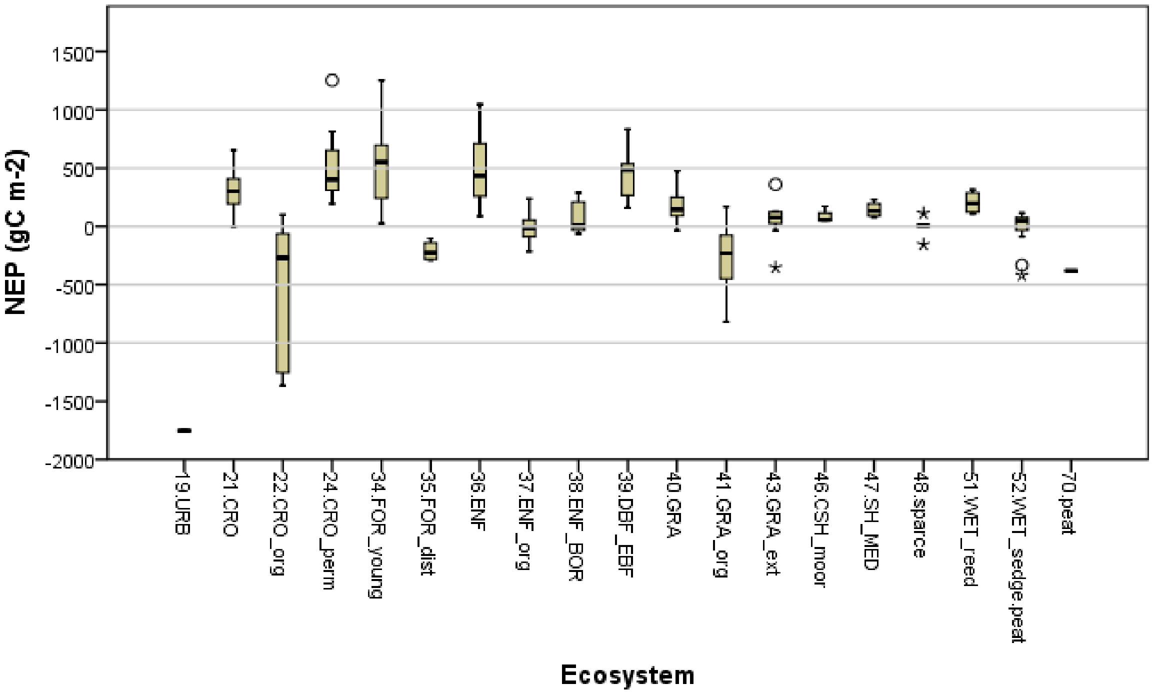


Figure 3.10: NEP of European ecosystems with interquartile ranges, outliers (dots) and extreme outliers (stars)

The values for the urban ecosystems are actually from sub-urban areas (Swindon and Helsinki) and are very similar, another two sites were excluded from the boxplot because of their very high carbon source values there, London (-12720 gC m^{-2}) and Florence (-8270) according to Ward et al. (2015). The average NEP of the four urban sites is -6124 gC m^{-2}. The median of the exposed peat sites is likely unrepresentative because the two sites are from Finland and Estonia (average NEP = -311 gC m^{-2}), more southerly sites would emit higher CO_2 volumes.

Extreme outliers include a natural grassland in Slovenia (Podgorski crass), a sparse vegetation site in Spain (ES-Balsablanca, ES-Amo) and a salt marsh in the UK. All of these sites need further investigation to be assessed as outliers resulting from measurement issues or as distinct ecosystems. Therefore, the customized ecosystem classes applied well for distinguishing typical carbon flux patterns but fail to detect outliers.

3.3.3 Carbon fluxes relations with NDVI

Overall relations

Relations between the carbon fluxes and NDVI were examined on scatterplots with distinguished five dominating land cover types (e.g. crops, forests, grasslands, wetlands and shrublands) in Europe. Annually matched values of NDVI and fluxes (GPP, RE and NEP) were plotted on figure 3.11.

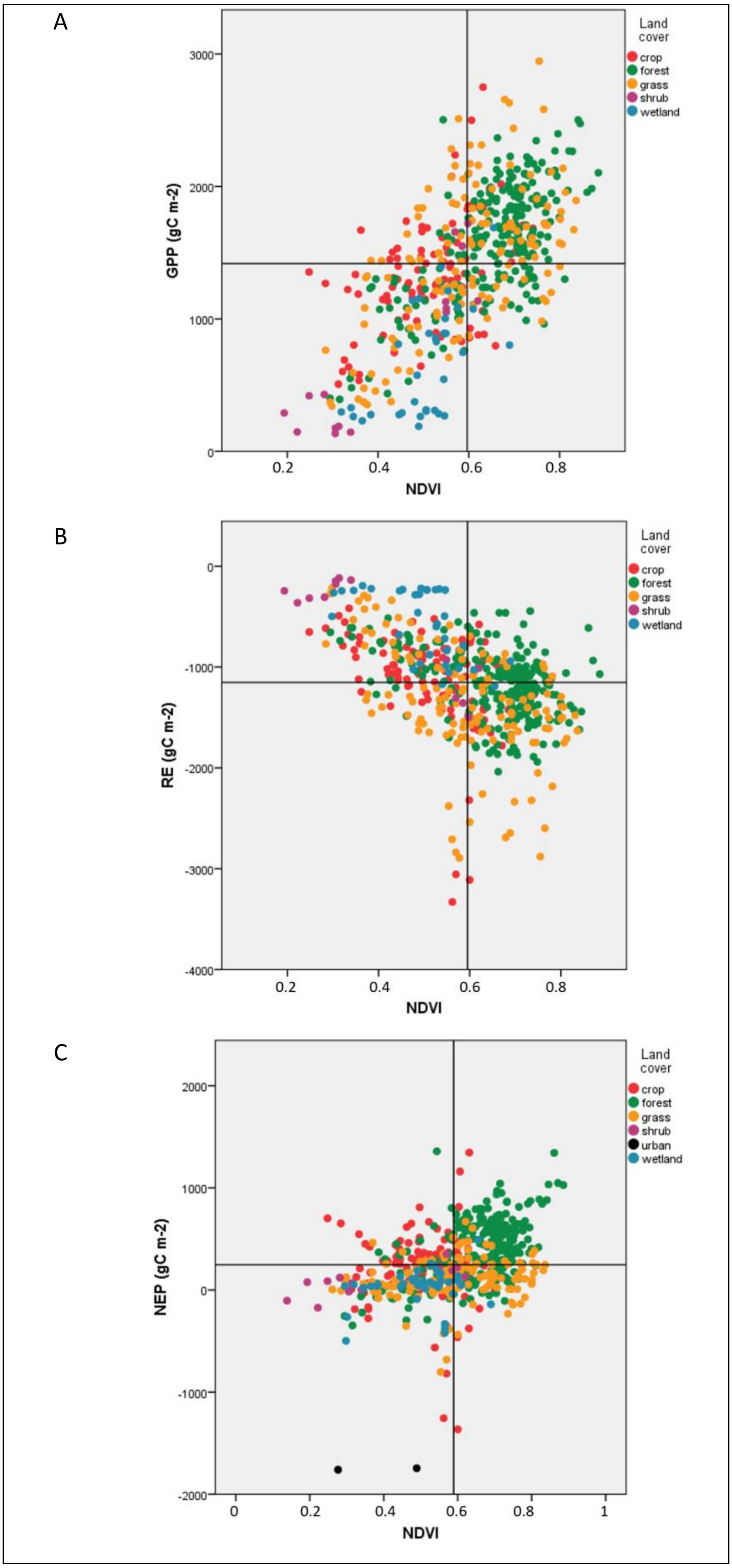


Figure 3.11: Scatterplots of NDVI with (A) GPP, (B) RE and (C) NEP

GPP has strongest association with NDVI with clear gradient along increasing values. Forest sites show less scatter than the rest, but overall, the five dominating vegetation types are similarly associated with NDVI. The shape of the scatter implies that GPP has linear and positive correlation with NDVI, with only a little saturation effect at high productivity (e.g. above NDVI values of 0.7 and GPP above 1500 gC m^{-2}). Stronger saturation effects are widely discussed in the literature (e.g. Baret and Guyot 1991, Huete et al. 2002, Piñeiro, Oesterheld, and Paruelo 2006). A likely reason for the little saturation shown in this study is that European fluxes do not reach so high values and NDVI correlates well along the entire gradient, and another is that the annual values of both GPP and NDVI smooth out the very high rates like those during peak summer growth. However, the crop and grass sites display wide dispersion, wider than forests, which implies that there are certain limitations of NDVI to capture important factors affecting crop and grass GPP. A few clusters as well as isolated outliers are apparent.

The association of NDVI with RE is similar to the one of GPP, but more dispersed in particular for forests and grasslands, and includes also a group of grass and crop sites which have very high RE values that are not correlated with NDVI. This subset of sites needs further investigation against factors which are likely to affect the size of RE.

NEP has different patterns of relations with NDVI for the different land cover types. Positive correlation is apparent for forests, almost no correlation for grass and wetlands, and much dispersed pattern for crops. Two urban sites stand as strong outliers because of very large negative NEP values. Outliers can be distinguished mostly on crops and grassland sites.

Class-averaged values of GPP and NDVI display distinguishable patterns where highest, intermediate and lowest values match well between the two variables.

Ecosystem	Count GPP	**mean GPP**	St. err GPP	**mean NDVI**	St. err. NDVI
19.URB				**0.26**	807
21.CRO	26	**1432**	56	**0.52**	193
22.CRO_org	6	**1238**	261	**0.49**	564
23.CRO_rice	2	**1306**	38	**0.37**	918
24.CRO_perm	6	**1497**	241	**0.58**	311
34.FOR_young	13	**1638**	101	**0.65**	282
35.FOR_dist	3	**560**	89	**0.36**	853
36.ENF	16	**1673**	86	**0.68**	274
37.ENF_org	5	**926**	234	**0.53**	421
38.ENF_BOR	8	**1066**	92	**0.55**	394
39.DBF_EBF	16	**1716**	72	**0.69**	94
40.GRA	25	**1600**	78	**0.62**	203
41.GRA_org	15	**1772**	117	**0.63**	249
43.GRA_ext	9	**949**	74	**0.47**	228
45.OSH	1	**1642**	.	**0.58**	.
46.CSH_moor	3	**574**	175	**0.53**	147
47.SH_MED	4	**710**	206	**0.39**	990
48.sparce	4	**216**	48	**0.27**	164
51.WET_reed	4	**1124**	99	**0.54**	350
52.WET_sedge.peat	7	**545**	118	**0.46**	276
70.peat				**0.29**	.

Table 3.3: Ecosystems mean GPP and NDVI

The analysis of relations between NDVI and GPP found the following patterns. Classes where NDVI and GPP values match closely include young, deciduous and needle-leaf forests, permanent crops, and grasslands and reed-wetlands. Classes where higher NDVI values correspond to lower GPP values include crops and forests on organic soils, disturbed forests, Boreal forests, extensive/natural grasslands, moors, Mediterranean shrublands, sparsely vegetated areas and wetlands with sedge. Possible reasons for the higher NDVI in these classes could be the influence of organic soils and permanent greenness of conifer forest (including in Boreal areas) moors and Mediterranean shrublands. On the other hand, crops on mineral soils have lower NDVI, and rice fields have very low average NDVI, likely because of being submerged for prolonged periods of time, during which NDVI can be close to 0 or negative.

Influence of measurement method on GPP – NDVI relation

The flux measurement method, distinguished as eddy-covariance (EC) or biometric (BM, which includes soil chambers and biomass-based estimates) has a clear influence on the relation between GPP and NDVI. Figure 3.12 illustrates that eddy-covariance estimates are well correlated with NDVI on both site-averaged and annual values (R^2 = 0.51 for averaged, and R^2 = 0.47 for annual), while biometric estimates are only slightly correlated on the site-average values and no-correlation is detected on the annual values.

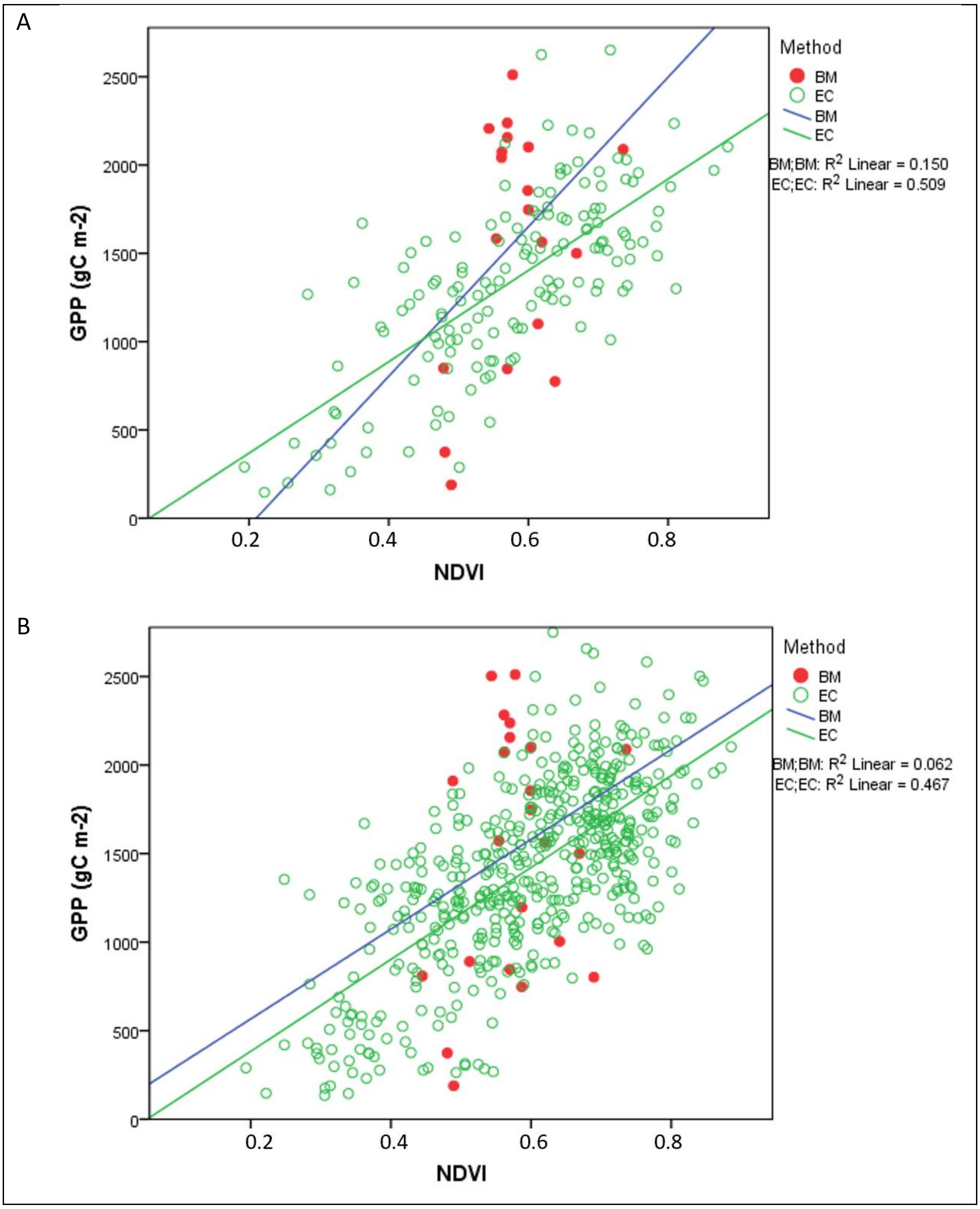


Figure 3.12: Scatterplots of GPP and NDVI according to flux measurement method with site averaged values (A) and site/year values (B)

The figure 3.12 confirms that EC methods are superior in their applicability for grid-analysis because of the wider spatial footprint of the towers which match well the spatial details from MODIS NDVI at 250m grid. Biometric estimates cannot be assessed as less reliable on the basis of this analysis, only that they do not match well with the grid-values of NDVI, the likely factors are limited spatial and temporal representability of the chambers and biomass measurement methods to estimate fluxes. This result indicates that only EC data can be applied for grid assessment studies of carbon fluxes.

3.5.2 Outliers on scatterplots of EC-GPP and NDVI

Since biometric methods do not match with grid-NDVI only the EC subset of site-averaged GPP was assessed by inspecting the site-values which lie outside the 95% confidence interval of the trend-line between GPP and NDVI, shown on figure 3.13.

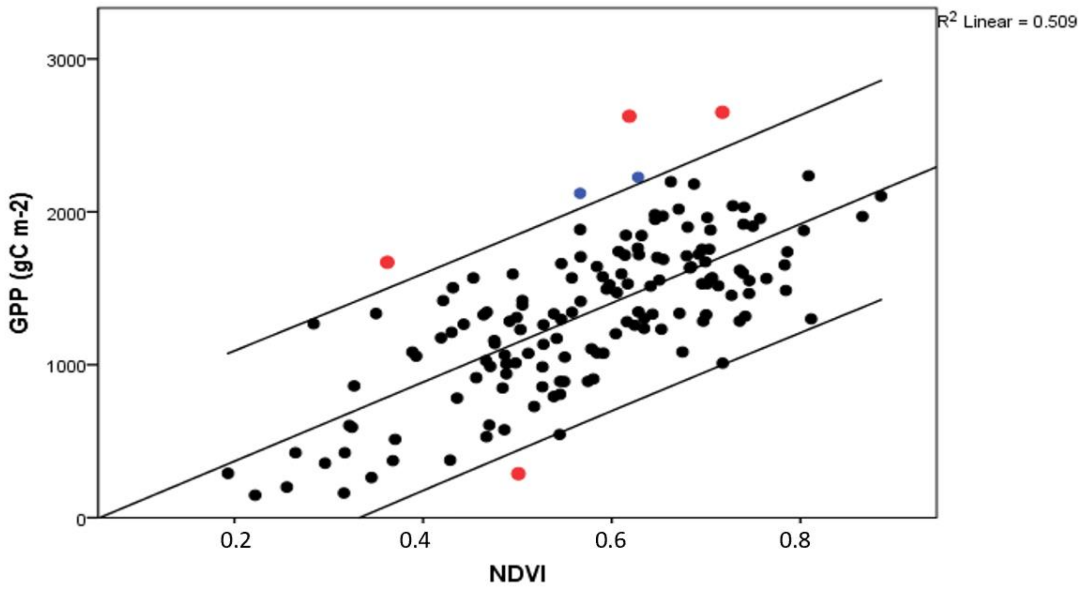


Figure 3.13: Scatterplot of GPP against NDVI, with trend-line, 95% confidence interval and outliers (in red and blue)

The following outliers which have particularly high mismatch between GPP and NDVI can be observed:

- Lowest GPP with relatively high NDVI: Irish moor site - IE-Kil;
- Very high GPP with low NDVI: olive orchard (IT-Ctv); grass site (CH-Cha); crop site (CZ-Zab);
- Less distant outliers of high GPP and lower NDVI include two grass sites (CH-Fru; BE-Dor).

The mismatch between GPP and NDVI of the third group could be explained as these grassland sites are very intensively cultivated, mowed more than 3 times a year which might be the reason to display lower average NDVI, but maintain high levels of GPP. Hence only the first two groups were marked as 'bad outliers' whose GPP might be affected by a measurement issue. After tagging and filtering the above outliers, the coefficient of determination between GPP and NDVI increased, R^2=0.56.

Further outliers were sought by plotting the dominant land cover types separately, e.g. forests, crops and grass scatterplots as shown next.

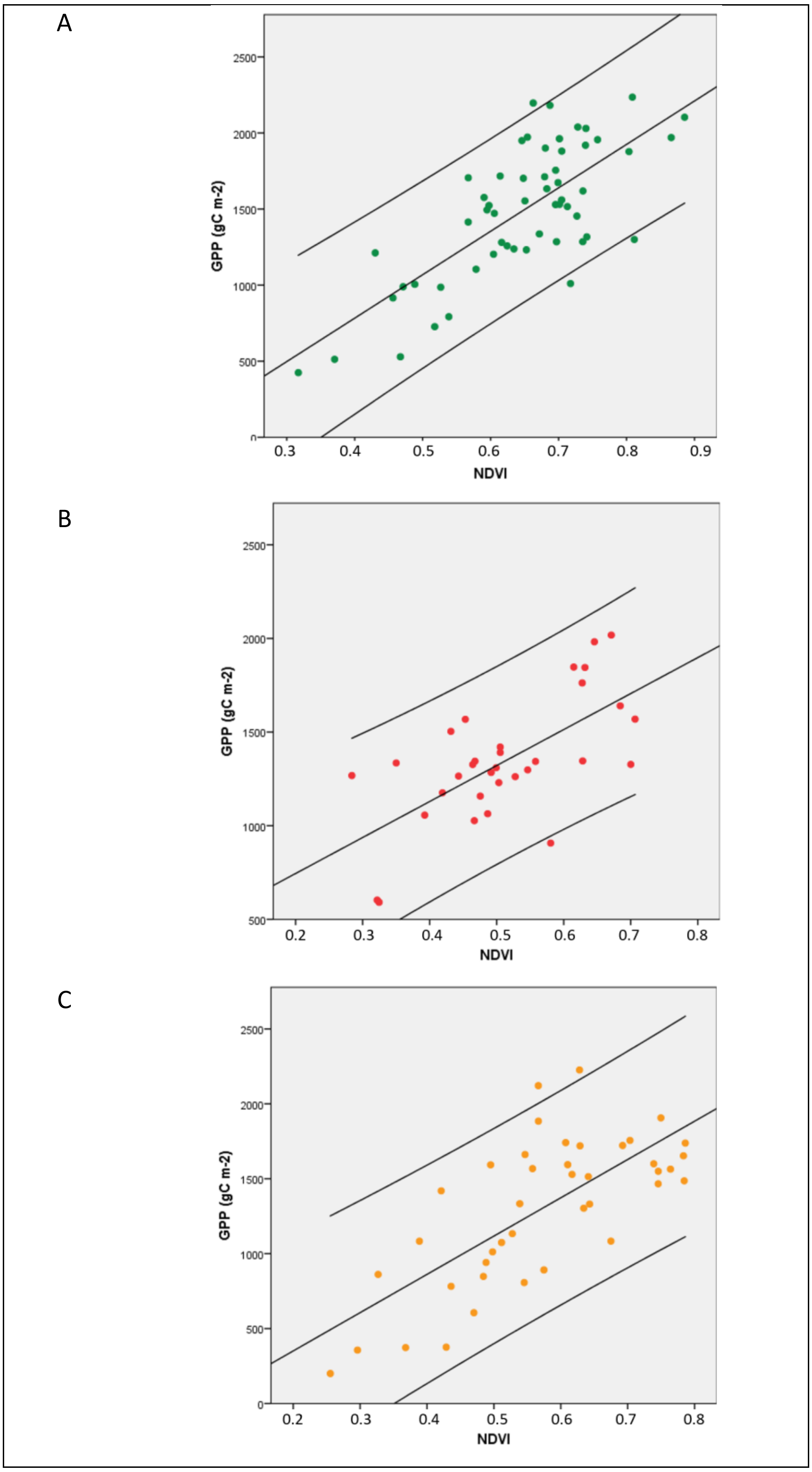


Figure 3.14: Scatterplots of (A) forest, (B) crops and (C) grass sites with confidence intervals of linear trends between GPP and NDVI

The above scatterplots helped to identify the following additional outliers:

- Forest sites: IT-Lec, CZ-St and DE-Hart
- Crops: IE-Ca1
- Grass: CH-Fru and BE-Dor

The two less distant grasslands observed in fig. 3.14 were detected again and tagged as outliers. One forest site (IT-Lec) has a particularly strong mismatch between NDVI and GPP, the other forests and crop sites have less strong mismatch, but were tagged too. The coefficient of determination after filtering the above six sites became $R^2 = 0.6$.

In conclusion, the correlation between GPP and NDVI can be applied for assessing annual and multi-annual fluxes, given that influences of other confounding factors can be controlled.

3.4 Conclusions

A comprehensive database of ground carbon fluxes data could be compiled from the available data sources which established a large sample size for the main biomes in Europe. Yet, the biomes appeared too broad and a number of additional classes had to be distinguished in a customized classification combining IGBP with ecoregions, soil carbon and forest age. The customized classes revealed better defined carbon flux profiles for 21 ecosystem types in Europe, with most of them having a large sample size (and small standard errors of the means). This allowed to clearly distinguish ecosystems functioning as carbon source, neutral or sink. Ecosystems defined as urban, bare peat, rice cultivations and temperate shrublands had only 2 or 3 sites each, therefore mean flux values could not be assessed as broadly representative, yet these ecosystems could not be merged with any of the other, better defined ones.

The assessment of flux data from different sources and processing methods supported an improved understanding of the quality issues of the fluxes. Assessing uncertainties introduced with the partitioning methods, e.g. day-time versus night-time in Fluxnet2015 dataset, showed that 30 out of the 50 sites resulted in re-estimated (from the partitioned GPP and RE) NEE deviating within 5% of the measured for night-time (7 crops, 3 grass and 19 forest, 1 shrub) and only 13 sites of the day-time partitioning method (5 crops, 7 forest), which rendered the day-time values unsuitable for further application here. Further inspection of the biome-averaged flux values from Fluxnet2015, showed that all grassland sites have large difference between day-time and night-time partitioned GPP and RE fluxes, while most forest sites and crop sites have rather similar values.

Despite the quality issues introduced with different flux processing methods, this study affirms fluxnet (or eddy-covariance method) as the most suitable for continental assessments of fluxes, in terms of ecosystem representability, data quality and sample size. Yet peripheral areas, such as south-east Europe are covered with very few flux-towers, therefore these large areas and ecosystem types need to be better represented in future studies. Because of the well-known correlation between NDVI and GPP (Huete et al. 2002), MODIS NDVI (v6) at 250m grid was successful at detecting several strong outlier flux values which are likely to result from measurement issues and were tagged as 'bad outliers'. Consequently, NDVI displayed significant (at 99% CI) and high correlation with GPP which increased from $r = 0.66$ using all data to $r = 0.78$ after removing the outliers and biometric data. The correlation between NDVI is lower with RE ($r = 0.65$ but also significant at 99% CI), and rather low with NEP ($r = 0.4$). These results are similar with the findings of Chen et al. (2015) who assessed EVI against the fluxes of global biomes. The correlation between NDVI and GPP did not show strong saturation effect at high values, possibly because of using annually averaged values in this study (which smoothed the values of peak growth and senescent periods) but also because European ecosystems do not reach as high productivity values as for example the tropical forests do.

The flux values distributions after filtering all quality tagged sites (with biometric studies and NDVI outliers) became symmetric for RE with skewness 0.25, Shapiro-Wilk test value 0.992, with significance 0.57. But eliminated most of the negative NEP values which made its skewness positive (skewness statistic 0.609) and non-normal with Shapiro-Wilk test value 0.974, significance 0.005. Several strong outliers on NEP remained.

In conclusion, the growing Fluxnet network in combination with long timeseries of vegetation indices and modelled flux data offers opportunities to strengthen ecosystem carbon accounting. The next step in this study is to apply the compiled eddy-covariance dataset to assess the quality of grid-modelled products on the main carbon accounting variables.

Chapter 4: Carbon budget modelling and grid-maps quality assessment

4.1 Introduction

The previous two chapters affirmed that GPP and NEP are the key carbon budget variables needed to assess most provisioning and carbon sequestration ESs. These key variables can be applied as measures of the intermediate services, GPP for assessing how well ecosystems capture carbon and NEP how well they retain it. Consequent paths of carbon allocation into plant organs, such as seeds, stems, tubers etc., and storage in biomass and soil, reveal the mechanisms of generating final ecosystem services. Chapter 3 (section 3.3.3) also revealed that MODIS-NDVI is highly correlated with annual GPP from fluxnet, with a slight saturation effect in European ecosystems, and certain dependencies exist with NEP for forests and other natural vegetation ecosystems. The question of how can ESs be mapped with earth observation (EO) data is a one of the most intriguing in the field of ESs assessments. Multiple EO products, models and modelled grid-products on variables which may be applied in a way corresponding to both, intermediate and final ESs exist, but the examples of complete studies are few, and mostly based on NDVI (de Araujo Barbosa, Atkinson, and Dearing 2015) or NPP (Costanza et al. 2017). The focus of this chapter is on grid-modelling of carbon budget variables for continental level ESs mapping, it includes the overview, selection and quality assessment of grid-modelled products of GPP and NEP, harvests of crops, timber and animal products in Europe.

4.1.1 Mapping ecosystem services with carbon budget grid-data

The ability of ecosystems to capture carbon through high NPP or GPP rates, and to retain it (with low CO_2 emissions), or store it in the SOC and biomass stocks, are the key processes underpinning a number of ecosystem services (Braun et al. 2017). Carbon fluxes and forest biomass are the most studied, measured and modelled components of the carbon budget, and modelled grid-products based on remote-sensing inputs are of particular relevance to assessing ESs at continental scale, because of the synoptic, continuous and synchronized observation of wide areas (de Araujo Barbosa, Atkinson, and Dearing 2015).

Running et al. (2004) introduced the MODIS (MOD17) algorithm for monitoring of the global gross (GPP) and net (NPP) primary production. It estimates the rate of primary production on the basis of FAPAR (fraction of absorbed photosynthetically active radiation) which is linearly correlated with remote sensing NDVI. Hence FAPAR and light-use efficiencies (Etzold et al. 2011) according to vegetation types and climate variables determine the rates of GPP and

NPP. MODIS GPP and NPP data have been continuously improved (Wang et al. 2017) during the last two decades and are a widely used source of primary production grid-data. Applying equivalent remote sensing inputs (NDVI or EVI), CASA ecosystem model (Potter 1993) simulates further steps of the ecosystem carbon cycle, besides NPP also biomass accumulation, litter fall inputs to the soil carbon pools (Potter, Klooster, and Genovese 2012), soil respiration, and finally NEP. CASA grid-data on NPP, soil respiration and NEP are distributed globally at 8 km grid resolution through CQUEST[15].

Another approach to estimating NEE was developed by Mahadevan et al. (2008) applying the Vegetation Photosynthesis and Respiration Model (VPRM), which uses EVI for predicting FAPAR and Land Surface Water Index (LSWI) for leaf water content to determine water-stress limitations on primary production. The model was applied for predicting NEE at fluxnet sites in the US. Its photosynthesis part (VPM) was applied for global GPP modelling by Zhang et al. (2017) at 500m resolution. They applied an improved LUE, distinct for C3 and C4 photosynthesis pathways, as well as improved quality of the vegetation indices, EVI and NDVI. Zhang et al. (2017) assessed the new product as highly accurate and discussed that multiple similar products exist but with much varying quality when assessed against eddy-covariance GPP from Fluxnet. So, several map products for assessing the intermediate provisioning ESs are readily available but they still need an additional assessment in the context of this study to ensure that the best product is applied.

On the other hand, only CASA CQUEST product with soil respiration and NEP was identified as a suitable proxy to assess how well ecosystems retain carbon. There is no published work on any validation of ecosystem respiration, while grid-NEP validation was done in a US study by Potter et al. (2012). This leaves a certain gap in our ability to assess how well carbon sequestration ESs can be mapped.

Maps of annual crop and timber harvests at 1km x 1km grids were generated for the European Union countries (Weber 2011), specifically for ecosystem accounting, nevertheless an independent validation would be beneficial for their further improvement and wider applicability.

The need to apply high-quality and consistent grid-products to map and assess ESs at European level faces several challenges: identifying the best product on variables where multiple sources exist (e.g. GPP and NPP) but with often inconsistent or even contradictory

[15] http://cquest.arc.nasa.gov:8399/casa/cquestwebsite/enter2.html

validation results from the published studies (see next section 4.1.2); developing a robust method to validate the variables which have not been comprehensively validated yet; and ultimately ensuring a consistent quality assessment across the key carbon budget variables so that carbon balances and trade-offs between the ESs can be estimated with confidence.

4.1.2 Grid assessment studies on NPP, GPP and NEP

Several large-scale grid-assessment studies have been performed on MODIS NPP and GPP products. Turner et al. (2005) designed a specific evaluation approach for the purpose of assessing the MODIS algorithm of Running et al. (2004). This was a part of a project, called BigFoot which prescribed sampling and scaling methodology to link site observed data with the 1km x 1km grid remote-sensing estimates of GPP and NPP at six selected sites varying widely in climate, land use and vegetation. Comparisons were made for 25 grid-cell at each site, for eight-day average of GPP and annual NPP. The Biome-BGC model was applied for the scaling purposes, using Landsat ETM imagery to develop first a 'reference' layer, called BigFoot product, which was assessed and improved in comparison with the observed site data. Afterwards the modelled BigFoot outputs were compared with the MODIS algorithm outputs. The authors did not detect consistent over- or under-estimation of the MODIS NPP but significant deviations at the arid and crop-land sites. They explained these deviations by analysing the inputs for the MODIS algorithm, namely the FAPAR and climate data, which were consequently improved (Zhao et al. 2005).

Other studies reported more concerning quality issues of MODIS GPP. Yang et al. (2007) reported an average error of 50.3% for non-forested ecosystems, and the largest underestimation was for cropland (61%, irrigated maize, USA). Wang et al. (2017) assessed the quality of the latest MODIS GPP product (MOD17A2H) at 500m grid resolution, along with another 3 algorithms for six global biomes against the latest FLUXNET2015 dataset for 18 flux towers. The agreement was assessed in terms of r^2, bias (difference between flux and grid estimates) and RMSE. The overall r^2 was 0.62 at annual level, with substantial underestimation of the sites with higher fluxes. None of the algorithms showed significant correlation for croplands. The representativeness of the validation sample (only 18 sites, with 3 croplands) in the study of Wang et al. (2017) might be compromised, nevertheless it is likely that the MODIS GPP grid maps contain considerable uncertainties, especially for croplands.

Another validation study based on fluxnet was done to assess CASA's grid-estimates of NEP in the US (Potter et al. 2012). 196 monthly measurements of NEE (considered equivalent to the inverse of NEP) were applied, from 4 Ameriflux towers selected for the validation purposes. Linear correlation between CASA and Fluxnet NEP with coefficients of determination r^2 = 0.41 was reported (Potter et al. 2012). Overall, these validation studies demonstrated moderate agreement between ground and grid- estimates of the fluxes, which was based on spatially limited representation with only a few towers included in the validation sample. Presently, Fluxnet offers opportunities for much more comprehensive assessments of the fluxes at continental levels, with large sample size for biome-specific assessments.

Verma et al. (2014) analysed correlation, bias and errors between GPP from MODIS and Fluxnet in a more comprehensive and systematic way than any study before. They assessed 10 variables globally, including proxies based on NDVI and EVI, and modelled outputs on GPP derived from MODIS, against La-Thuile fluxnet GPP dataset which satisfied high-quality (more than 95% daily data per site available) from 144 towers distributed globally. Spatial variation and temporal- annual anomalies were addressed separately. The study revealed that both the remote sensing proxies and the modelled GPP are able to capture spatial variation of fluxnet GPP in all biomes but croplands, while interannual GPP variability could be explained to a limited degree. The Modis GPP product had highest agreement for evergreen broadleaf forest (EBF, $r^2 \approx 0.6$) and evergreen needleleaf forest (ENF, $r^2 \approx 0.55$), lower for grass ($r^2 \approx 0.45$) and other classes ($r^2 \approx 0.5$), and rather low for deciduous broadleaf forest (DBF, $r^2 \approx 0.15$) (no agreement for crops, $r^2 \approx 0.05$) (Verma et al. 2014). Further on, regressions based on remote sensing proxies and temperature/precipitation provided the best overall GPP prediction.

In their next study, Verma et al. (2015) assessed 11 modelling tools for seven biomes, similarly against La Thuile GPP, but applying Willmott’s index of agreement (Willmott 1981) between daily measured and modelled GPP. These modelling tools were structured to reflect on increasing complexity, starting from simplest linear prediction of GPP by EVI (Schubert et al. 2012) and ending with neural networks model developed by the authors (Verma et al. 2015) . The MODIS GPP (Running et al. 2004) and VPM GPP (Xiao et al. 2004) algorithms were included in the evaluation. Verma et al. (2015) concluded that more complex models could predict better than EVI the spatial variation of GPP in four biomes (not in crops and EBF), but not interannual anomalies.

Similarly, Zhang et al. (2017) validated their new VPM-GPP product against 113 flux-tower sites from FLUXNET2015 dataset. Ground GPP was estimated as average from the night-time and day-time partitioning and only the highest quality data were retained. All data points at 8-day resolution were used which resulted in a sample of 28378 points; and interannually the anomalies were estimated for sites with more than 5 years of flux data. An overall r^2=0.74 was achieved at 8-day resolution with high coefficients of determination for all biomes except EBF and CSH, while the annual anomalies correlated poorly. The new GPP product underestimated ENF with 27%, EBF with 30% and croplands with 15%.

The studies of Verma et al (2014 and 2015) and Zhang et al. (2017) demonstrated an improved understanding of the quality of the available GPP grid-products, based on their agreement with Fluxnet GPP. However, the assessment results from the different studies do not provide strong basis to select which grid dataset is the most accurate. Moreover, not a single study on validation of RE was identified, hence there remains the need to assess consistently the key fluxes, GPP, RE and NEP. The study of Zhang et al. (2017) reported rather high correlation between their product and Fluxnet GPP, but as seen in the previous chapter, ground-measured NEE and its partitioning into GPP and RE is subject to substantial quality issues, and the day-time values for grasslands were assessed as mostly overestimated (section 3.4). Therefore, a new comparative assessment of the available grid-products is needed.

Study objectives:

- Review available carbon budget grid products at European (continental) scale and assess their suitability for accounting;
- Review RS-based flux validation studies and select the most appropriate validation method;
- Assess the accuracy of the available carbon budget grid products against the ground data presented in the previous chapters;
- Test methods for enhancing the accuracy of the grid maps with vegetation indices.

The outcomes of this study are expected to complete a comprehensive assessments of the available carbon budget grid-data covering Europe.

4.2 Methods

Because of the interdisciplinary nature of the ESs, their assessment and mapping require ability to work with broad range of spatial data with different properties. Such data when readily available, would in many cases be created for different purposes, that may match the needs for ES assessment, or not. This section provides an overview of a new grid-assessment methodology, structured to guide the review, selection and quality assessment of carbon-budget grid products for mapping ESs. It follows the ES definition approach discussed in chapter 2, and ground-data compilation in chapter 3. The main novelty is assessing the key carbon budget variables comprehensively and, in an accounting-structured way to ensure that the best grid-products are selected for consequent consistent and comparable assessment of ESs and their trade-offs.

4.2.1 Review and selection of grid-data

A set of grid-data suitability criteria for the carbon budget components was constructed prior to the grid-products review. These criteria include general data quality issues when developing environmental statistics, as well as criteria specifically applicable to ESs assessment. The general criteria were derived from EUROSTAT's European statistics code of practice[16] and summarised in table 4.1. In addition, the ESs accounting specifications were drawn during testing options for simplified ecosystem accounts (SECA) mapping in Europe (Weber 2011), led by the European Environment Agency (EEA). The experience from these tests included data exploration for the purpose of international and seamless accounts estimation and mapping. Consequently, data selection was driven by the generally applicable criteria, expert knowledge and literature reviews to examine the varying quantitative contributions of the main carbon budget components to a consistent estimation of NECB, possible redundancies, and other quality issues.

Criterion	Accounting specifications
1. Relevance	Applied directly or adjusted to match the expected range of values of an accounting item
2. Coverage	Global or at least for the EU countries, preferably applicable for international comparative analysis
3. Spatial detail	Ability to distinguish course landscape patterns, in particular changes of vegetation gain and loss
4. Temporal coverage	Annual timeseries of data covering et least a decade
5. Accuracy and data quality	Data quality need to be proven by a satisfactory accuracy against independent reference sources; or good agreement and coherence with other proven sources

Table 4.1: EUROSTATS's quality criteria for official statistics and specifications for European ecosystem accounts

All five criteria have to be satisfied during the review of available data sources, the first four are of rather technical nature and easier to evaluate. Assessing spatial and temporal accuracy of data covering large areas is challenging, therefore this criterion has to be addressed individually for each ES accounting item and in a way ensuring that the most robust statistical analysis can be done (discussed in section 4.2.2).

[16] http://ec.europa.eu/eurostat/documents/64157/4392716/ESS-QAF-V1-2final.pdf/bbf5970c-1adf-46c8-afc3-58ce177a0646

Review of available grid-data

The first reviews of available data were done in the framework of the EEA's SECA. For the carbon fluxes (primary production and respiration) and stocks (in soil and biomass) several input datasets exist, but of varying spatial details and other quality issues dependent on the underlying estimation models. Data on harvesting of crops, timber and animal products and deposition of manure on the fields were produced by the EEA, specifically for the ecosystem accounting purposes in spatially explicit form. Table 4.2 presents a review of the relevant datasets for each accounting item. The timing for the fluxes and harvests spans the decade 2000 – 2010.

Accounting items		Characteristics	Coverage, Spatial resolution	Source, reference
Stocks	Soil organic carbon	Organic carbon content in the upper 30cm layer of soil (OCTOP)	EU, 1km x 1km	Jones et al., 2003
		Organic carbon content in the top-soil (30 cm depth) and the sub-soil (to 1 m depth)	Global, 1km x 1km	Hiederer and Köchy, 2012
	Biomass	Carbon stock in aboveground forest biomass and growing stock for the EU countries	EU, 500m x 500m	Gallaun et al. (2010)
		Living forest biomass and carbon stock	EU, 1km x 1km	JRC (Barredo et al. 2012)
		Global Forest Growing Stock, Biomass and Carbon Map based on downscaled FAO statistics	Global, Half degree	Kindermann et al. (2008)
		Carbon stocks of above-ground vegetation incl. forest and other vegetation types	EU, 1km x 1km	EEA – SECA (Weber, 2011)
Changes (fluxes, flows, transfers)	Primary production	MODIS Net and Gross primary production, at 8 day interval	Global, 500m x 500m	Running et al. (2004)
		VPM Gross primary production, at 8 day interval (GPP-VPM)	Global, 500m x 500m	Zhang et al. (2017)
		GEOSUCCESS Net primary production and Net ecosystem production maps, at 10 day interval	Global, 1km x 1km	GEOSUCCESS
		CQUEST Net primary production, at monthly interval	Global, 8km x 8km	NASA CQUEST, (Potter et al. 2012)
		Gross primary production maps, at monthly interval	Global, Half degree	Jung et al. (2011)
	Ecosystem respiration	CQUEST Soil respiration at monthly interval	Global, 8km x 8km	NASA CQUEST, (Potter et al. 2012)
		Ecosystem respiration, at monthly interval	Global, Half degree	Jung et al. (2011)
	Human use of primary production	Crop production, livestock distribution and other agricultural parameters	EU, 1km x 1km	Kempen et al. (2005)
		Annual carbon exports from the ecosystems through crops, timber and animal products	EU, 1km x 1km	EEA – SECA (Weber, 2011)
		EFI map of timber harvests	EU, 1km x 1km	EFI, (Verkerk et al. 2015)
	Carbon imports	Annual imports of carbon to the ecosystems through sludge and manure deposition	EU, 1km x 1km	EEA – SECA (Weber, 2011)

Table 4.2: Data sources for carbon budget mapping in Europe

The carbon stocks data were not assessed further in this study, based on the reported validation results of Avitabile and Camia (2018) the forest biomass stocks map of Barredo et al. (2012) was considered for further applications for ES mapping. The authors performed European level validation of four AGB maps, using National forestry inventories statistics. The grid data accuracy was assessed at area-aggregates (national, NUTS) and individual grid-cells. In the latter case several steps of validation data preparations were done to ensure good correspondence with grid values, including outlier detection based on logarithmic regression between tree cover and biomass values (with positive correlation until the saturation of tree cover) removing all plots laying outside the 75% prediction interval (Avitabile and Camia 2018).

The upscaled data on GPP, RE and NEE from fluxnet, of Jung et al (2011) at half degree were not assessed further in this study because the datasets could not be applied for landscape level assessments. The supply of GEOSUCCESS data was discontinued and could not be further assessed either, which left the rather course CQUEST NEP and soil respiration data of Potter et al. (2012) as the only source for these variables. MODIS and VPM-GPP at 500m x 500m were assessed as particularly suitable for estimating carbon-based ESs, and similarly the European Forestry Institute's product of timber (Verkerk et al. 2015) and EEA's crop harvests developed for SECA.

There are other sources of spatial data which do not provide carbon estimates of the above variables, but proxies or covariates. For example Hansen et al (2013) provide global and annually updated maps of deforestation at high spatial resolution, and also areas where new forest was established. The European Corine land cover product includes land use change inventories which can be used to determine areas where forests were lost, and where new forests were created (as well as other relevant categories, e.g. wetlands, permanent crops, etc.). These data products were not addressed further in this chapter but were applied in the next ones.

4.2.2 Accuracy assessment of the selected grid-products

Assessing the accuracy of the selected carbon budget grid products in statistically robust, comprehensive (addressing the key budget components) and biome-specific way was determined as the critical part of this chapter study. Moreover, the assembled key budget components need to be assessed with comparable validation samples and statistics that are suitable to evaluate biases and spatial patterns, to ensure that all variables are consistently assessed. As mentioned in the previous section, there are no similar examples of comprehensive assessments addressing multiple variables, besides forests in Europe (Ťupek et al. 2010). Several studies addressed multiple biomes assessments but considering only a single variable of the carbon budget, GPP. The objective of these studies was to compare the performance of different modelling tools.

Among the reviewed validation examples, Verma et al. (2014) provided the most comprehensive scheme applicable here, as it was done using La Thuile flux GPP and assessed grid-products based on MODIS, including vegetation indices as proxies and modelled GPP. The grid samples extraction was done using the MODIS sub-setting tool[17] with 3x3 for the 500m grid-cell and 7x7 for the 1km pixels retaining only those that match the flux site land cover. The retained pixels were averaged to minimize random variation and grid-generation artefacts (Verma et al. 2014). The following grid-products on GPP were assessed: (1) growing period length; (2) growing season integral of EVI; (3) growing season mean EVI; (4) growing season mean NDVI; (5) MOD17 GPP (Running et al. 2004) product; (6) temperature and greenness model; (7) vegetation photosynthesis and respiration model; (8) a non-parametric neural network model; (9) MOD17 GPP calibrated with the very tower climate data; and (10) regression with one of the four proxies and mean annual temperature and precipitation. Four of the above models were calibrated with flux data at biome-level and cross-validated with leave-one-site-out method. The analysis were done with estimating baseline biome statistics first, which compared 5% inherent measurement uncertainty of annual flux-tower GPP with the standard deviation within each biome to ensure that measurement uncertainties were not greater than the spatial variation, which was the case for all biomes, but grasslands and ENF had higher uncertainties. Consequently, the agreement between grid products and fluxnet GPP was assessed using R^2, slope coefficients, RMSE and mean bias between modelled and measured GPP.

Building on the studies of Verma et al. (2014 and 2015) and Zhang et al. (2017), the following statistics were applied for assessing the selected grid products in this study: correlation coefficients (*r*), biases (between modelled and measured) and percent bias estimated from the mean ground value of the biome. The biases were considered significant if exceeding the 5% uncertainty threshold specified by Verma et al. (2014) but assessed as strongly affecting the ES accounting purposes if larger than 20%. The biomes assessed were: broad-leaf forest (BF, including deciduous and evergreen), needleleaf forests (ENF), grass (GRA), crops (CRO), other natural vegetation (NAT, shrubs and wetlands). The assessed variables were GPP (from

[17] https://modis.ornl.gov/cgi-bin/MODIS/global/subset.pl

MODIS and VPM); NEP (CQUEST); crop harvests (from EEA-SECA), and total harvests, combining crops, timber (from EFI) and animal products (EEA-SECA). The ground data selected for the assessment included the combined GPP and NEP dataset where abnormal outlier values were filtered out (section 3.3); crop harvests and combined harvests dataset, the latter includes food-crops, energy and fodder crops, animal products, and timber. The ground data sample sizes for animal products and timber were very small and could not be considered representative for assessing these two variables individually. The timber values were transformed into a decade-average (e.g. the individual year harvest was divided by 10). Site-averaged values were applied where multiple-year of the above variables exist. All statistical analysis were done with SPSS.

4.2.3 Downscaling method for enhancement of grid-products

Because of the high and nearly linear correlation between NDVI and GPP obtained for the European ecosystems in the section 3.3.3, a statistical downscaling method was tested to investigate if possible to correct biases and enhance the correlation between ground and grid GPP using MODIS NDVI at 250m resolution. The downscaling method resembles regression-based prediction of GPP by NDVI, where the ratio between the two is applied as a correction factor according to the following formula:

$$dGPP_{i,j} = \sum GPP_x / \sum NDVI_x * NDVI_{i,j}$$

$dGPP_{i,j}$ is the downscaled value for grid-cell *i,j*; $\sum GPP_x$ is the original grid-modelled value aggregated for territorial unit *x,* composed of n grid-cells; $\sum NDVI_x$ is a downscaling (or reallocation) covariate aggregated for the same territorial unit x; and $NDVI_{i,j}$ is the grid-cell value.

This procedure does not alter the carbon budget value (e.g. GPP) when aggregated (or averaged) for the territorial units, but adjusts the grid-cell values in accordance with the chosen covariate, assumed to be more sensitive to the carbon budget distribution at local (grain) scale. The territorial units can be biomes, administrative areas, catchments or other delimitations. The effect of applying one or another type of units was explored previously (in the framework of EEA-SECA), in this work the European country delimitations were applied as territorial units and MODIS NDVI at 250 m resolution (version 6) as a downscaling GPP covariate. Therefore, at national level the aggregate GPP retains the same value as the original product with adjustments possible only between the grid-cells and consequently, the ecosystems within the country.

This downscaling method was developed during the SECA. It was applied to map grazing livestock distribution and crops harvests at 1 km grid, by disaggregating national statistics at NUTS-2[18] level for the European countries. All regional statistics were acquired from EUROSTAT. The crop harvests were downscaled applying corresponding Corine land-cover classes (annual crops, olives, vineyards, *etc.*) to define where the crops were cultivated. Similarly, the grazing animals were allocated on pastures and natural grasslands. The land cover data was expressed in a quantitative form denoting number of hectares per grid-cell of each class. In this way each land cover class was expressed at 1km x 1km grid as a continuous variable with values ranging from 0 to 100ha derived from the 100 m raster version of Corine land cover. The downscaling products had limited assessments previously, therefore this study is the first attempt to validate the downscaling method with ground data.

4.3 Results

This section presents results from the comprehensive assessment of the carbon budget grid-products in Europe. The variables are selected for their relevance to mapping ESs and for their ability to reflect landscape level variation of the carbon fluxes and harvests. The quality of the original (and freely accessible) data and the downscaling improvement of GPP are comparatively discussed below.

4.3.1 Assessment of grid products quality on scatterplots

The overall relationships between the grid-modelled carbon budget components, GPP and harvests were assessed on scatterplots against the ground measured values, displayed on fig. 4.1.

[18] European Commission's Nomenclature of Territorial Units for Statistics, http://ec.europa.eu

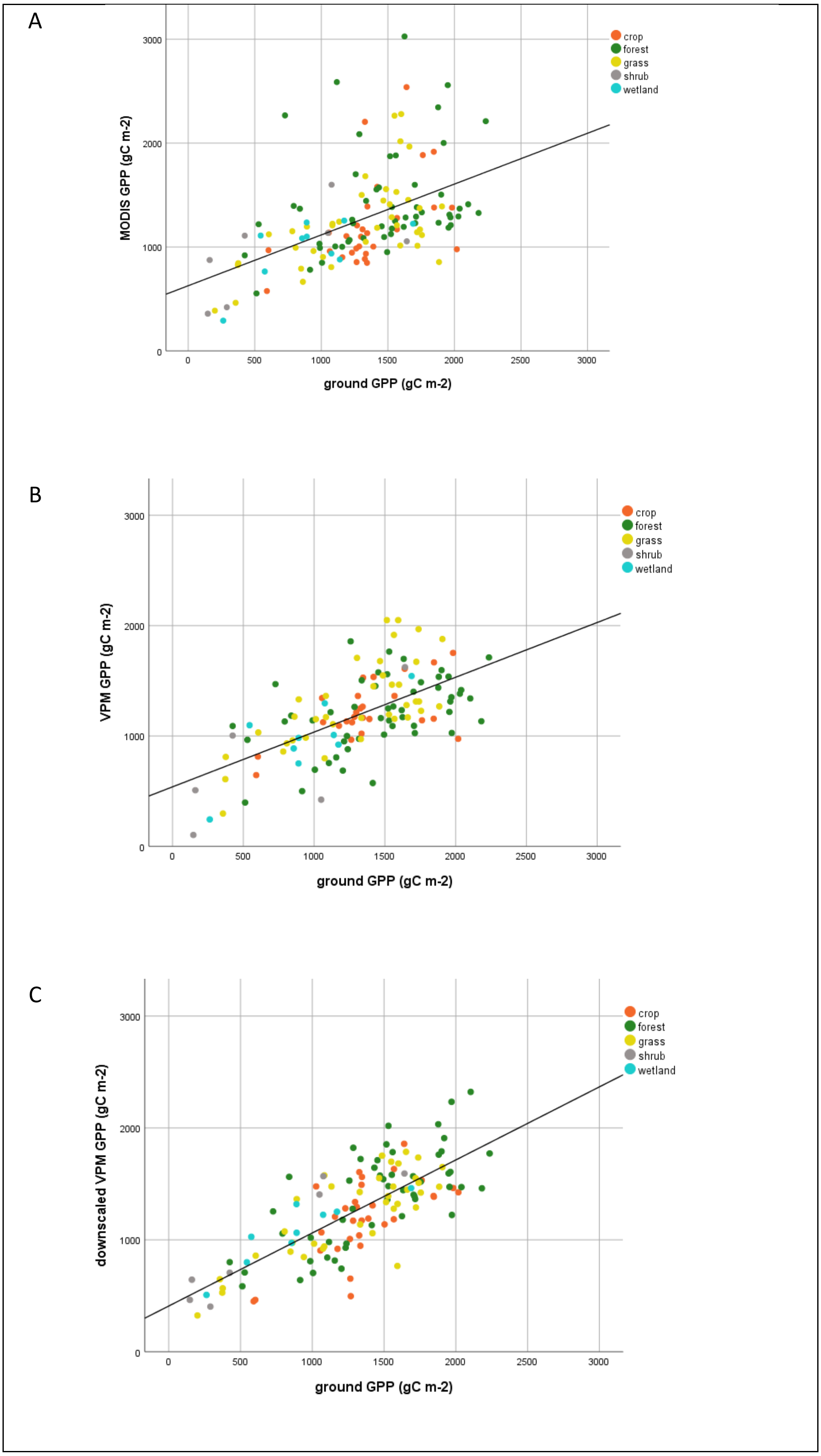


Figure 4.1: Scatterplots of grid-modelled GPP from MODIS (A), VPM (B) algorithms and downscaled VPM GPP (C)

The scatterplots of GPP reveal an agreement between grid and ground data without apparent class-specific dispersions. The MODIS and VPM modelled original GPP data have strong heteroscedasticity dispersion towards the high GPP values, which the downscaling with 250 m MODIS NDVI has eliminated. Several outliers of extreme values can be distinguished:

- On MODIS GPP the highest values are EBF forests and permanent crop site (citrus orchard) possibly as a result of the LUE coefficients applied for evergreen vegetation in the MODIS algorithm, while the two lowest GPP sites (crops in UK and Denmark) cannot be explained.
- On the downscaled GPP an outlier with very low grid value is the rice field of El Saler (Spain) clearly - a result of the rather low NDVI affected by prolonged water submergence. No saturation at high GPP values can be distinguished.

The scatterplot of harvests (fig. 4.2) displays an agreement for crops, and lack of agreement for timber harvests, yet the ground data on harvests could not be considered representative in this study, because of rather limited sample size.

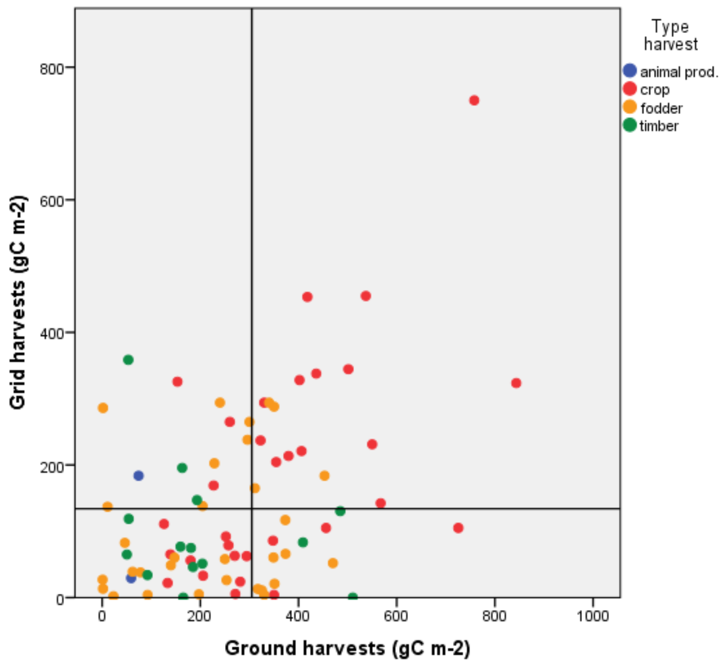


Figure 4.2: Scatterplot of harvests from combined EEA-EFI grid products against site estimates from published European studies

The overall shape of the scatter implies that the grid-data would be applicable for assessing the corresponding provisioning services, however one part of the sample points, the ones labelled as fodder are a result of the input land cover mismatch (or error). Fodder harvests grid data were not applied in this study, therefore the correspondences detected and plotted above are a result of crop harvests or animal products in the grid layers which coincided with fodder (hay) harvests in the ground samples.

4.3.2 Correlation and biases between grid and ground carbon budget components

European biomes with their carbon budget statistics including correlations, biases and mean values are summarized in table 4.3. The biome labels follow the IGBP scheme but aggregated as follows: CRO includes all crops (permanent and annual), GRA – grass, BF – broadleaf forests (deciduous and evergreen) and NF – needleleaf forest (evergreen and deciduous). NAT is natural vegetation composed of several shrubland sites, mostly wetland sites and one savanna site. The 'crops only harvest' category includes the values of harvested edible crops (cereals, tubers, fruit), while the next category includes also straw, energy and fodder crops and other by-products. The final category of 'total harvests' includes the former and also timber (from EFI) and animal products.

		n	*R*	mean ground value	mean grid value	Bias	Bias (%)
MODIS GPP	CRO	32	**0.49**	1359	1198	-161	-12
Overall *r* = 0.53	GRA	39	**0.58**	1275	1226	-49	-4
Grid size = 1 km	BF	22	-0.08	1579	1499	-80	-5
	NF	33	**0.47**	1424	1296	-128	-9
	NAT	18	**0.62**	831	883	51	6
VPM GPP	CRO	33	**0.71**	1359	1216	-143	-11
Overall *r* = 0.67	GRA	39	**0.72**	1275	1348	73	6
Grid size = 500 m	BF	23	0.47	1579	1716	137	9
	NF	32	**0.62**	1424	999	-425	-30
	NAT	18	**0.93**	831	781	-50	-6
downscaled VPM GPP	CRO	32	**0.65**	1359	1208	-151	-11
Overall *r* = 0.76	GRA	37	**0.81**	1275	1246	-29	-2
Grid size = 250 m	BF	20	0.45	1579	1552	-27	-2
	NF	32	**0.78**	1424	1272	-152	-11
	NAT	18	**0.89**	831	935	104	13
CASA NEP	CRO	33	0.38	305	179	-126	-41
Overall *r* = 0.21	GRA	39	0.09	109	122	12	11
Grid size = 8 km	BF	23	0.25	438	208	-230	-53
	NF	33	0.09	288	35	-253	-88
	NAT	20	0.10	64	99	35	54
Crops only harvests (1 km)		25	**0.64**	267	111	-155	-58
Crops and similar harvests (1 km)		39	**0.52**	347	166	-181	-52
Total harvests (1 km)		82	**0.44**	274	136	-138	-50

Table 4.3: Biomes' statistics with sample size, Pearson correlations (r) and biases between ground-measured and grid-modelled carbon budget components. In red are shown all non-significant statistics, in blue – those that are significant at 0.05 level and in bold are those - significant at 0.01 level.

The table reveals that - overall the grid-products are statistically correlated with the ground data, besides NEP. The downscaled VPM GPP version has the highest correlation (*r* = 0.76), followed by the original VPM GPP and MODIS GPP with lowest. The comparison of CASA NEP at 8km grid with flux towers NEP is most likely inappropriate because of the spatial mismatch between the grid-cell size and the towers' footprints. Only crops show certain NEP agreement, significant at 0.05 level, which is realistic because croplands are the dominant land use type in many of the European areas, while very few forest sites extend over more than several square kilometres. The grid-modelled harvest also have statistically significant correlation with ground-measured data. The overall correlation coefficients give an impression that correlation increases with grid-size, but biome specific correlations do not confirm it. However, the downscaling improvement of VPM GPP does produce higher correlation in comparison with the original product of Zhang et al. (2017).

The biome-specific figures reveal that crops, grass and NF have large sample sizes (exceeding 30 samples), while BF and NAT do not. Consequently, BF correlations are the lowest (even negative for MODIS GPP) and cannot be considered further in this study. Natural vegetation on the other hand shows highest correlations in all GPP grid-products which results in statistically significant figures despite the smaller sample size.

The bias estimates reveal that MODIS GPP has closest agreement between grid and ground mean values, although all but grasslands exceed the 5% threshold specified by Verma et al. (2014). Crops have persistent 11% - 12% underestimation in all GPP products, which is similar to the one reported by Zhang et al. (2017), 15%, but lower than the figures reported in earlier studies. The VPM GPP product has slight positive bias for BF and GRA, and a large underestimation of NF (by 30%), which is likely a result of EVI application to estimate FAPAR, given that EVI has remarkably lower values for coniferous forests in comparison to broadleaf. The downscaling of VPM GPP with NDVI corrected most of this bias (reduced it to 11%) and almost eliminated those for BF and GRA. However, it changed and increased the bias of NAT, from 6% underestimation to 13% overestimation. The grid-products on harvests contain large negative biases, which is likely an effect of the rather large grid-size modelling, 1km x 1km, while most of the site-measurements were done for fields of smaller size, hence the bigger grid cells are likely to contain additional areas where no harvests took place. The biases exceeding 20% uncertainty thresholds were considered to render the corresponding datasets unsuitable for estimating ES, since in accounting context the quantitative accuracy is as important as the spatial and the temporal ones. Based on the above assessment, only the downscaled VPM GPP product can be confirmed as suitable for consequent ES assessments.

4.4 Discussions and conclusions

This work was informed by the methods applied by Verma et al (2014) and Zhang et al. (2017). Main difference is that the above studies assessed only GPP while this study assessed all key variables of the carbon budget. Still, in the case of GPP this study performs more sensitive assessments for European ecosystems by applying ground data on fluxes with more detailed geographical coverage and acceptable quality as assessed in the chapter 3.

The biome-specific correlations of grid and ground flux data for Europe have both similarities and differences with those reported by Verma et al (2014) and Zhang et al. 2017). For example, the study of Verma et al. (2014) also assessed DBF from MODIS GPP as having very low agreement with fluxnet, while the CRO and ENF underestimations reported by Zhang et al. (2017) are nearly like the ones estimated in this study (15% versus 11% for CRO and 27% versus 30% for ENF). Other figures differ strongly in these studies, e.g. crops with no agreement in Verma at al. (2014) have moderate agreement in the present one and very high correlation in Zhang et al (2017). It is possible that some of these differences can be linked to the differing grid-sampling approaches and the influence of spatial heterogeneity. Verma et al. (2014) applied 3x3 grid-cells selection windows around each flux tower and retained only the cells with the same land-cover type, while single cells pertaining to the towers' location were applied in this study. Possible effects of different vegetation types in the tower footprints were examined here, by removing the tower sites which had more than 25% different land cover in the 200m and 500m buffers around the towers. The latter were visually determined using GoogleEarth. However, the new correlation coefficients and biases based on more spatially homogenous samples did not differ essentially from the ones presented in the results section.

In conclusion the new grid-assessment methodology produced statistically robust parameters to assess multiple grid products, but there remain considerable uncertainties regarding the quality of the modelled carbon budget components because of the limited number of ecosystem types assessed here, e.g. five dominant ones. Climate variables, broad vegetation types and remote-sensing vegetation indices were used in all of the above modelled fluxes, with each of these having limitations. In part, some of these uncertainties originate from the pronounced spatial and temporal variability (as noted in chapter 3) of the fluxes. The temporal variability of both GPP and NEP is substantial, depending on varying precipitation (mostly in lower latitudes), temperature (mostly in higher latitudes) and on vegetation types. Herbal vegetation is the most sensitive to either of these controlling factors (Zhang et al. 2011), coniferous forest and broad-leaf forests - less. Crops and pastures management obscures some of the influence of these factors on cultivated areas.

In addition, some of these uncertainties result from large discrepancies between data derived from different sources and models. Specific challenges persist in validating grid data against site measurements, despite the nearly two decades of advancing research, likely because certain vegetation types are much underrepresented in fluxnet, e.g. shrublands, wetlands and natural grasslands in Europe. It is expected that these uncertainties can be narrowed by increasing the number of flux measurement sites and converging multiple evidence sources, including fluxnet, forest biomass and soil carbon stocks inventories.

The aim of this chapter was to assess to what extent remote-sensing based grid-products are applicable for mapping provisioning and carbon sequestration ESs. The assessment included review of available grid-products which satisfied a set of criteria to ensure that the input data properties match accounting needs, such as spatial detail, relevance and accuracy. MODIS and VPM GPP, harvests mapped, as well as CASA NEP (despite its course spatial resolution) were assessed against the ground data compilation introduced in the previous chapter. VPM GPP was evaluated as the most accurate product spatially, but with large underestimation of needleleaf forests GPP. The downscaling corrections introduced by reallocating the GPP values over MODIS NDVI at 250m grid within the European countries' boundaries eliminated most of this bias. The assessment based on biome-specific quantitative and spatial agreement between the ground and grid data rendered only the downscaled VPM GPP suitable for ES mapping. Since NEP and NECB cannot be estimated with the available grid data only provisioning ES can be assessed on the basis of GPP, and consequently further work is needed to assess trade-offs between provisioning and carbon sequestration ES.

The next chapter introduces a new method for mapping ecosystem carbon budgets comprehensively.

Chapter 5: Estimation and mapping of carbon budget, NECB and related ecosystem services in Europe

5.1 Introduction

The assessment of the available carbon budget map products for Europe revealed that only gross primary production, VPM-GPP (Zhang et al. 2017) has certain agreement with ground-measured data from Fluxnet eddy-covariance measurements (r = 0.67). The remaining budget variables were found to be either too coarse (as CASA-NEP, and harvests) for comparability with the collected ground-data or contained accuracy issues, such as overall low agreement with the ground data (MODIS-GPP product) or classes with bias (ENF in VPM-GPP, crop harvests). Despite the advances of mapping methods and their products, NEP, ecosystem respiration (RE), harvests and other carbon budget variables, showed dissimilar patterns, both in quantitative values and geographic gradients across Europe. Once carbon enters the ecosystems through GPP, the main variables affecting the carbon balance are RE, (as part of NEP) and harvest, of which RE and NEP were assessed as 'the largest unknowns' within the set of grid carbon budget data. With such quality issues, carbon budget and balance cannot be estimated in a consistent spatially-explicit way. Adequate spatial detail of the carbon variables is needed to assess ESs related to growth of trees, crops and other vegetation, to understand the mechanisms of sustaining ecosystems while providing for human needs.

NECB, defined as the difference between all inputs and outputs of (physical, biological and anthropogenic) carbon in an ecosystem, is needed to assess ecosystems carbon sequestration (Chapin et al. 2006) and other fluxes and transfers in a consistent manner. Chapin et al. (2006) proposed the following formula for NECB estimation:

$$NECB = -NEE + F_{CO} + F_{CH4} + F_{VOC} + F_{DIC} + F_{DOC} + F_{PC}$$

Where the components are net changes, including input and output of carbon (commonly expressed in gCm^{-2}) from and to an ecosystem unit, in the following forms: NEE – net ecosystem exchange (the inverse of net ecosystem production, NEP), CO – carbon monoxide, CH_4 – methane, VOC – volatile organic compounds, DIC – dissolved inorganic carbon, DOC – dissolved organic carbon, and PC – particulate carbon transferred through animals, humans (including harvests and manure) and environmental factors (for example movement of logs by floods and avalanches).

However, a variety of methods have been used to estimate NECB in the literature. It is often considered equal to NEP in forests (Minunno et al., 2010; Verlinden et al., 2013) and grassland ecosystems (Ferlan et al., 2011) where no harvesting has taken place; as aggregation of NEP and lateral inputs including seeds and manure and harvesting outputs in croplands (Kutsch et al., 2010; Ceschia et al., 2010; etc.); and NEP aggregated with inflows and outflows of carbon in wetlands and water bodies (Waletzko and Mitsch, 2013). More inclusive NECB definitions were applied by Rutledge et al. (2014) and Oates and Jackson (2014) who studied grazed pastures where also carbon inputs as fodder for animals were addressed, and the carbon outputs considering animal products exported from the ecosystem, methane and lateral outflows. Even if some NECB results from these studies are comparable, in ecosystem carbon accounting designed for consistent accounts over large areas, the NECB needs to be defined and applied in a uniform way.

When the balance estimation is scaled up over an entire region or a country it is termed Net Biome Productivity (NBP, Chapin et al., 2006) which is usually applied for a particular dominant ecosystem type in the study area, such as forests in the mid-west USA (Peckham et al., 2013); the west Cascades in the USA (Turner et al., 2015), European forests (Luyssaert et al., 2010), croplands in the EU-25 countries (Ciais, et al., 2012) and European grasslands (Chang et al., 2016). Apparently, there is a lack of seamless NECB mapping applications at landscape level, covering alternating ecosystem types over large areas. Such applications are needed to assess trade-offs between ESs in an international context where heterogeneous terrains and varying/mixed land cover types occur. The only similar examples of NECB modelling at coarse resolution (half degree) was done for the Arctic basin with TEM6 (Huntzinger et al. 2012) and at high resolution for a Boreal region in Canada (40km^2) with InTEC model (Govind et al. 2011).

TEM is an ecosystem process model and simulates various forms of carbon exchange between land, ocean and atmosphere. It addresses harvests in the form of CO_2 emissions after their decomposition, hence forming part of net ecosystem exchange (NEE), and does not apply ecosystem explicit accounting. NECB is estimated by considering also CH_4 and DOC flows besides NEE. The InTEC (Integrated Terrestrial Ecosystem Carbon Balance Model (Chen and Chen, 2000) is based on NPP as the main carbon input path to the ecosystems which is consequently allocated into the different carbon pools. NEP and carbon accumulation or loss in biomass and soil pool were simulated but other fluxes like DOC and methane were not considered in this application. The two examples demonstrate detailed carbon cycling modelling for assessing carbon balances, such as carbon sequestration ESs, but did not include processes for explicit accounting of provisioning ESs.

On the other hand, the ES assessment literature offers a different way of spatial analysis and modelling of both provisioning and sequestration ESs, by simplifying the carbon cycle processes to a storage rate or carbon stock indicators and the ecosystems with their carbon pools - to land cover classes (Costanza et al. 1997). Consequently, these indicators are allocated spatially over the suitable land cover classes. The approach is also called look-up method for mapping ESs. Although widely applied, including for carbon sequestration ESs (Sahle et al. 2018; Mokondoko et al. 2018, Kim et al. 2018) the approach is strongly criticised for oversimplifying the underlying ecological processes and structures (Akujärvi, Lehtonen, and Liski 2016). Nevertheless, its main merit is the ability to assess trade-offs between ESs consistently (further discussed in chapter 6.1).

Since the available grid data are not suitable for assessing the provisioning and carbon sequestration ESs in Europe and modelling tools do not offer readily applicable solutions, another option is to find a new way to map the carbon budget variables in a harmonized way and with comparable quality.

Site level statistics resulting from numerous studies in Europe provide basis for testing novel mapping methods. As mentioned above, the prevalent approach to ecosystem service mapping is the look-up method (Martínez-Harms and Balvanera 2012), relying on coefficients applied as weights on land-use/land-cover maps to quantify both bio-physical and monetary values, while advances on more accurate carbon uptake (GPP) were achieved with regression-based approaches (Verma et al. 2014). Therefore, this study will examine if possible, to map the carbon budget (and related ecosystem services) and balance in Europe by applying the combined advantages of the look-up and the regression-based approaches. Having compiled detailed ground- and grid data the following objectives are addressed:

- Explore modelling options with the available ground data to address the 'largest unknown' grid variables (e.g. NEP that did not correlate with ground flux data and RE which is not available at moderate resolution for Europe);
- Develop new model(s) with training and validation strategy for work with the available good-quality grid data (GPP, land cover, SOC, AGB and other auxiliary data);
- Estimate and validate NECB and the key carbon budget components.

If favourably assessed, the outcomes of this study would be suitable to distinguish the inputs to provisioning and carbon sequestration ESs within the mapped carbon budget variables and provide the basis to quantify these ESs on continental level.

5.2 Methodology

The study was undertaken in three parts: (i) it started with ground-data review and analysis to establish the relationships between the carbon budget variables comprehensively, (ii) determine what possibilities for modelling of the unknown carbon budget variables exist, and (iii) grid computations to map the carbon budget variables and validate the key ones. Statistical analyses were undertaken with R (version 3.5.1) and SPSS (Statistics 24) and grid-computations with ArcMap (version 10.3.1).

5.2.1 Ground and grid data for carbon budget modelling options

5.2.1.1 Ground data

The first step was to organize all the ground data in a way suitable to comprehensively review the carbon budget values of European ecosystems, and establish what drivers affect them and how should these patterns be depicted spatially. Literature cites climate, land use, carbon stocks in biomass and soil, vegetation type (with dominant species), forest age and management as the main drivers and so, information on each of these variables was extracted from the published sources for each site, as shown in the table 5.1.

Site code	Year	IGBP	Eco-region	Land use	Dominant species	Soil type	SOC (at 30cm	Age (yr)	author
AT-Neu	2003	GRA	Alpine	Fodder - hay (3 cuts)	*D. glomerata, F. pratensis*	Fluvisol	5890	-	Wohlfahrt, et al. (2008)
BE-Bra	2010	MF	Atlantic	Thinned forest	*P. sylvestris*	Arenosol	8990	88	Gielen, et al. (2011)

Table 5.1: Descriptive site information for an Alpine grassland site Neustift in Austria and mixed forest site Brasschaat in Belgium

Overview of continuous and categorical variables

The ground data shown in chapters 2 and 3 contains multiple carbon budget variables (42 were listed in chapter 2) with records on continuous scale, as well as descriptive (categorical) data on the ecosystem structures and drivers affecting the carbon budget (such as vegetation type, soil type and land use).

The complete set of ground data (including also a few sites with records that were assessed as abnormal) includes:

- 226 sites with up to 18 years of recorded fluxes, which amount to 667 site/year records for GPP, 666 for RE and 712 for NEP. Even though certain areas of west Europe contain larger number of sites, all European ecoregions have at least a few sites with flux measurements;
- 102 sites with harvests (hay with 57 site/year records, grazed biomass - 18, crops - 88, animal products - 29 and timber harvests - 24). Harvested crops, timber, hay and animal products define the total carbon export from the ecosystems;
- 48 sites with wood-growth measurements with a total of 80 site/year records;
- 36 sites with DOC, with 62 site/year records;
- 41 sites with other fluxes/transfers, including 61 site/year records of CH_4, 81 - of manure deposition, 36 site/year records of seed and animal feed applied in the fields. The sum of manure, seeds and animal feed define the total carbon returns to the ecosystems;
- Published NECB values are available for 91 sites which were assessed to be comparable in terms of definition and estimation method, with a total of 110 site/year records;
- Data on carbon stocks includes 130 sites with SOC (which are not time-explicit) and 80 with AGB, the latter - even if time-explicit, rarely contain more than one record per site;
- Other numerical data include age for perennial and permanent vegetation.

The following descriptive categorical variables affecting the carbon budget were extracted for each site and harmonized to the extent possible:

- The IGBP classes were applied as specified in each study;
- Precipitation and temperature records are reported for most but not all studied sites, hence the climate influence was addressed using six broad European ecoregions (Boreal, Atlantic, Continental, Mediterranean, Alpine, Pannonian). Ecoregions were defined by intersecting the point locations of the sites with EEA's ecoregions dataset[19];
- Information on dominant species is specified for most cultivated sites, but not for natural ecosystems. So, crops and timber cultivations were recorded with the specific species, while natural formations with the listed first species assumed to be a good representation of the dominant ones. In this way, 112 categories representing a

[19] https://www.eea.europa.eu/data-and-maps/data/digital-map-of-european-ecological-regions

species or an association were defined. The dominant species were further summarized into 34 vegetation type categories (shown in Annex 3);

- Land use and management were summarised into 18 categories, ranging from protected to most intensive cultivations;
- Forest age and biomass (AGB) were reported in readily comparable form for most sites. Age and biomass were also recorded for permanent and perennial crops. The age was then summarized into four categories, distinguishing disturbed/clear-cut (0 – 2 years), young (3 – 30 years), mid-age (up to 100 years), and old and ancient forests (above 100 years);
- Soils were distinguished as mineral, organic and highly-organic soils (exceeding 12% SOC).

In addition to the above, ecosystem type was determined for each site applying the classes defined in section 3.2.3. These classes were defined by extracting and comparing the medians and means of the fluxes (GPP, RE and NEP) and harvests (crops, fodder, timber) with their standard errors by IGBP land cover classes, which were split into additional classes to address differences stemming from the above drivers and factors. Consequently, the ecosystem classes were consolidated in a way striving to maximize the differences between them and to minimize the standard errors of their means. Two ecosystem classification subsets were defined, one for the natural fluxes and flows (NEP, RE) and another for harvests, with a minor difference between the two (see Annex 4).

The land use, vegetation type and ecosystem classifications which were developed specifically for this study are shown in Annex 5.1.

Carbon budget consistency

Since the above-listed carbon budget variables originate from different ground studies (few sites contain all of them), next, a budget balance (or closure) was constructed for assessing the consistency and completeness of the collected budget components. This was done by expressing the carbon allocation pathways (including woody biomass growth, outward fluxes, transfers and exports of carbon) as percent from the total carbon input (TCI, the sum of GPP and carbon returns) to that unit. Because of the small and or skewed samples of some classes, these were extracted as median values per ecosystem class as defined in section 3.2.3, which include needle-leaf forest, crops and intensively used grassland areas distinguished by SOC content (mineral and organic soils), forest distinguished by age (young, up-to-30 years, disturbed/clear-cut and remaining), natural vegetation in shrublands and wetlands. The budget closure was interpreted taking into consideration that not all carbon allocation pathways are entirely constrained by the annual GPP and carbon returns. For example, disturbed soils emit carbon from the SOC stocks and burned forests from the AGB stocks. To what extent the carbon budget components depend (mostly) on GPP and how complete is the carbon budget, can be interpreted from the percentages shown in the next table (5.2).

Ecosystem	TCI	RE	wood-growth	fodder	crops	anim. Prod.	DOC	CH_4	Total
Herbal croplands	1354	78%	0%	0%	35%	0%	1%	1%	115%
Crops on org. soils	663	117%	0%	0%	26%	0%	1%	0%	144%
Woody croplands	1281	68%	11%	0%	16%	0%	1%	0%	96%
Young forests	1621	65%	31%	0%	0%	0%	1%	0%	97%
Disturbed forests	804	118%	0%	0%	0%	0%	1%	1%	119%
Needle leaf forests	1668	72%	11%	0%	0%	0%	1%	1%	85%
N. forests on org. soils	890	104%	11%	0%	0%	0%	1%	1%	116%
Boreal forests	1059	89%	11%	0%	0%	0%	1%	1%	101%
Broadleaf forest	1754	72%	20%	0%	0%	0%	0%	0%	93%
Pastures	1732	89%	0%	14%	0%	2%	0%	0%	106%
Pastures on org. soils	1600	100%	0%	13%	0%	0%	1%	0%	114%
Nat. grasslands	961	92%	0%	5%	0%	0%	0%	0%	98%
Shrublands	429	84%	11%	0%	0%	0%	2%	2%	99%
Sparse veg.	169	98%	0%	0%	0%	0%	0%	0%	98%
Reed wetlands	1167	87%	0%	0%	0%	0%	0%	2%	88%
Sedge wetlands	466	89%	0%	2%	0%	0%	3%	2%	96%

Table 5.2 Partitioned carbon components (according to median values per class) and overall carbon budget

The table above omits one key pathway of carbon allocation in the ecosystems, namely the storage into SOC, which could not be quantified from the collected published studies, since very few studies reported its temporal changes. Therefore, one of the possible reasons to have ecosystem types with budget closure below 100% is that there might be accumulation of carbon in the soil. On the other hand, where the total of the carbon losses and wood-growth exceeds 100%, there might be net loss of carbon from the stocks, either in the soil, or the biomass. This is clearly the case for crops and grasslands on organic soils. For most natural vegetation classes (shrubs, natural grasslands, sedge wetlands, Boreal forests) the carbon budget closure is near 100% which indicates consistently assembled carbon budget components. Needle-leaf forests have lower, 85% completeness which is likely caused by underestimated wood-growth and also - likely accumulation of carbon in the soil, similarly but lower is the gap for broadleaf forests. On the other hand, the wood growth figure for shrubs is questionably high. DOC, methane and animal products play a rather small role in the carbon budget with values rarely exceeding 1%. DOC values on the other hand are likely higher for all ecosystems in mountains and on steeper slopes.

5.2.1.2 Grid data

From the assessed carbon budget flows only the GPP VPM product of Zhang et al (2017) showed high correlation with the ground data, which leads to the need to model the remaining key variables of the carbon budget. For this purpose several grid-products were assessed as suitable in terms of spatial resolution, including carbon stocks in the soil (OCTOP, Jones et al., 2003), aboveground biomass (Barredo et al. 2012) and Corine land cover for four years, 1990, 2000, 2006 and 2012.

5.2.2 Assessing carbon budget modelling options

In order to address the 'largest unknowns' in the carbon budget, RE and NEP, the first step in this study was to examine linear and non-linear regression modelling options (McGuire et al., 2010) to assess how this gap can be filled with the available ground data on GPP and carbon stocks. DOC and CH_4 were found to play a minor role in the carbon budget and their prediction requires other variables (even though DOC is driven by GPP, McGuire et al. 2010), including slope and water run-off, therefore DOC and CH_4 were not considered further in this study. For provisioning services, the coefficient of production use efficiency (PUE) applied to GPP or NPP was introduced in section 2.2.3 as an appropriate function to estimate the biophysical value of ESs in terms of carbon. PUE was found to be relatively stable (with small standard error of the means) and distinct for the main categories of provisioning ESs, e.g. crops, fodder, and animal products. The provisioning ESs quantities (expressed in gC m^{-2}) are linearly correlated with GPP or NPP (crops ρ =0.64, wood growth ρ =0.69, and fodder ρ =0.63), further detail on their spatial modelling is specified in section 5.2.2.2. Carbon imports, e.g. the deposition of manure (on the fields) were addressed separately since these do not have (direct) relations with GPP or carbon stocks, their spatial distribution was approached through look-up values (see section 5.2.2.3).

5.2.2.1 Multivariate regression analysis for predicting RE and NEP

The above mentioned 667 site/year records for GPP and RE, and 712 for NEP with several categorical descriptors (including species and ecosystem) provide ample data to explore the usefulness of more detailed vegetation and ecosystem types than those routinely reported in the published literature (e.g. biomes). For regression analysis RE and NEP were considered as dependant variables; while GPP, percent SOC, AGB and forest/perennial vegetation age as continuous numerical independent variables and vegetation types, dominant species, land-use and land-cover, as independent categorical variables. The independent variables were selected considering the available grid products reviewed in chapter 3: e.g. GPP-VPM, AGB and OCTOP as well as the possibilities to approximate the ecosystem types with Corine land cover.

Relationship between dependant and independent variables

The first step of the regression analysis was to assess the correlations between the dependant variables RE and NEP and the continuous numerical independent ones as well as correlations between these independent variables to assess if issues of multi-collinearity exist. The significance was also assessed as reported below in table 5.3. The correlations were assessed twice, first by applying the site-average values which eliminates issues of similarity between the annual values within the sites, and second by applying annual values whereby the influence of land management such as selection of crops, application of manure, forest management interventions (such as selective logging) etc. is taken into account. In the second case, to reduce the effect of similarity of the values belonging to the same site, only odd years were applied for model-building purposes and even year - for cross-validation. In the second case percent SOC could not be applied as an independent variable since all its values are expressed as average per site.

	GPP			Percent SOC			AGB			Age		
	n	***r***	*p*	*n*	***r***	*p*	*n*	***r***	*p*	*n*	***r***	*p*
NEP	197	**0.274**	0.000	101	**-0.437**	0.000	63	**0.51**	0.000	83	0.173	0.118
RE	188	**0.788**	0.000	89	**0.4**	0.000	52	**0.301**	0.03	72	0.212	0.074

Table 5.3 Correlations between the dependant and independent variables using site-average data. Significant correlations are in bold

With site-average values, both NEP and RE display significant but mostly weak correlations with GPP, percent SOC and AGB. NEP has positive correlation with AGB (r = 0.51) and negative with percent SOC (r = -0.44) which are significant at 0.01 level (2-tailed), however the sample distribution is not well representative throughout Europe (large areas in the east lack overlapping records of NEP and stocks). RE has more representative coverage, with higher and significant correlation with GPP (r = 0.79), and low, but also significant with percent SOC (r = 0.4).

	GPP			AGB			Age		
	n	***r***	*p*	*n*	*r*	*p*	*n*	*r*	*p*
NEP	345	**0.368**	0.000	45	**0.3**	0.045	183	**0.208**	0.005
RE	344	**0.827**	0.000	43	0.125	0.426	173	0.145	0.057

Table 5.4: Correlations between the dependant and independent variables using annual data. Significant correlations are in bold

The annual-data correlations of NEP and RE with AGB and Age exclude some site/years which were separated for validation, therefore these are less representative than the values based on site-average data. Strongest and significant at 0.01 level correlation is observed between RE and GPP ($r = 0.83$) with annual values.

	SOC%	AGB	Age
GPP	0.123	**0.483**	0.281
SOC%		0.093	0.192
AGB			**0.559**

Table 5.5: Correlation between the independent variables

GPP is (significantly) correlated with AGB, also AGB is (significantly) correlated with the age of perennial and forest vegetation. Based on the above observations, the following regression modelling options were further analysed.

Using site-average data RE can be modelled with GPP and percent SOC:

- RE = y + x1*GPP + x2*SOC

Using annual data, RE can be modelling with GPP as the only numerical predictor:

- RE = y + x1*GPP

NEP have rather low correlations with the independent variables so regression modelling was not analysed for it further.

Best fitting models for RE

Step-wise multiple regression analysis was applied to assess the best fit model for RE based on a minimum number of continuous numerical (GPP and percent SOC) and categorical variables (land cover, dominant species, land use, ecosystem class). With site-average data dominant species could not be applied since these differ/alternate in the case of crops.

With site-average data, the following initial regression model for RE was assessed:

(1) $RE = \beta_0 + \beta_1 GPP + \beta_2 SOC + \beta_3 LandUse + \beta_4 LandCover + \beta_5 Ecosystem + St. error$

All the available site-average data was used since the coverage of SOC was assessed as not well representative geographically.

Independents		Model summary				
Continuous	Categorical	r^2	Adj. r^2	St. error	DF	p-value
GPP	-	0.62	0.62	344	186	0.00
GPP, SOC	-	0.66	0.65	362	99	0.00
GPP, SOC	Land use	0.76	0.71	335	84	0.00
GPP, SOC	Land cover	0.74	0.71	332	92	0.00
GPP, SOC	Ecosystem	0.83	0.8	276	84	0.00

Table 5.6: Models tested for RE with site-average data

The models indicate that predicting RE from GPP, percent SOC and ecosystem class (as categorical predictors) achieves the highest coefficient of determination (r^2 = 0.83) and lowest standard error, yet the standard error remains rather high (about a quarter of the average RE values). Adding more than one categorical predictor does not increase r^2 or reduce the standard errors since the ecosystem classes were defined in a way that addresses the key land use and land cover differences.

For optimum use of the available site/year values, the analysis with annual data was done using a subset which includes the even years as to reduce the effect of within-site similarity (mentioned above in section 5.2.1) as well as to use the odd years for cross-validation.

The following initial regression model for RE with annual data was assessed:

(1) $RE = \beta_0 + \beta_1 GPP + \beta_2 LandUse + \beta_3 LandCover + \beta_4 Species + \beta_5 Ecosystem + St.\ error$

Independents		Model summary				
Continuous	Categorical	r^2	Adj. r^2	St. error	DF	p-value
GPP	-	0.68	0.68	269	342	0.000
GPP	Land use	0.77	0.76	235	325	0.000
GPP	Land cover	0.74	0.74	245	333	0.000
GPP	Species	0.85	0.8	215	257	0.000
GPP	Ecosystem	0.85	0.84	190	326	0.000

Table 5.7: Models tested for RE with annual data

With annual data the coefficients of determination are similar but standard errors are reduced. The highest coefficients of determination and lowest error were achieved with ecosystem classes as the categorical predictor. Yet, the relation between GPP and RE is not uniformly linear, it spreads out at higher values, with organic cultivations having a different (much steeper slope) as illustrated on figure 5.1. The differences in slopes is what determines the sign of NEP, positive for ecosystems that act as carbon sink and negative for those that act as carbon source. As indicated in section 5.2.1 and 3.3.2, cultivations on organic soils and disturbed forest have RE rates which are higher than GPP and act as strong source of carbon emissions. Young forest and permanent crops on the other hand have lowest RE compared to GPP and act as strongest sink (see these differences contrasted for five subsets in table 5.8).

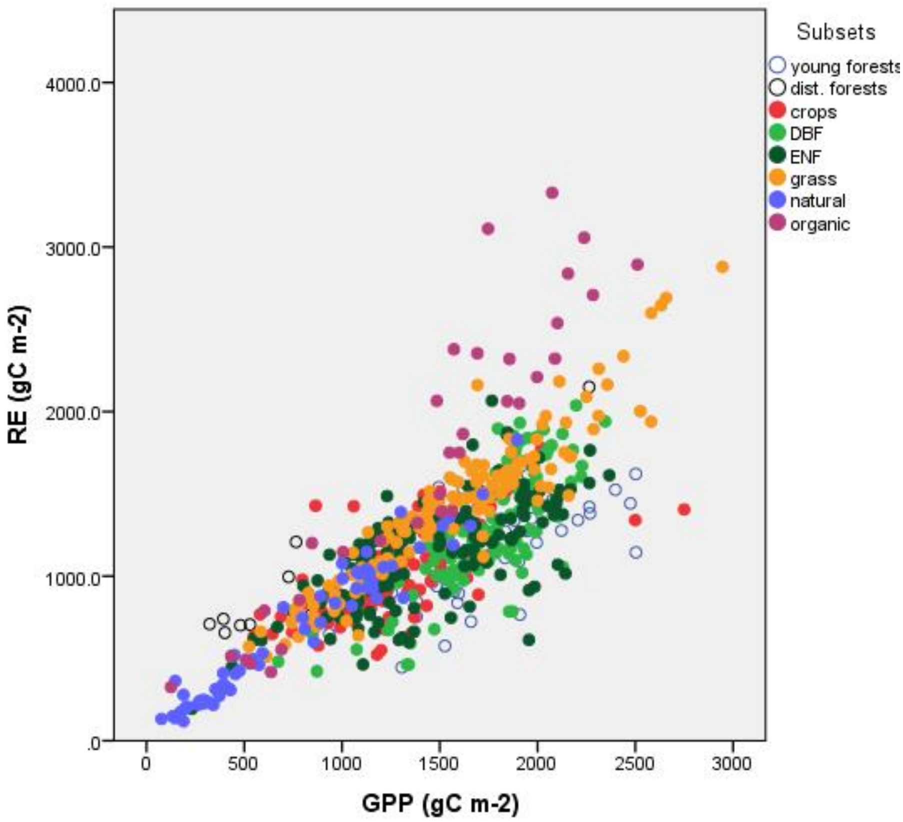


Figure 5.1: scatterplot of RE against GPP for classes for which distinct regression slopes can be developed

In order to address the non-linearities, the annual data was split into five subsets, whereby the different regression slopes distinguish several categories of source/sink function. The subsets were defined by merging the ecosystem classes with similar mean NEP values, e.g. ecosystems acting as carbon source are with negative NEP, neutral with NEP close to 0, weak, strong and strongest sink have increasing NEP values on the positive side (see the detailed classes in table 5.9).

Subset	Independents		Model summary				
	Continuous	Categorical	r^2	Adj. r^2	St. error	DF	p-value
Source	GPP	Ecosystem	0.88	0.87	280	32	0.00
Neutral	GPP	Ecosystem	0.96	0.96	108	90	0.00
Weak sink	GPP	Ecosystem	0.84	0.83	138	62	0.00
Strong sink	GPP	Ecosystem	0.6	0.59	203	106	0.00
Strongest sink	GPP	Ecosystem	0.68	0.65	160	33	0.00

Table 5.8 Piece-wise regression models for RE

Piece-wise regression models built for the five subsets achieve the smallest standard errors while maintaining high coefficients of determination, therefore these were applied to predict RE. The five regression models were applied to define distinct slopes for the five subsets and distinct intercepts for all the ecosystem classes (shown in table 5.9).

Predicting RE and model assessment

Slopes and intercepts coefficients were extracted for each ecosystem class from the models introduced in table 5.9.

Subset	Ecosystem	Intercept	Slope
Source	22.org_crop	67.9	1.192
Source	35.dist_forest	-13.6	1.192
Source	37.org_NF	-116	1.192
Source	41.org_grass	-66.8	1.192
Neutral	38.BOR_NF	-38.8	0.927
Neutral	40.grass	6.2	0.927
Neutral	43.exten_grass	7.2	0.93
Neutral	48.sparce	4.2	0.927
Neutral	52.wetland_sedge.peat	-5.8	0.927
Weak sink	45.shrub	79.6	0.749
Weak sink	46.moors	79.6	0.749
Weak sink	47.MED_shrub	79.6	0.749
Weak sink	51.wetland_reed	174	0.749
Strong sink	36.NF	96.9	0.719
Strong sink	39.DBF_EBF	44.2	0.719
Strongest sink	23.crop_rice	147.9	0.504
Strongest sink	24.crop_perm	185.8	0.504
Strongest sink	34.BF_NF_young	277.9	0.504

Table 5.9: Slopes and intercepts coefficients for ecosystem classes estimated with piece-wise regression models

RE was predicted from GPP applying the above coefficients. Cross-validation was performed by comparing the predicted RE with the RE of the odd-number years which were not used to develop the models. A strong correlation was achieved (Fig. 5.3) as well as minimal bias (26 gC m^{-2}) of overestimation.

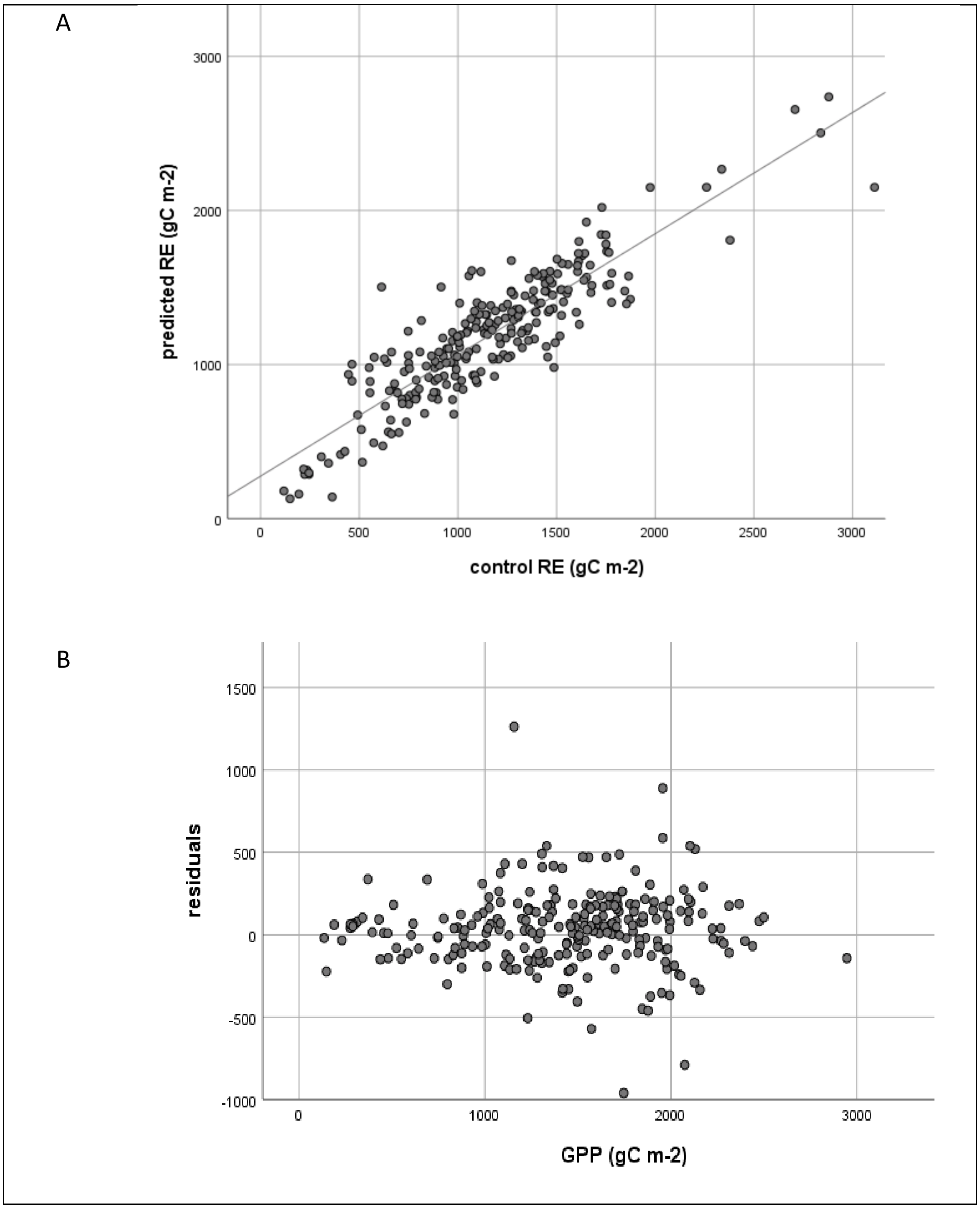


Figure 5.2: Plot of predicted against control RE (A) and plot of residuals (B)

The plot of residuals against GPP does not show remaining correlation patterns. The Pearson correlation coefficient is $r = 0.895$, significant at the 0.01 level (2-tailed).

5.2.2.2 PUE for provisioning services

The concept of productivity use efficiency (PUE), which builds on the concept of carbon use efficiency (CUE, estimates NPP as a fraction of GPP, DeLucia et al. 2007) was applied here to analyse the relation between GPP and the provisioning ecosystem services. In terrestrial ecosystems the growth of crops, grass and wood (as shown in section 2.3.5), are influenced also by cultivation intensity with input of organic fertilizers. Since GPP is the only accurate grid-product, the main goal here is to study how GPP can be partitioned into distinct ESs (or budget sub-components), each one showing where carbon goes in the ecosystem and in what form, based on ecosystem type and management. Consequently, these fractions can be applied for large-area mapping of the provisioning ESs. This GPP-based approach limits the mapping options, addressing only terrestrial vegetated ecosystems.

Annual values of PUE were estimated for each ES that has a relation with GPP and where both values coincided in a given site/year.

(4) PUE = product / GPP, where the products are either harvested crops, fodder or wood growth.

The annual, rather than site-averaged values were estimated to address the variability of PUE in relation to different vegetation (e.g. crop species) and management types, with annually alternating crops, thinning, logging and growth of forests, *etc.* For wood-growth this produced wood-growth 68 (PUE-wood-growth) site-year estimates in total; for fodder 62 (PUE-fodder) of which 48 are hay (only hay is considered carbon export from the ecosystem); animal products 26; food-crops 36, total crops 76 (PUE-crops). Timber harvest has 22 site values, which did not correlate nether with GPP not AGB, likely because of very small sample size which includes very distinct management regimes, from clear-cut logging, to selective logging with variable intensity. Hence timber harvest were not modelled in this study, for mapping purposes the product of Verkerk et al. (2015) was applied.

The following PUE values were applied as slopes to predict the corresponding ESs from GPP.

	PUE-wood-growth
24.crop_perm	0.11
34.BF_NF_young	0.31
35.dist_forest	0
36.NF	0.11
37.org_NF	0.11
38.BOR_NF	0.11
39.BF	0.20
45.shrub	0.11
46.moors	0.11
47.MED_shrub	0.11

Table 5.10: PUE for growth of woody biomass

	PUE-Hay	PUE-Crops (incl. by-products)	PUE-Fodder (hey and grazed biomass)
21.crop	NA	0.31	NA
22.ATL_crop	NA	0.35	NA
23.crop_rice	NA	0.31	NA
24.crop_perm	NA	0.16	NA
40.grass	0.09	NA	0.12
41.ATL_grass	0.13	NA	0.15
43.exten_grass	NA	NA	0.05

Table 5.11: PUE for growth of hey, crops (including by-products such as straw) and total fodder (including grazed and mowed grass)

As shown previously harvests and wood-growth have clear positive correlations with NPP and GPP (section 2.3). Further analysis showed that SOC is not correctly applicable for distinguished crop or grass PUE, because most cultivations on highly organic soils are energy and fodder crops in northern Europe, with lower PUE (mean 0.28), compared to most food-crops in the rest of Europe (0.38). Since food, fodder and energy crops could not be distinguished with the available grid-data, ecoregions were applied to estimate distinct PUE of crops and pastures, whereby Atlantic crops and grass cultivations appears to be more efficient in terms of carbon-assimilation into products (median values of 0.35 versus 0.31 for crops and 0.13 versus 0.09 for hay production). This is likely because of the more intensive and optimized cultivation patterns in northwest Europe, rather than climate or carbon stock factors. This is why, another set of ecosystem classes was defined for mapping, in which the organic soils distinction was removed and Atlantic crops and grasses introduced. In addition, a separate class of protected forest was introduced, where no harvest take place. These classes were applied for estimating PUE for hay and total crops (total including straw, permanent-, energy- and fodder crops).

The ecosystem classification for NEP/RE was used to estimate wood-growth PUE where short-rotation-coppice (SRC) plantations are included in the class of woody crops (median CRE of 0.11), and distinct from young forests, which have the highest median PUE value of 0.31 and broad-leaf forests (0.2). Needle-leaf forests on organic soils were merged with the rest of the needle-leaf (including Boreal) with median wood-growth of 0.11. Woody plant growth of shrub ecosystems were merged in a single class (moors, shrubs and Mediterranean scrub) for which the same median value of 0.11 was obtained, and which is likely to be rather high.

5.2.2.3 Look-up estimation of carbon returns

Deposition of manure on crops and pastures and carbon returns (or inputs) through seed and animal feed were averaged by the ecosystem classes for harvests, but the distinction between Atlantic areas and elsewhere was removed. Since carbon exports through animal products (milk and meat) were not processed for grid-mapping, the inputs through animal feed were ignored too. Nevertheless, the mean values of the two categories are very close (17 gC m^{-2} for animal feed and 13.2 for animal products) and therefore their omission should not distort the carbon balance significantly. Because of the impossibility to find any class-specific pattern on manure deposition, a mean value of 94 gCm^{-2} was applied for all pastures and crops (the mean for pastures is 94, while for crops it is 90, and the mean for seeds to grow crops is 4.5).

5.2.5 Carbon budget grid-modelling

Grid computations were done by reproducing first the ecosystem classes defined above with grid-data and by applying class specific equations to map the carbon budget variables.

Mapping ecosystem units for fluxes and harvests

The site-data patterns and corresponding ecosystem classes were applied for European level mapping of the carbon budget using the following grid-data inputs:

- Corine land cover (CLC) at 250m resolution, used to define where wood, crops and grass grow, also shrublands, wetlands and sparse vegetation, and also to map young forests (where non-forest class was turned into a forest class in the next CLC time step) and lost forest (where forest was turned into a non-forest class)
- Organic carbon content in the topsoil (OCTOP, Jones et al. 2005), was applied to distinguish mineral and low organic from high organic soils (above 12% carbon content) and those were filtered for crops, grass and needle-leaf forest. The latter includes natural forests and plantations on drained peat-bogs.

The above grid-inputs were applied to approximate the ecosystem types defined via the ground-data descriptions, following the rules according to the flux and harvests patterns studied in section 2.3. The grid computations were done in ArcMap, in the following order:

a) Corine maps from 1990, 2000, 2006 and 2012 were reclassified from 44 into 16 classes of terrestrial vegetation with the following codes: 20.annual crops, 23.rice, 24.permanent crops, 25.mixed annual-perm. crops, 26.mixed crops – natural vegetation, 39.broadleaf, 36.needle-leaf, 31.mixed forests, 40.pastures, 43 natural grasslands, 45.transitional woods and shrubs, 46.moors, 47.sclerophylous/Mediterranean shrubs, 48.sparce vegetation, 51.inland marshes – reed wetlands, 52 peat and salt marshes – sedge wetlands.

b) For fluxes mapping, the following adjustments were made using spatial masks from the above grid data: annual crops (20), pastures (40) and needle leaf forest (36) were distinguished on organic soils (where OCTOP exceeds 12 %) and recoded to 21.organic crops, 41.organic grass, 37.organic needle-leaf forests; young forest (where non-forest changed to forest) were distinguished and reclassified to 34, disturbed forest to 35 (where forest changed to non-forest); Boreal forest were distinguished (using the Boreal ecoregion) and recoded to 38.
c) For harvests mapping, crops (20) and pastures (40) were distinguished if Atlantic (recoded to 21 and 41), and forests if protected (31).

The resulting ecosystem classifications for fluxes and harvests are shown in Annex 4.

Mapping RE and NEP

Based on piece-wise regressions, the slopes and intercepts from table 5.9 were applied for grid mapping of RE. Then grid-NEP was estimated by subtracting RE from GPP. For validation purposes, the grid-NEP values were compared with the ground NEP for the above years, for which the ground data of GPP and RE were not used to develop the regression models. The quality of the mapped NEP was assessed in terms of Pearson correlation (r), *RMSE* and biases estimated per dominating land cover types, as in section 4.3.2.

Mapping harvests and wood-growth

Harvests were mapped with estimated PUE coefficients for hay and total crops harvests. Grazed biomass was not mapped, since most of it was considered to end up in the same grazing place. PUE for wood-growth, hay and total crop harvests were estimated by dividing their site/year values with matching GPP values. All data records were used for developing the mapping equations, since the ground data sample sizes are not large enough to separate subsets for independent validations. However, the quality of the mapped harvests of crops could be partially assessed in an aggregated form e.g. at national level by comparing the values with corresponding values from national statistics.

5.2.6 Estimation and validation of NECB

Grid NECB was estimated in the following way:

NECB = (GPP + manure) – (RE + harvests)

Finally, grid NECB was extracted for 71 sites (shown in Annex 1 and 2) and compared with their 95 site/year ground NECB records. The agreement between ground and grid NECB was assessed as for NEP, on a scatterplot with Pearson correlation (*r*), *RMSE* and biases per dominating land cover types.

5.3 Results

The results from the grid-mapping of carbon variables and their validation are presented.

5.3.1 Carbon budget grid-maps

Total carbon input (GPP and carbon returns); carbon exports through harvests (which constitute most of the provisioning ESs), NEP and NECB were mapped for years 2001, 2003, 2005, 2007, 2009 and 2011. The decadal mean grid values are shown below on fig 5.4.

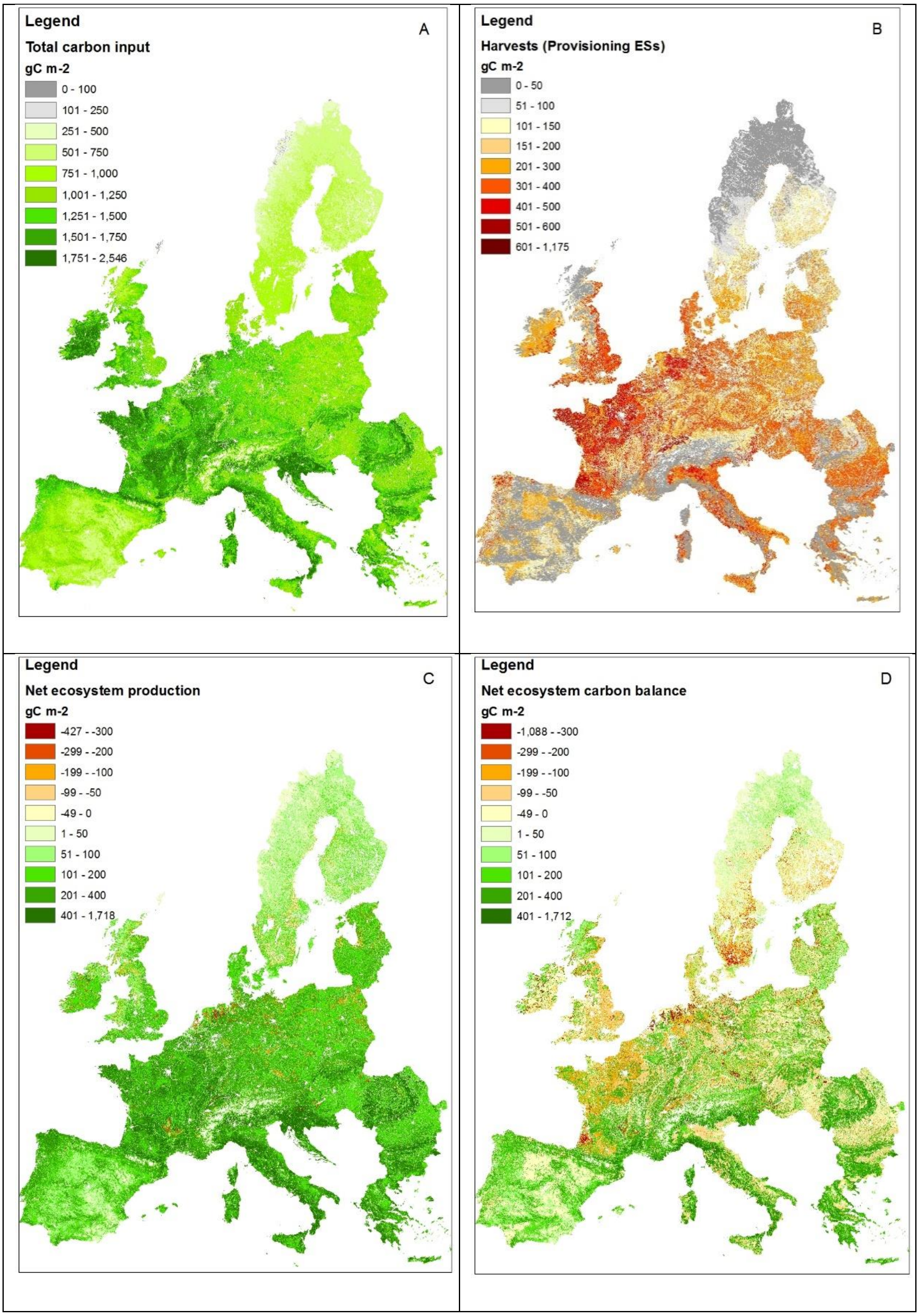


Figure 5.2: Carbon budget components (A) TCI, (B) harvests, (C) NEP and (D) NECB for year 2011 at 250m resolution grid

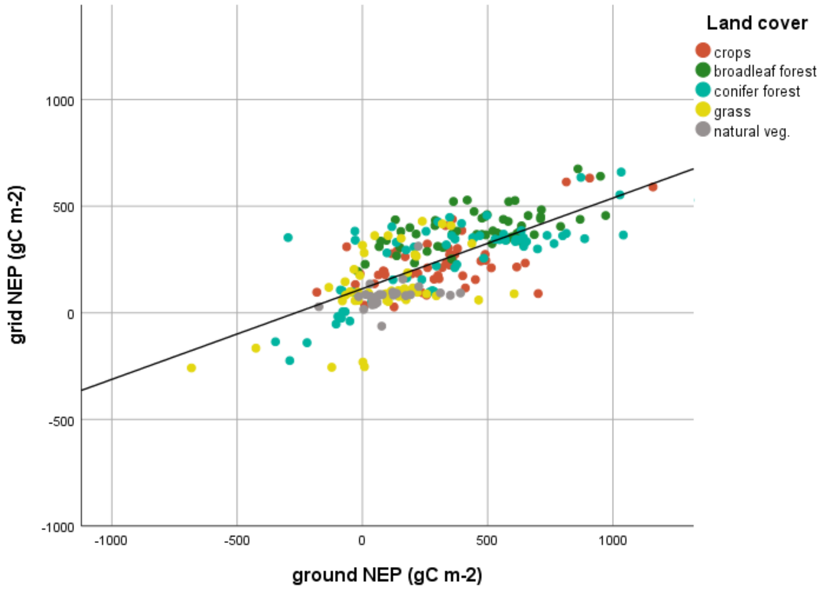
The patterns of TCI reflect in fact GPP, since manure was only applied for crops and pastures and with a uniform value of 94 gC m^{-2}. The GPP values were assessed in section 4.3.2, to be in agreement with ground GPP with r = 0.76 applying 139 site-averaged estimates. The harvests show highest quantities in north-western part of Europe, including England, and much lower in the south, east and north periphery of the continent. NEP follows GPP over most of the territory except on organic soils where it is negative. NECB shows slightly positive values in northern forest and natural vegetation areas (e.g. Scotland, Scandinavia), and much higher in southern (Iberian and Apennine peninsula) and east Europe. NECB is low, with negative values in most intensive crop and timber production areas. Some of the patterns are repeating, such as clearly outlined negative NECB in the areas of intensive agriculture in the Po valley, north France and West Germany. Mountain areas display somewhat more positive NECB, but steep slopes may be considerably affected by run-off DOC which is not addressed here. On the other hand, floodplains and wetlands may be receiving significant imports of carbon, also unaccounted here.

5.3.2 Validation results

Validation of NEP and NECB

NEP and NECB grid maps were validated using the records extracted from the European published studies for years 2001, 2003, 2005, 2007, 2009 and 2011. First the overall agreement was assessed with Pearson correlation coefficients between the ground and grid data, which for NEP is r = 0.71 significant at 0.01 level, and for NECB, r = 0.59, also significant at 0.01 level.

A



B

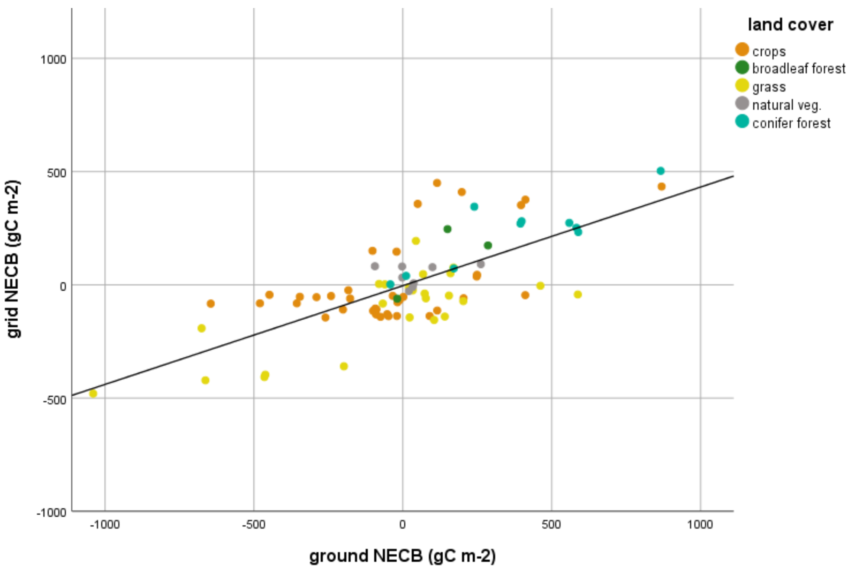


Figure 5.3: Scatterplots of grid against ground values of (A) NEP and (B) NECB

Several outlier points were observed on both NEP and NECB scatterplots and were analysed further. The most distant outliers result from values in the input grid data on SOC and Corine land cover which contradict the corresponding values from the ground data for these sites. The largest differences between grid and ground NEP, and consequently NECB were found where sites with very high SOC on organic soils appeared to have low SOC in OCTOP. Several outliers were found also as a result of land cover mismatch (or errors) introduced with Corine, for example a flux-tower site with grass, classified as forest on the CLC map. These outlier values caused large *RMSE* for both NEP and NECB grid estimates. When these input data errors were marked, and filtered in the validation datasets, Pearson correlation coefficients increased, especially for NECB. For NEP the new r = 0.73 and for NECB new r = 0.72. RMSE remained high, 166 for NEP and 227 for NECB (see tables 5.5 and 5.6).

NEP bias and more detailed correlations coefficients were assessed for the dominating land cover classes applied also in section 4.3.2.

Dom. land cover	***N***	***R***	**mean ground NEP**	**mean grid NEP**	**bias**	**bias (%)**	**RMSE**
broadleaf forest	56	0.6	463	392	-71	-15	178
crops	48	0.61	315	238	-77	-24	170
grass	53	0.5	90	115	25	27	142
natural veg.	29	0.4	103	80	-23	22	71
conifer forest	65	0.75	358	262	-96	-26	212
Total	251	0.73	287	234	-53	-18	166

Table 5.2: Bias, RMSE and Pearson correlation coefficient for NEP per dominating land cover classes

The assessment of NEP biases per dominating land cover types in table 5.5 show a systematic underestimation of grid-NEP which is on average 18%. This, as a whole is lower than the dominating class biases because both negative and positive NEP values are underestimated. The underestimation is highest for conifer forest (-26%) and crops (-24), lower for broadleaf forests (-15). Grasslands and natural vegetation have overestimated NEP, respectively 27% and 22%. The correlation coefficients by land cover types are mostly lower than the overall (r = 0.73), between 0.5 and 0.6, except for natural vegetation which is rather low 0.4 and needle-leaf forest which is the highest (r = 0.75). It needs to be noted that a portion of the underestimation of crops and conifer forests NEP is inherited from the underestimation of the input GPP values (shown in section 4.3.2, e.g. 11% for both classes). Also, despite the grouping of the detailed ecosystem classes into larger dominating land cover types, their values distributions contain outliers and some still deviate from normal (e.g. grasslands) therefore these mean values are not all representative. Overall, the higher biases and lower correlations per land cover type indicate that further studies are needed but based on larger samples of ground data with improved ecosystem representability.

Because of the smaller sample size and stronger outliers, NECB biases per dominating land cover types were assessed applying median values (table 5.6). The assessment shows that both ground and grid values are closer to neutral when considering the overall sample which is mostly composed of crop and pasture sites.

Dom. land cover	n	median ground NECB	median grid NECB	Bias	RMSE
broadleaf forest	4	218	174	-44	88
crops	37	-52	-59	7	232
grass	24	38	-54	-92	261
natural veg.	8	27	55	28	95
conifer forest	10	397	261	-131	224
Total	83	20	-40	-60	227

Table 5.3: Bias, RMSE and Pearson correlation coefficient for NECB per dominating land cover classes

The median NECB grid values are lower than the ground for grass and conifer forests and higher for natural vegetation (for grasslands NEP was overestimated while NECB is underestimated). Despite these differences, there is an overall consistency between the grid and ground data, and also in agreement with previous studies, e.g. forests with higher positive NECB (Luyssaert et al., 2010) and crops with negative NECB (Ciais, et al., 2012).

5.4 Discussion and conclusion

5.4.1 Carbon budget grid-mapping

In the absence of readily applicable grid-data or models to map the European NECB and carbon budget, this combined grid-modelling approach produced grid outputs in agreement with ground data for NEP (r = 0.73) and NECB (r = 0.72). Forests are underrepresented in the NECB studies, whereby if NEP is considered equivalent to NECB in the absence of harvests in protected forests, the agreement will be increased.

Since the ground data samples size on crops were not sufficient to be split into training and validation subsets, the mapped harvests of crops were compared with the official statistics at national level, after aggregating all grid-values within the countries' boundaries. For this purpose, the harvested crop produce was extracted from Eurostat at standardized humidity for the EU countries. All crop categories for which the humidity is reported (as %) in Eurostat, could be consequently converted to dry matter and finally – to carbon content (50% of dry matter). For most countries these crops represent the majority of harvested crops, both by area and volume. It includes cereals (rice separately), oil-seed crops and pulses. Root and tuber crops are not reported with humidity, whereby a heuristic 80% value was applied following expert-based assumptions developed for EEA-SECA (Weber 2011). Green harvested fodder crops are reported in standard humidity but only half of the European countries produced statistics. Other crop categories including fruit, vegetables, nuts etc. were not included because of the difficulties to assign representative humidity values, therefore the values from the official statistics are lower than those extracted from the grid-estimates.

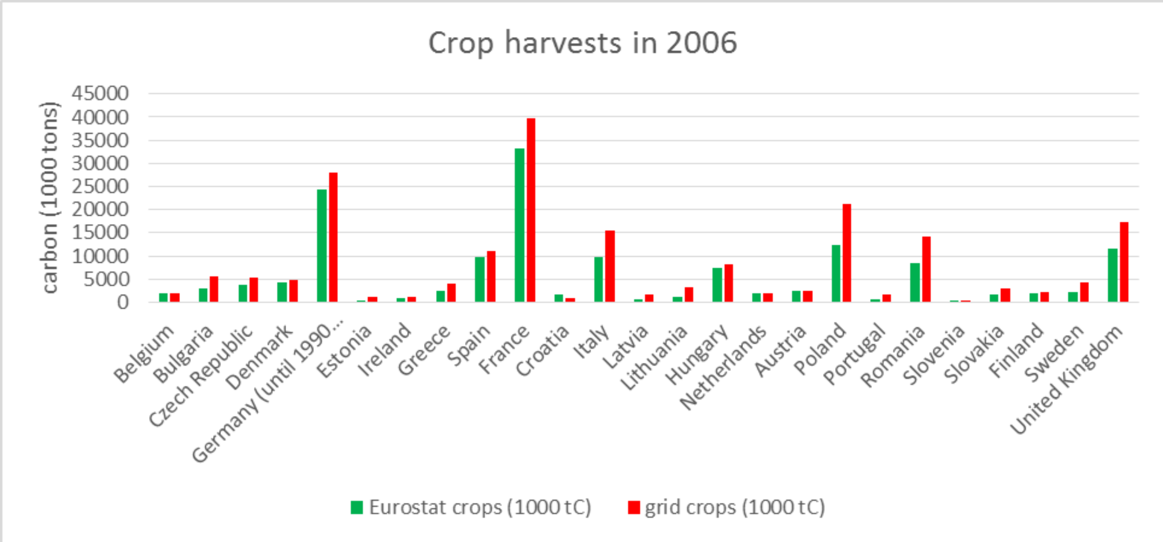


Figure 5.4: Crop harvests from Eurostat and grid-estimates for year 2006

The crop harvest statistics show that nationally aggregated grid-values are about 25% higher than Eurostat's and there is systematic overestimation. Overestimation by more than a third can be seen for some east European countries, and also for Italy and the UK. However, in part this can be attributed to the fact that not all crops from the official statistics could be expressed in terms of carbon content and also because harvests in the form of green fodder from arable lands were only reported for some countries. Overall, there are consistent quantitative patters of the countries' crops harvests.

This triple consistency between figures from ground, grid-modelling and national statistics increases the confidence about the quality of the mapped carbon budget variables, in particular the ones that underpin the main carbon sequestration and provisioning ESs, such as growth of crops and forests.

The study demonstrated the possibility to define and map NECB in a uniform way across different biomes, countries and ecosystems with the help of input-output and item-balancing logic which is common in national accounting practices. The intricate balance between carbon fluxes, transfers and change in stocks is important to assess for a number of policy applications. Global climate change mitigation actions, regional regulatory functions, such as meteorology and hydrological cycles (Makarieva and Gorshkov, 2007; 2010) and local habitats and biodiversity maintenance (Haberl et al., 2004, Neuenkamp et al., 2013) would benefit from improved and accurate mapping of carbon budget and balance. The applied accounting structure and its outputs (e.g. NECB and wood-growth) need to be cross examined with the equivalent ones from existing carbon accounting mechanisms, mostly based on differencing carbon stocks. Accounting in the AFOLU sector according to the IPCC guidelines for GHG inventories[20] and MVR for REDD+ are of particular relevance.

Although the mapped NECB and its components are equivalent to those applied in other studies, for example NBP of crops (Ciais, et al., 2012) and forest (Luyssaert et al., 2010) in Europe, this is likely to be the only international medium-resolution and validated NECB map. Nevertheless, the NECB and the carbon budget component maps need improvements. For example, the regression-based prediction of RE from disturbed organic soils is likely more uncertain (than from mineral soils) since certain portion of the emitted RE is sourced from the SOC stocks, as well as deposition of manure into these stocks. DOC outflows should be accounted, especially on higher grounds and slopes, also carbon inputs in wetlands and flood plains through the inflow of DOC. The training data on harvests of crops and hay is mostly from west Europe where cultivation patterns are more intense, so the resulting quantities mapped for east Europe are likely overestimated as indicated by the comparison with national statistics on harvests. Set-aside effects on crop harvests were not addressed here, while in some countries, e.g. Spain - such crop areas are about 30 % from all croplands.

5.4.2 Relations between carbon budget variables and ecosystem services

The carbon budget variables were selected with the objective to apply them as a measure of the ecosystem services which can be expressed in terms of carbon, e.g. provisioning services and carbon sequestration. As previously noted, the positive multi-annual values of NECB apply as a measure of carbon sequestration (Braun et al. 2017), while harvests in the form of timber, crops and fodder can be applied as proxy of provisioning services. The exact definition in the latter case is more debatable because of the influence of multiple human inputs and related management activities, which make it challenging to distil the contribution of nature to the growth of crops, fodder and timber. As introduced earlier, this study does not attempt to separate in a more explicit form the influences of nature and people in the supply of ESs, rather relies on an eco-physiological approach to quantify the related process in a sound manner. The concept of productivity-use efficiency (PUE) was applied as the most appropriate way to define and map the provisioning services. The outcome of this approach is equivalent to the one applied by Haberl et al. (2007) to estimate human appropriation of net primary production (HANPP), which is based on crops, timber and livestock statistics and revealed similar spatial patterns as the harvests in Fig. 5.3 across Europe for year 2000.

[20] https://www.ipcc-nggip.iges.or.jp/public/2006gl/

For carbon sequestration ES, the regression slopes defined in the piece-wise analysis in section 5.2.2.1 (see table 5.9) express a rate of carbon retention within the ecosystems where RE is smaller than GPP or carbon loss where RE is greater. This retention efficiency was defined building on to the PUE concept to assess what share of the annual supply of carbon (e.g. in the form of GPP plus other inputs) is retained by the ecosystems rather than lost in the form of RE or laterally through DOC. Consequently, carbon retention coefficients (CRE) could be defined to depict the strength of the ecosystems source or sink function.

$$CRE = 1 – (carbon\ loss / (GPP + manure))$$

Alternatively, this can be viewed as a rate of carbon loss (the inverse of retention) as interpreted in table 5.2 for the 22 ecosystem classes where essential differences could be observed, first within the column on RE and finally as percent from the total carbon losses where all transfer are taken into account.

Since GPP or NPP is often the only accurate grid-product available for many terrestrial parts of the world, the concepts of PUE and CRE provide basis for large-area mapping of the carbon budgets and the associated ESs. This GPP-based approach limits the mapping options, addressing only terrestrial vegetated ecosystems. Bare peatlands, coastal mudflats and urban areas have substantial carbon emissions (as shown in section 3.3.2) but cannot be assessed here, because of lacking or very limited GPP rates. Nevertheless, the approach offers a good option for mapping the budget in a way suitable to assess trade-offs between provisioning and carbon sequestration ESs with distinct PUE and CRE. If more data was available on rates of DOC and linear correlation could be established the above equation would be applicable to grid-map DOC as another essential variable in the carbon budget.

Chapter 6: Assessment of synergies and trade-offs between carbon sequestration and provisioning ES in Europe

6.1 Introduction

The aim of this final research step is to differentiate further the different types of provisioning and carbon sequestration ESs and to evaluate the synergies and trade-offs in their supply. The research hypothesis stated at the beginning of the PhD study (section 1.5) was that 'the more carbon is removed from the ecosystems with provisioning ESs, the less sequestration takes place and hence additional carbon emissions end up in the atmosphere'. Yet, it is known that forest thinning enhances strongly radial growth of many forest types e.g. oaks (Cañellas et al. 2004, Bréda, Granier, and Aussenac 1995), pines (Vincent, Krause, and Zhang 2009, Peltola et al. 2007), beech (van der Maaten 2013). The rate of radial growth is considered here a measure of carbon sequestration in above ground biomass (AGB), which is related to belowground biomass, litter accumulation, etc. In addition, the thinned wood is considered a product of provisioning service. Therefore, appropriately done forest thinning provides an example of synergistic supply of both provisioning and carbon sequestration ESs, or even in some cases - an example of provisioning ESs enhancing further sequestration. Clear-cut logging on the other hand is affirmed to cause carbon stocks depletion significantly in longer terms (Dean, Kirkpatrick, and Friedland 2017), especially if old-growth forests are logged. There are examples of studies which did not find such depletion in shorter terms (Hyvönen et al. 2016).

Other types of interactions between ESs have been reported, for example in rangelands, effects of grazing and browsing by large herbivores clearly decrease AGB (Tanentzap and Coomes 2012) (while supplying provisioning ESs in the form of animal products), but increase the rates of belowground storage in some cases (Ford et al. 2012, Pucheta et al. 2004), and decrease them in others (Johnson and Matchett 2001). As reported earlier, crop cultivations on organic soils lose as much as 1 $kgCm^2$ annually in north Europe (Elsgaard et al. 2012), which is one of the strongest trade-off examples between provisioning and carbon sequestration ESs. So, a key research question to address in this chapter is to investigate in which cases provisioning and sequestration ESs impede- and in which - enhance each other.

A thorough framework for ecosystem interactions and 'bundles' analysis, with trade-offs and synergies was introduced by Spake et al. (2017). They defined ecosystem service bundles as

‘Sets of ES that appear together repeatedly across space or time’, with synergies where the supply of one ES enhances one or more other ESs; and trade-offs, where the increase in supply of one ES causes reduction in the supply of one or more other ESs (Spake et al. 2017). They demonstrated the approach with ES values calculated for municipal units in the French Alps, with interactions assessed with principle component analysis (PCA) and clustering of ES associations. The key limitations explained by the authors were that only patterns and no processes could be applied in the ES indicators estimation, as well as the scale issues impeding the defining and mapping of ESs in a comparable manner.

An example of highly explicit trade-offs between carbon sequestration (as a global benefit) and provisioning ESs (locally relevant), was shown by Kim et al. (2018) in a region of Indonesia. Carbon sequestration was assessed applying REDD+ Verified Carbon Standard (VCS) guidelines recommending accounting for forest AGB and long-lived wood products (with other pools optional), and where the size in the pools and their changes were assessed by weights on land use. Provisioning ES were identified within four types of forest use areas and evaluated based on interviews of local stakeholders. Actual values and trade-offs were assessed in monetary terms, but no biophysical data was shown, on which the monetary valuation was based. The main interest in this study is to assess the trade-offs in biophysical terms, applying carbon as a unit of common measurement (expressed in gCm^{-2}). Carbon sequestration and provisioning services (including food, fibre and timber) are among the biggest ESs (Millennium Ecosystem Assessment 2005) and directly reflected in many ecosystem carbon budget studies. Understanding their trade-offs is of importance to climate change and other environmental policies.

The previous chapter revealed that carbon budget can be mapped comprehensively and consistently, with key variables linked to identifiable ES (with corresponding products) and other processes. The biggest provisioning ESs (growth of crops, wood and fodder), NEP and NECB could be assessed in comparison with national statistics (on crops), and validated against NEE from Fluxnet, and NECB from the published studies. It is recognized that an assessment based on carbon solely will omit the value of certain ESs with corresponding products like milk and meat from grazing livestock which form very small part of the carbon budget (about 1% from GPP) but their monetary value is much higher than most crops and timber values when compared at marketable ‘live weight’. This stresses the need to analyse biophysical and monetary values of ESs and their products side by side, but the aim of this chapter is to test if ESs and their trade-offs can be assessed on the biophysical side, applying the previously developed ecosystem accounting framework. Consequently, the research objectives are:

1. Map the ESs in terms of carbon;
2. Assess synergies and trade-offs between provisioning and carbon sequestration ESs;
3. Assess and map the prevailing patterns of ES interactions in European ecosystems.

The accounting framework can be applied to structure the key accounting items including ESs and their products that can be expressed at different units of measure, including carbon, marketable (live) weight, and monetary values.

6.2 Methods

The conceptual accounting framework introduced in chapter 3 consists of a set of variables corresponding to ESs supply and another set corresponding to ESs use, where item-wise use needs to match exactly the supply, in accordance to the SEEA-EEA guidance (UNSD, UNEP, and CBD 2017). For provisioning ES the processes of growth of harvestable parts of wood, crop and fodder were considered to be the ES supply items, while the harvested timber, crop and fodder – the ES use items, which consequently may be used in different sectors of the economy.

Carbon sequestration is the part of wood-growth which remains and is not harvested (hence exported from the ecosystems), and also the processes of incorporating carbon in soil organic matter (SOM). Correspondingly, the product of these ES is the remaining woody biomass (after harvest) and SOC. The use component in the case of provisioning ES involves transfer of carbon from the ecosystem to the economic sectors and in the case of carbon sequestration, the transfer is from the atmosphere to the ecosystems. This conceptual framework was applied to structure further the grid-data analysis and complete the ES assessments in this chapter.

6.2.1 Input data and mapping method for ESs

The grid maps of growth of crops and fodder, shown in chapter five, are applied as the sum of provisioning ES supply in this chapter. Growth of crops include also by-products such as straw, catch crops, energy, perennial and permanent crops. Yet, in the case of crops the total amount of the ES supply is likely exaggerated (when expressed in terms of carbon) since, as discussed in section 5.3.4, the growth includes also non-harvested production, for example on lands set-aside from crop production (but still considered cropland).

Growth of grass harvested as hay and total fodder (including mowed and grazed grass) were mapped separately. The total fodder was applied as a type of provisioning ES, while only half of the mowed grass was applied for re-estimating the NECB (to assess carbon sequestration), under an assumption that roughly half of the pastures are mowed in alternating years, while the remaining are grazed, and most of the grazed biomass is returned in the same ecosystem.

Timber harvest was directly applied from EFI's published dataset (Verkerk et al. 2015).

The final carbon sequestration ES was considered to be equal to the positive NECB grid values, as in the study of Braun et al. (2017). In this chapter the NECB was applied as mentioned above (excluding grazed biomass), then wood-growth was subtracted from NECB to obtain an estimate of the soil carbon balance, of which the positive values constitute carbon sequestration in the soil (the negative are carbon losses from the soil). Sequestration in AGB and soil are considered as different ES types here, given that the ecological processes for their generation are fundamentally different.

The decadal mean values of the provisioning and carbon sequestration ESs of 26 European Union countries, Switzerland and the UK, were assessed. Croatia was not included in the timber harvests of EFI.

6.2.2 Assessment of synergies and trade-offs

As recommended by Spake et al. (2017) the interactions between provisioning and carbon sequestration ESs were assessed applying cluster analysis.

The clusters were identified through K-mean classification algorithm using the total provisioning, carbon sequestration in above-ground biomass (wood-growth) and carbon balance of the soil, all in carbon values (gCm^{-2}) and as a mean of the mapped years 2001, 2003, 2005, 2007, 2009 and 2011. The clustering was done using the mean values of the three variables extracted per spatial units defined by the intersection of NUTS3 and the 23 classes of ecosystem units (about 18000 units in total). The latter were spatially processed and the means of the three variables were extracted with zonal statistics in ArcGIS.

The number of clusters were determined applying the Elbow method, which is based on plotting within class-sum of squares (WSS) against progressive number of clusters. Since the objective is to reach minimized WSS and maximized between-class sum of squares, the point where WSS decrease levels off along increasing number of clusters is used to determine the optimum number of clusters. The Elbow method WSS plot was run in R, using the following script[21]:

```
set.seed(123)
k.max <- 30
data <- df # (variables: 1.prov. ES, 2.C seq. in AGB, 3.soil carbon balance)
wss <- sapply(1:k.max, function(k){kmeans(data, k, nstart=50,iter.max = 100 )$tot.withinss})
wss
plot(1:k.max, wss,  type="b", pch = 19, frame = FALSE,
    xlab="Number of clusters K",
    ylab="Total within-clusters sum of squares")
```

Figure 6.1 illustrates the WSS decrease along progressing number of clusters.

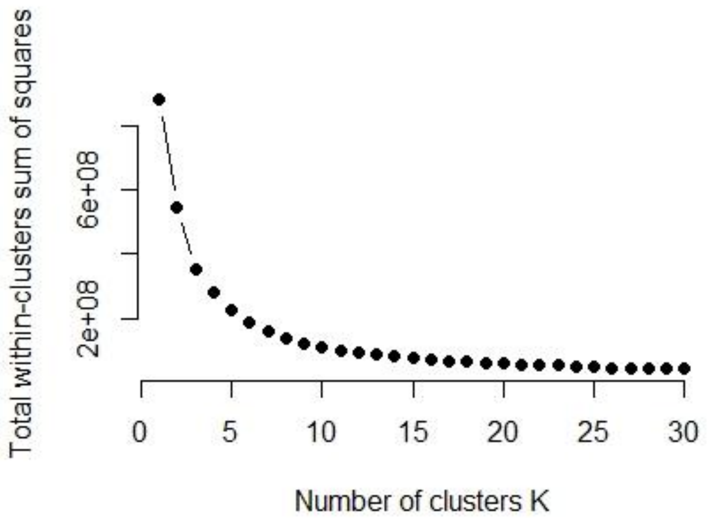


Figure 6.1: Plot of WSS against number of clusters

Five clusters were determined appropriate to partition the overall relations between the three variables and were applied for k-means classification in SPSS. Consequently, final cluster centres were defined and interpreted to assess where provisioning and sequestration ESs trade-off against each other and where they occur in synergy. In addition, trade-offs between sequestration in AGB and soil were analysed. The number and type of ecosystem units in each cluster were extracted and analysed with the help of a pivot table in excel.

[21] Source: https://datascienceplus.com/finding-optimal-number-of-clusters/

Finally, the cluster membership of each spatial unit was mapped and visualized in ArcGIS. In this way the spatial patterns of ESs trade-offs and synergies could be observed and assessed.

6.3 Results

The spatially explicit final ESs expressed in carbon (gCm^{-2}) are presented in this section. Trade-offs and synergies assessments based on cluster analysis are presented too.

6.3.1 Maps of provisioning and carbon sequestration services

Total provisioning ES is the sum of crops, EFI's timber harvests and fodder (both grazed or mowed). Hence the value of the total provisioning service here is higher than in chapter five, where are grazed biomass was excluded from the harvests. Animal products were also excluded since their very low value (when expressed in carbon) is not commensurate with the other assessed ESs. Carbon sequestration in AGB is considered equal to the annual wood-growth estimated in chapter 5. Soil carbon balance (the positive part of which is considered as sequestration in the soil) was estimated by subtracting wood-growth from NECB. All the maps are at 250m resolution. Provisioning ES and sequestration in AGB have only positive values, while soil carbon balance can be with positive or negative values (representing carbon losses).

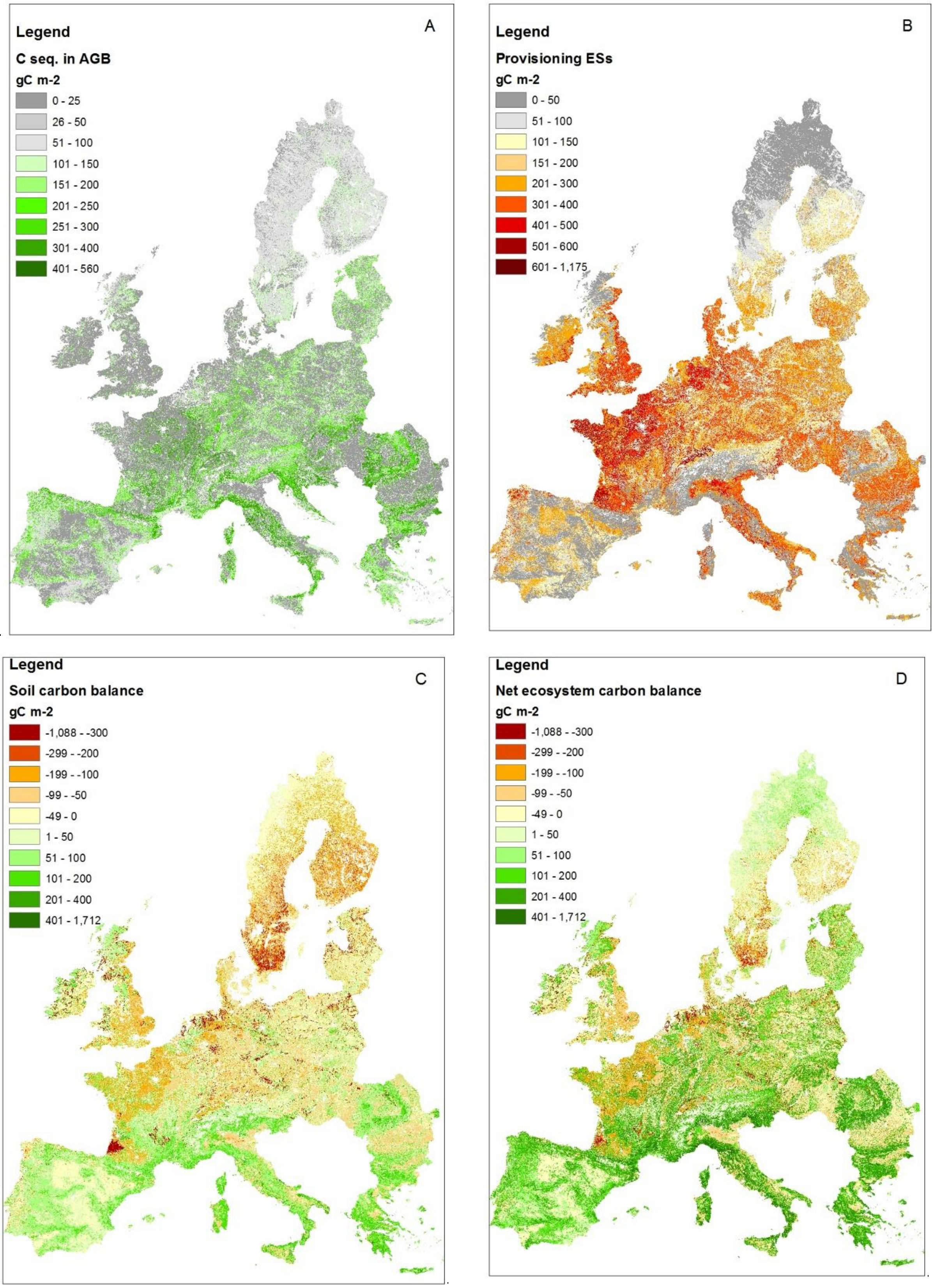


Figure 6.2: Maps of carbon sequestration in AGB (A), total provisioning (B), soil carbon balance (C) and NECB (D) of the EU countries for the period 2001 - 2011

The map of total provisioning ES (fig. 6.2-B) shows similar patterns as the ones presented in section 5.3.3, figure 5.7-B e.g. with highest rates in northwest Europe, but with lower values for east and south Europe. The new NECB (fig. 6.2-D) show most croplands as carbon source (as the version shown in section 5.3.3, figure 5.7-D). Neutral or slightly positive NECB is assessed for extensive and mixed croplands and grasslands. The intensive forestry areas of French Aquitaine and south Sweden are also shown as strong carbon source areas, because of the largest timber harvests there. Verkerk et al. (2015) explained that timber harvests in south France (French Aquitaine) are among the highest in Europe because of forestry practices based on plantations and the impact of several storms after which harvest were intense. The effect is especially pronounced on the soil carbon balance, because of the high rates of wood-growth following those harvests (e.g. in young forests). The indicated losses from the soil may be exaggerated, yet local studies do indicate such losses (Kowalski et al. 2003).

The values and patterns of soil carbon balance (fig. 6.2-D) are more uncertain than those of the provisioning ES. The patterns of carbon sequestration in AGB generally follow forest areas and GPP rates in Europe with values slightly differentiated on the basis of the ecosystem units introduced in chapter 5, e.g. young forests with highest wood-growth rates, and Boreal forests with lowest - because of the much lower GPP rates in the north.

Soil carbon balance (fig. 6.2-D), estimated as a residual from NECB and wood-growth, is the most uncertain component from all grid maps generated here. Its values may be underestimated in some areas and overestimated in other because of the impossibility to address all relevant processes (e.g. DOC inflows and outflows). It shows negative values, e.g. carbon losses from most of the territory of Germany, Sweden and Finland. Intense cultivations on organic soils can explain only a small fraction of these large carbon losses. Most of them result from the high levels of crops and timber harvests in these countries, which the carbon inputs through GPP cannot offset. Another effect is that carbon sequestration in AGB and soil trade-off among each other too. Such trade-offs have been documented elsewhere, for example soils under poplar cultivations being a large carbon source during the first two years following plantation (Arevalo et al. 2011), and also high soil carbon losses assessed for a young temperate forest (Pregitzer and Euskirchen 2004).

6.3.2 Patterns of synergies and trade-offs

Since the biggest trade-offs are likely to occur on one hand between the provisioning and carbon sequestration ES (as a whole) and between sequestration in AGB and soil in the other, the three variables (total provisioning, sequestration in AGB and carbon balance of the soil) were applied as input to cluster analysis. As explained above, provisioning and sequestration in AGB are only positive in their range, while soil carbon balance has both positive and negative values. The central cluster values of provisioning ESs and carbon sequestration/losses established as cluster centres are shown on fig. 6.3. These values helped to assess what are the most typical associations between the three variables across the European ecosystems.

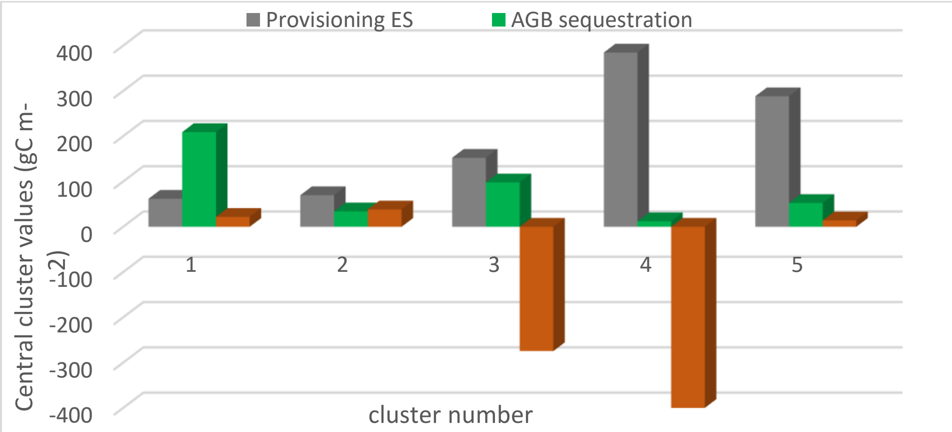


Figure 6.3: Patterns of interactions between provisioning and sequestration services in the European countries

The graph shows rather contrasting types of associations between the three variables. Cluster 1 (with 5503 out of 17925 units and 24% of the mapped European territory which is 3992567 km^2) has the highest rate of carbon sequestration, mostly in AGB, with low rate of provisioning ESs, hence the ecosystems in this cluster may be interpreted as having a trade-off in favour of carbon sequestration. Cluster 2 (with 4248 units, 27% of the territory) has synergistic and balanced supply of the tree types of ES, the rate of carbon sequestration in the soil is the highest, certain amount is sequestered in AGB and the provisioning ES are at a low rate compared to the other clusters. Cluster 3 (1763 units, 10% of the units and 5% of the territory) has higher rates of provisioning ES and sequestration in AGB, but on the expense of high rates of carbon loss from the soil. Clusters 4 has the largest trade-offs between provisioning ES and carbon losses from the soil (includes 684 units, 4% of the units and 1% of the territory). This cluster has the highest rates of provisioning ESs while lacking sequestration in AGB and with highest loss of carbon from the soil. Cluster 5 contains ecosystems where ESs are traded-off in favour of provisioning types. This cluster has the highest number of units, 5727 (32%) and covers 43% of the mapped territory.

The ecosystem composition of each cluster is shown in table 6.1.

Ecosystem	1	2	3	4	5
21.CRO	0%	0%	0%	0%	22%
22.CRO_org	0%	0%	2%	87%	0%
23.CRO_rice	0%	0%	0%	0%	1%
24.CRO_perm	0%	3%	0%	0%	12%
25.CRO_mix	0%	1%	0%	0%	17%
26.CRO_nat	0%	3%	0%	0%	18%
31.FOR_mix	22%	0%	0%	0%	0%
34.FOR_young	9%	3%	2%	0%	7%
35.FOR_dist	13%	1%	23%	0%	0%
36.ENF	20%	0%	0%	0%	0%
37.ENF_org	0%	0%	34%	4%	0%
38.ENF_BOR	0%	1%	1%	0%	0%
39.DBF_EBF	23%	0%	0%	0%	0%
40.GRA	0%	8%	0%	0%	17%
41.GRA_org	0%	1%	34%	8%	0%
43.GRA_ext	0%	19%	0%	0%	2%
45.OSH	7%	13%	3%	0%	3%
46.CSH_moor	4%	9%	0%	0%	0%
47.SH_MED	2%	2%	0%	0%	0%
48.sparce	0%	10%	0%	0%	0%
51.WET_reed	0%	16%	0%	0%	0%
52.WET_sedge.peat	0%	11%	0%	0%	0%
Grand Total	100%	100%	100%	100%	100%

Table 6.1: ecosystem composition of five ES supply clusters

The table (6.1) illustrates the following patterns:

- 87% of cluster 1 is occupied by forest ecosystem types, 13% are shrublands.
- Cluster 2 has mostly shrublands (34% of the units), followed by wetlands (27%), grasslands (also 27%), mixed and permanent crops (7%), forests (5%).
- Cluster 3 has mostly forests (disturbed and on organic soils, 59% in total), followed by grasslands on organic soils (34%).
- Cluster 4 has 87% of the croplands and 8% of the grasslands on organic soils.
- Cluster 5 is occupied by 48% of the croplands, 18% of the forests and 19% of the grasslands.

The cluster numbers were joined to the spatial units defined by intersecting the 22 ecosystem types with NUTS2 to visualize their spatial distribution.

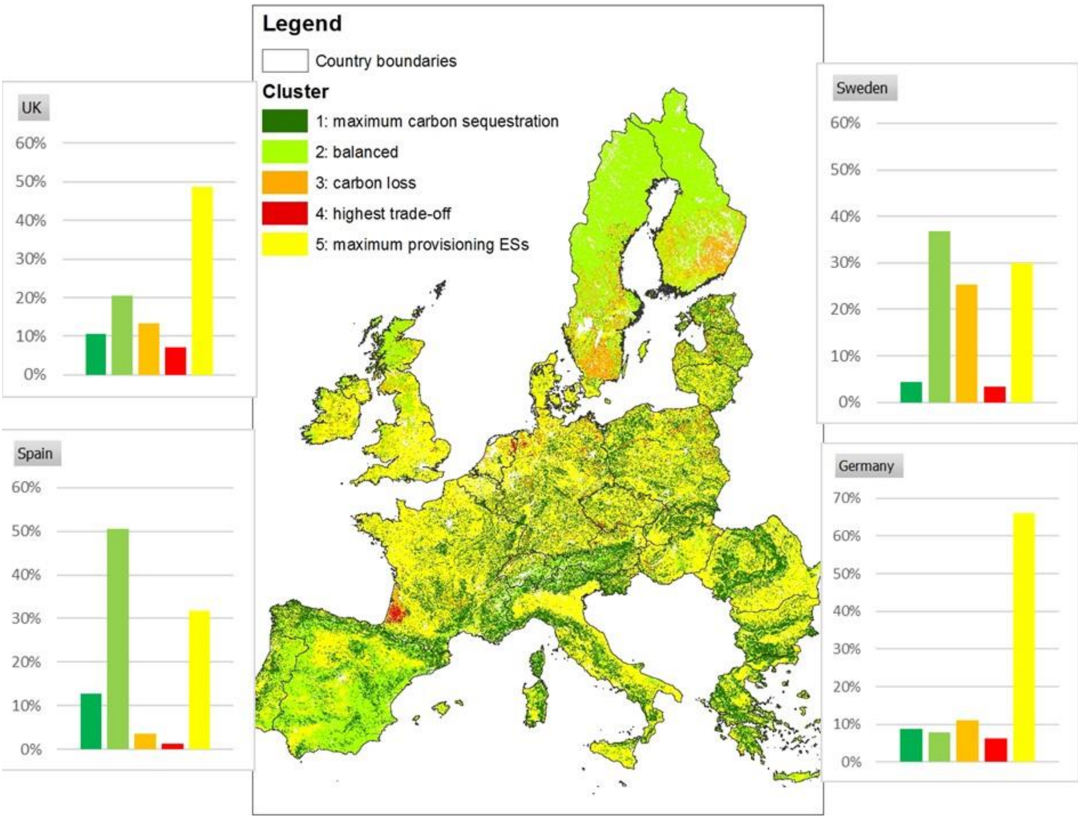


Figure 6.4: Spatial patterns of the interaction between provisioning (prov. ES), carbon sequestration in AGB (wood-growth) and soil carbon balance. In dark green are the areas with highest rates of carbon sequestration, in red and orange – high carbon losses associated with high provisioning ESs and in yellow the highest provisioning ES. Synergetic interactions are in light green. The bar plots illustrate varying proportions of the five clusters (expressed as percent) in four European countries, the UK, Spain, Germany and Sweden.

As also indicated by the number of cases in each cluster, about a quarter of the European territory has synergistic and balanced supply of provisioning and carbon sequestration services. Overall, south and north Europe (the light green areas in Fig. 6.4) have the largest areas, because of less intense or lacking agriculture and forestry. This pattern is especially pronounced on the graph of Spain where 51% of the ecosystem units are in cluster 2, in Sweden, respectively – 37%. In Sweden this cluster includes forest (24%), grasslands (22%), shrublands and wetlands (21% each), permanent and mixed crops (10%). In Spain, cluster 2 includes mostly shrublands (37%), followed by permanent/mixed crops (22%), grasslands (20%), wetlands (11%), and forest (8%).

Northwest Europe has predominantly single type, e.g. provisioning ESs (in yellow – crops and pastures) and smaller areas with large trade-offs because of cultivation of crops and pastures on highly organic soils, which supply higher harvests (roughly by a third if judged upon the central values above) but on the expense of largest SOC losses amongst all ecosystems. In Germany, 89% of cluster 4 is occupied by crops on organic soils, and in the UK – 100%.

Young and disturbed forests are mostly present in patches that are too small to be distinguishable on map 6.4. The intense forestry cultivations in French Aquitaine and south Sweden display clear patterns of big trade-offs, because of the loss of carbon associated with high timber harvests from mostly young forest stands. Permanent crops across the Mediterranean region and forest from south and east Europe with little or no harvest stand out as large and compact areas with high rates of carbon sequestration associated with moderate rates of harvests.

6.4 Conclusions and discussions

This study assessed synergies and trade-offs between provisioning and carbon sequestration ES in Europe using grid-modelled data. The estimated main ES and processes that affect NECB show ability to establish a balance for most European ecosystems where such has previously been reported e.g. cultivations of crops (Ciais et al. 2010) and pastures (Chang et al. 2015) on mineral soils, natural vegetation, or to explain its lack – on smaller areas affected by SOC or AGB losses. Nevertheless, areas like shrublands are likely somewhat imbalanced in terms of soil carbon balance, because of too high wood-growth rates which 'causes' SOC losses when soil carbon balance is estimated as a residual from NECB and wood-growth.

The spatial analysis revealed that large areas of south and east Europe have synergistic association between the analysed ESs, because of the high annual GPP rates and less intense cultivation patterns in comparison with west Europe. Permanent crops, natural vegetation and forests across the Mediterranean demonstrate strongest synergy between provisioning ES (harvests), and concomitant sequestration of carbon in AGB and soil. On the other hand, also large areas of west and north Europe show lack of carbon sequestration in the soil or even SOC losses because of too high harvests there. These patterns demonstrate how one type of ESs can be increased on the expense of another.

Assessing trade-offs between carbon sequestration and provisioning ES is of paramount importance to land management considering climate change mitigation needs. The SOC is the largest terrestrial carbon pool (Mishra et al. 2010) but mapping and modelling its changes remains most challenging (Scharlemann et al. 2014). If the SOC losses or increases in Europe could be independently validated in geographical perspective across the continent, the developed ESs assessment method will produce more robust outputs. Besides validating the mapped ES trade-offs and in particular SOC changes, other research needs which can improve the quality of the mapped ESs include:

- Independently developed grid-data on biomass growth and loss, for example with higher detail SAR, LiDAR, and optical remote sensing sources which can reduce uncertainties regarding the rates on carbon sequestration in AGB (Rodriguez-Veiga et al. 2017, Hudak et al. 2012);
- Grid-data on fires can improve the maps of ecosystems with forest disturbance, as well as shrublands which were mentioned above to have rather high rates of woody biomass growth;
- Gains and losses of carbon through DOC flows on slope terrains, floodplains and other relevant areas;
- Deposition of organic fertilizers on agricultural lands.

Chapter 7: Conclusions, discussions and future research

This chapter includes key reflections on the research findings, the contributions made to the emerging discipline of ecosystem accounting and suggestions for further research on related fields of study.

7.1 Summary of research findings

The aim of the study was to evaluate how carbon sequestration and provisioning services interact and trade-off in spatially-explicit way across the European countries, applying carbon cycle and carbon budget approach. This was carried out through statistical analysis of ecosystems' carbon budget at ground level and spatial modelling at seamless grid-level. Data quality and accuracy issues were encountered at both ground and grid levels and addressed through remote sensing vegetation indices. Because of the high correlation between NDVI (from MODIS) and GPP (from Fluxnet), the former was applied to detect sites with abnormal (outlier) GPP values and inconsistencies with other carbon budget variables. This allowed to ensemble a high quality ground dataset, and consequently to enhance the grid GPP estimates produced with the Vegetation Photosynthesis Model (VPM) of Zhang et al. (2017). Then, the ground carbon budget data was applied to train and validate a new grid modelling method based on VPM-GPP, and ecosystem types defined based on Corine land cover, soil organic carbon (SOC) and European ecoregions. Provisioning ESs, including harvests of crops, timber and fodder were compared with carbon sequestration in the soil and biomass to assess the main ESs trade-offs.

The soil carbon balance mapped in chapter 6 indicated that large areas of European croplands, pastures and forest plantations cultivated on organic soils have about two or three times larger RE fluxes than those on mineral soils. The additional quantities of CO_2 emissions are most likely sourced from SOC pools and are therefore causing their depletion. Even if the annual losses from the stocks might appear negligible when considered as a proportion from the total stocks, the rates are alarming given that SOC stocks were accumulated slowly over geological periods of time. Other large areas in west and north Europe are likely experiencing similar but lower rates of SOC depletion, because of overly intense harvesting of crops and timber which reduce the input of organic matter to sustain the SOC stocks. On the other side, Continental and Mediterranean areas of forests and other natural vegetation, and permanent crops were assessed as the biggest sinks of carbon in AGB and in soils at present. Yet, the high sequestration rate of permanent crops on slopes is possibly overestimated where higher DOC flows occur, concomitant with higher soil erosion rates (Panagos et al. 2015). Extensive search of ground data sets could not identify suitable records to validate the patterns of soil carbon losses and gains in Europe, neither did the previous pan-European carbon balance studies of Ciais et al. (2010) and Chang et al. (2015) report such patterns. One reason for not reporting patterns of soil carbon changes earlier could be that modelling of the carbon budget was done at much coarser spatial resolution (e.g. model LPJmL was run on a 0.25° grid for the EU25 countries (Ciais et al. 2010). However, several point studies of SOC changes, which include sets of sites, do support the patterns presented in section 6.3.2. For example Elsgaard et al. (2012) reported large SOC losses on eight agricultural sites on organic soils in Denmark, Jacobs et al. (2007) reported contrasting source and sink functions of Dutch grasslands in relation to their SOC content. Large volumes of carbon sequestered by permanent crops in Italy were reported by Scandellari et al. (2016) who assessed nine sites with orchards and vineyards.

Another finding of this study is that terrestrial carbon budget and balance can be spatially modelled using four variables of grid data (as a minimum): GPP, land cove/use, ecoregions and SOC (as explained in section 5.3), provided that the different paths of carbon allocation and release can be properly defined with ground data. Rates of net ecosystem production and crop/timber harvests were found to be the biggest determinants of the terrestrial carbon balance in Europe, in other words these variables show how much carbon is retained in the ecosystems and how much is exported from them through harvests. Correspondingly, the retained carbon was defined as a measure of the carbon sequestration ES and the exported carbon as a measure of the provisioning ES. Other processes like DOC transfers, methane emissions and carbon removed through animal products play a smaller part in the carbon balance. Large uncertainties remain on how much organic fertilizers, and other 'carbon returns' to the ecosystems impact the balances in Europe, in particular, the rates of carbon sequestration in soils and sediments.

The key carbon budget components for Europe were validated using Fluxnet net ecosystem exchange and further assessed with European official statistics on harvests of crops. NECB was validated against ground data from published studies. There was a statistically significant correlation between the generated grid and the collected ground data across the studied ecosystems, however many ecosystem types in Europe have remained unstudied or understudied in terms of their carbon balance. For example, there was a single published study on the carbon balance of south-east European ecosystems, in Croatia (Marjanović et al. 2011), while species and vegetation diversity is among the highest in this region, compared to other European regions. A single study was found on shrubland's carbon balance (Beier et al. 2009) with 6 sites from 6 countries. Also, only very few studies addressed the complete NECB of forests, while most of the collected NECB values for 71 sites are crops and pastures. However, about 30 forest sites, with no recent harvest history had multiannual NEE from Fluxnet which can be considered close to NECB given the absence of timber exports. Because of the comparable correlations between ground and grid values of NEP and NECB (r = 0.73 for NEP and r = 0.72 for NECB, see section 5.3.4) the overall quality of the grid products can be considered acceptable.

One of the main benefits from this study is the development of a method to spatially model the carbon budget and balance with a minimum of four spatial data inputs mentioned above: GPP, land cover, ecoregions and SOC, of which the timeseries of GPP and land-cover proved helpful to develop a decadal timeseries of grid-estimates. The regression equations presented in chapter 5 contain coefficients of slopes which were well determined for the key mechanisms of provisioning and sequestration processes based on primary production.

Land cover patterns were well document on European level based on the timeseries of Corine land cover data (e.g. from 2000, 2006 and 2012, and 2018) and do not show significant change on European level during the last two decades as illustrated in table 7.1.

	Artificial surfaces	**Agricultural areas**	**Forests and semi natural areas**	**Wetlands**	**Water bodies**
2018	5.05	45.25	44.41	2.58	2.7
2012	4.99	45.3	44.43	2.58	2.7
2006	4.89	45.42	44.42	2.58	2.69
2000	4.76	45.53	44.44	2.52	2.61

Table 4: Percent coverage of main land cover types from the total area of the EU 28 countries (source: European Environment Agency)

However, large land cover changes took place in certain regions, for example afforestation of croplands in west Europe in the nineties, agricultural land abandonment and natural reforestation in east Europe (net forest cover increased from 1985 to 2012 by 4.7% according to Potapov et al. 2015). Zanchi et al. (2007) reported that the forest areas increase in some areas of west Europe reached 30% after 1950. These figures provide additional evidence for the assessed synergetic supply of ES, however since forest areas are no longer expanding (according to the Corine data in table 7.1) the patterns will likely switch to a more singular type of provisioning ESs. The continued cultivation practices on organic soils will also maintain the trends of depletion of the soil carbon stocks, in particular in the north and west of Europe.

The carbon budget modelling method developed in this study can be (most readily) reproduced for areas of the European neighbourhood, where the same or similar coefficients of the ground data would likely apply. Similar would be the values of PUE and CRE also for other continents with Boreal, Temperate and Mediterranean-like climates.

7.2 Contribution to assessment and accounting of ecosystem services

The field of natural capital has grown substantially in recent year, both in policy and academic discourses, carbon accounting is an important component of it, in particular, as it addresses links to climate change mitigation.

Ecosystem services (ES) are broadly defined as the benefits which people obtain from existing ecological components and processes. Ecosystem accounting aims to quantitatively record these benefits as well as the underlying structures/functions to make sure that issues like depletion or degradation are uncovered. There is much disagreement about how ES should be defined in detail, and how ecosystem accounting should be structured to capture the main issues and concerns. For example, strong anthropocentric views place the main focus on 'benefits to people', with less attention to conservation issues and broader appreciation of the right of nature to exist. The SEEA-EA framework and guidance presents a part of these discourses which is gaining acceptance, but remains at conceptual level which helped to structure more in-depth the needed components for measurement by focusing attention on correspondences with products, goods and services included in the SNA (and excluding or omitting those that are not in the SNA). On the other hand more inclusive definition and classification of ecosystem services, also termed nature contributions remains a challenge (Diaz et al 2018) to establish in an ubiquitous form, as we benefit and suffer from the same components of nature, which is often dependent on the perception and culture of the beneficiaries.

This study demonstrated how ES can be determined among ecological processes related to primary production, linked to products which people use, and expressed in common unit of measurement, e.g. carbon. The cycling of carbon is closely related with other main elements, namely nitrogen and phosphorus as explained in various studies of ecological stoichiometry ranging from an individual plant to the biosphere (Sterner and Elser, 2017). Ptacnik et al. (2005) argued that deeper understanding of these relations is needed to ensure the sustainability of ecosystem services. They provided evidence on agricultural and marine ecosystems where the increased nitrogen (through human inputs) boosts the ecosystems' productivity but decreases the quality of the related products (in part due to deficiencies of micro-elements). This study could not address the relations with the water and other main biogeochemical cycles and related processes, hence certain limitations apply for a comprehensive assessment of ESs and their trade-offs, e.g. services such as flood prevention, run-off retention, water and air filtration, etc. were not addressed (even though they do have relations with biomass). Also, cultural services and biodiversity support services could not be addressed, even though many types of use can be linked to the growth and accumulation of biomass, for example recreational activities related to wildlife, use of (non-timber) forest products, health benefits, etc. Nevertheless, balancing the supply of provisioning and carbon sequestration services based on the improved ability to model their distribution is an important objective of ecosystem management (Luyssaert et al, 2018).

Ecosystem carbon accounting can be more strongly addressing the eco-centric perspective since it can explain what happens with the key functions (as primary production) and stocks (as biomass), which enables comparability between all ecosystems. Although this study is limited to the terrestrial environment, it helped to assesses issues related to ecosystems' integrity (e.g. loss of carbon stocks) and functioning (for example decline of productivity). Expressing all values in carbon certainly oversimplifies both eco-centric and anthropocentric values but consolidates a key one, namely if ecosystems sustain carbon sink or carbon source functions. In the SEEA-EA framework the carbon accounting method can contribute with NECB as ubiquitously applicable indicator on ecosystem condition. In addition, it can support assessment of ES in both monetary and biophysical terms with consistent underlying variables. Therefore, carbon is a good metric to assess multiple ESs in biophysical terms. Further valuation work is needed, taking into account monetary values based on live mass which can be matched to the carbon content, to also properly address the ES which appear negligible in terms of carbon – e.g. animal products.

This study made specific contributions to defining in more depth than previous ES studies which eco-physiological processes supply ES to match known use values (e.g. the main provisioning goods and carbon sequestration benefits). These processes could then be mapped, namely the growth of plants parts for provisioning and sequestration in AGB, and supply of plant particles for sequestration in the soil. However, for assessing net benefit also the related processes of ecosystem respiration and other flows were recognised as an essential component of the accounting framework. Hence besides assessing the ES, another step is needed, assessing the losses and balances. Knowledge on both ES and their 'counter processes' is needed for improved land management for sustained ESs supply.

Contributions to ecosystem accounting were also made by defining ecosystem unit types, in a customised classification which helped to develop equations for mapping the key carbon budget components. This classification provided very essential input for the mapping of ES and the related processes.

The study addressed provisioning and regulatory (carbon sequestration) services, which trade-off on more than half the territory of Europe. Other trade-offs certainly exist (which were not addressed in this study), essentially – with recreation, regulation of hydrological regimes, and support to biodiversity. The mechanisms of these interactions are far from being readily accountable despite being conceptually well understood.

7.3 Further research needs

New research needs and challenges were outlined in each of the thesis chapters.

In an era of rapidly accelerating climate change, further understanding the carbon balance of ecosystems requires more attention since the balance underpins how well terrestrial ecosystems can mitigate the global warming effect by removing some of the greenhouse gases from the atmosphere, which according to the most recent IPCC Fifth Assessment Report[22] is about 30% of the anthropogenic emissions. More detailed and precise modelling of the processes of carbon capture (primary production) and retention would help to reduce the uncertainties in the continental and global level assessments. While this study contributed to an improved understanding of some sequestration and provisioning services further studies would be beneficial addressing the following areas:

- Spatial aspects need to be considered for better understanding of the carbon transfers between ecosystems. For example, with the transfer of organic matter through run off – are the 'spared' CO_2 emissions from mountain slopes released later as CH_4 emissions from lowlands and wetlands? If so, should ecosystem management focus more attention on enhancing carbon storage on the slopes (as opposed to wetlands deposits)? CH_4 has a much higher global warming effect, should this be reflected in the valuation of carbon sequestration services?
- Temporal aspects should be examined to improve the understanding of which forms of storage (in plant tissues, soils, deposits) last longer and under what sort of

[22] https://www.ipcc.ch/assessment-report/ar5/

management actions? How can this longevity be incorporated in the valuation of carbon sequestration services?

- Species diversity could be examined to determine what combination of species optimizes the carbon functions of the ecosystems, based on which functional traits (such as C3 and C4, warm and cold season plants) as well as food-webs?

On the **definition of ES**, there is a tendency to opening the scope of what is considered strictly economic benefits towards considering broader social and wellbeing values (Arias-Arévalo et al. 2018), and ultimately considering that human and other organisms share a single global ecosystem, so the anthropocentric views are losing their dominance. Also, tendencies exist that non-monetary benefits like contributions to a good-quality living environment, spiritual and cultural values are likely to outweigh what is conventionally addressed in natural resource accounting, as for example the provisioning ES are considered. Here, ES were defined according to the details of their generation, being an ecological process and their use, being recognizable product or benefit. Moreover, provisioning ES were assessed to feed into economic production processes directly, through supply of materials and energy, while regulatory, e.g. carbon sequestration – indirectly, through stabilizing regional and global climate. Certainly, further mechanisms of how ecological processes contribute to human wellbeing can be recognized, and in particular - taking into account quality aspects of the derived products and their benefits to human health as suggested by the studies on stoichiometry (Ptacnik et al., 2005).

Main challenge remains to define measurement units which would ubiquitously apply for multiple types of ES to assess their trade-offs in commensurate way. This was achieved partially in the present study. While for carbon sequestration, the mass of carbon is undoubtedly the most suitable metric, for provisioning ES it presents almost negligible values for the animal-based products. While the sizeable types of products such as crops, timber and fodder are reflected adequately, other products of provisioning ES could not be addressed at all, e.g. medicinal plants, herbs, forest berries, even game. Therefore, the trade-offs between provisioning and sequestration ESs could be assessed in an ecocentric way, by addressing the effects on the ecosystem carbon balance (NECB), without considering the fate of the related products in a winder view once exported from the ecosystems, e.g. furniture made of wood may retain carbon being stored in our houses for hundreds of years. Further or different valuation methods, e.g. based on the live mass of the plant and animal products would be needed to assess the above trade-offs in terms of costs and benefits to land owners, for example. Another issue is how to address the negative 'contributions' or losses inflicted from ecosystem components (e.g. wildlife) to some stakeholders while others may benefit (e.g. damage by game on crops versus benefits to hunters). One possibility is to assess both negative and positive effects (consistently) and present a net value.

Defining carbon-based ecosystem services in an **accounting context** has both advantages and challenges. While it helped to establish certain relations between the ecological functions and products/benefits to people, the scale issues between supply and use became apparent. For some provisioning ES both may match spatially, e.g. grown fodder and grazed fodder, while other mismatch, such as the case of carbon sequestration. Since according to the accounting double entry approach, supply and use are the same in quantity, this study focused on quantifying the ESs on the supply side. Further studies should address the scaling issues and establish further clarity on the use mechanisms taking into account where the products derived from the provisioning ES are consumed, exported, etc.

Further investigation of **available grid products** on carbon budget is needed too, most important on biomass with possible changes, which correlate with SAR backscattering (Rodriguez-Veiga et al, 2017; Hudak et al, 2012). Other products on NEP exist, for example from JULES (Clark et al., 2011) which could not be readily accessed and tested in this study, but could be of superior quality compared to C-QUEST NEP (Potter et al 2011). If no readily applicable and high quality NEP product exists, further research work is needed to develop one, with the help of the latest Fluxnet data. In European context, Fluxnet offers a very strong basis but additional coverage is needed for the underrepresented ecosystems, including those in East Europe. Several key components of the **carbon budget and balance** need to be modelled and validated on their own, including DOC flows, concomitant with soil erosion, but also including modelling of the areas where DOC deposits accumulate, like on floodplains. Further improvement in relation to mapping can be undertaken, using more detailed products such as the deforestation data of Hansen et al. (2013) and with more site data on rates of all types of harvests: timber, crops, fodder, animal products and others. Eventually, the equations developed for the different carbon budget components can be incorporated into existing ES modelling tools, e.g. InVEST.

On **earth observation data** for ecosystem fluxes and other carbon budget components, further work is needed to investigate how carbon fluxes and stocks can be monitored and mapped with such data products, including vegetation indices, besides NDVI, also EVI and LCWI and backscattering from SAR/LiDAR data with different wavelengths. In this study NDVI was found as particularly useful because of its high correlation with GPP, and NEP of natural vegetation ecosystems. However, further studies should improve the understanding of how clouds and other atmospheric issues impact the correlation between the vegetation indices and GPP. MODIS NDVI (v6) can be further analysed against GPP applying the different quality tags. While optical remote sensing products remain of utmost value because of the seamless coverage of the land vegetation (closely correlated with GPP) and long timeseries of data (starting from the seventies) new data is needed to address the 'biggest unknown' in the carbon balance, i.e. the respiration or CO_2 emissions emitted by the ecosystems. Current instruments including NASA's Orbiting Carbon Observatory-2 (OCO-2) perform high-precision monitoring the CO_2 concentration in the atmosphere by measuring how much of the sunlight reflected by the earth surface is absorbed by CO_2 molecules in an air column. The column observations are then analysed as regularly spaced samples within a 10 km wide swath within each orbit to derive estimates of (mostly natural) CO_2 emissions. By focusing on columns with footprint covering the plumes of major point sources of CO_2 in China, Zheng et al (2020) demonstrated that OCO-2 data can be applied to quantify anthropogenic emissions too. Despite these advances, the sparse sampling pattern of OCO-2 is a major limitation to applying the data for spatially detailed estimation of ecosystem carbon budget and balance. With rapidly accelerating climate change and its impacts, developing improved observation capabilities of the carbon budget is imperative. New instruments are needed to support national GHG inventories for enhanced quality and transparency of the internationally reported data (to UNFCCC) and ultimately for more successful climate negotiation processes.

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Annexes

Annex 1. Database of carbon budget studies in Europe: site descriptive data

	Site_code	Site_name	LC_IGBP	Vegetation type	Land use	Latitude	Longitude	Bio-climatic region
1	AT-Neu	Neustift/Stubai Valley	GRA	10. natural grass	17. intensive grazing/mowing	47.1167	11.3175	Alpine
2	BE-Bra	Brasschaat (De Inslag Forest)	MF	17. needle-leaf trees	7. selective logging	51.3092	4.5206	Atlantic
3	BE-Dor	Dorinne	GRA	9. sown grass	17. intensive grazing/mowing	50.3117	4.9683	Continental
4	BE-Lon	Lonsee	CRO	34. other annual crops	14. annual crops	50.5516	4.7461	Atlantic
5	BE-Vie	Vielsalm	MF	15. dec. broadleaf trees	7. selective logging	50.3051	5.9981	Continental
6	CH-Cha	Chamau	GRA	9. sown grass	17. intensive grazing/mowing	47.2102	8.4104	Continental
7	CH-Dav	Davos- Seehorn forest	ENF	17. needle-leaf trees	6. managed forest	46.8153	9.8559	Continental
8	CH-Fru	Früebüel	GRA	9. sown grass	17. intensive grazing/mowing	47.1158	8.5378	Continental
9	CH-Oe1-int	Oensingen grassland	GRA	9. sown grass	17. intensive grazing/mowing	47.2858	7.7319	Continental
10	CH-Oe2	Oensingen2 crop	CRO	34. other annual crops	14. annual crops	47.2863	7.7343	Continental
11	CH-Lae	Laegeren	MF	15. dec. broadleaf trees	6. managed forest	47.4781	8.3650	Continental
12	Cr-Ja	Jastrebarsko	DBF	15. dec. broadleaf trees	7. selective logging	45.6194	15.6878	Continental
13	CZ-BK1	Bily Kriz- Beskidy Mountains	ENF	17. needle-leaf trees	12. logging forestry	49.5021	18.5369	Continental
14	CZ-BK2	Bily Kriz- grassland	GRA	10. natural grass	4. extensive grazing	49.4944	18.5429	Alpine
15	CZ-wet	Trebon (CZECHWET)	WET	28. sedge/juncus veg.	2. unused (incl. abandoned)	49.0247	14.7704	Continental
16	DE-Akm	Anklam	WET	27. reed/rush veg.	3. restored (actively)	53.8662	13.6834	Continental
17	DE-Geb	Gebesee	CRO	34. other annual crops	14. annual crops	51.1001	10.9143	Continental
18	DE-Gri	Grillenburg- grass station	GRA	10. natural grass	17. intensive grazing/mowing	50.9500	13.5126	Continental
19	DE-Hai	Hainich	DBF	15. dec. broadleaf trees	1. protected	51.0792	10.4530	Continental
20	DE-Kli	Klingenberg - cropland	CRO	34. other annual crops	14. annual crops	50.8931	13.5224	Continental
21	DE-Lnf (Lei-111M in Mund 2004)	Leinefelde, Dün, 111yr	DBF	15. dec. broadleaf trees	7. selective logging	51.3282	10.3678	Continental
22	DE-Lkb	Lackenberg	ENF	17. needle-leaf trees	1. protected	49.0996	13.3047	Continental
23	DE-Meh	Mehrstedt 1	MF	15. dec. broadleaf trees	6. managed forest	51.2753	10.6555	Continental
24	DE-Obe	Oberbarenburg	ENF	17. needle-leaf trees	12. logging forestry	50.7867	13.7213	Continental

25	DE-Seh	Selhausen	CRO	2. cereals	14. annual crops	50.8706	6.4497	Atlantic
26	DE-SfN	Schechenfilz Nord	WET	26. riverine/wetland needleleaf trees	1. protected	47.8064	11.3275	Continental
27	DE-Spw	Spreewald	WET	25. riverine/wetland broadleaf trees	1. protected	51.8923	14.0337	Continental
28	DE-Tha	Anchor Station Tharandt - old spruce	ENF	17. needle-leaf trees	7. selective logging	50.9624	13.5652	Continental
29	DE-Wet	Wetzstein	ENF	17. needle-leaf trees	7. selective logging	50.4535	11.4575	Continental
30	DK-Eng	Enghave	GRA	10. natural grass	2. unused (incl. abandoned)	55.6905	12.1918	Continental
31	DK-Lva	Lille Valby (Rimi)	CRO	2. cereals	14. annual crops	55.6833	12.0833	Continental
32	DK-Lva	Lille Valby (Rimi)	GRA	9. sown grass	17. intensive grazing/mowing	55.6833	12.0833	Continental
33	DK-Ris	Risbyholm	CRO	34. other annual crops	14. annual crops	55.5303	12.0972	Continental
34	DK-Sor	Soroe- LilleBogeskov	DBF	15. dec. broadleaf trees	7. selective logging	55.4859	11.6446	Continental
35	ES-Amo	Amoladeras	OSH	31. arid sparce veg.	1. protected	36.8336	-2.2523	Mediterranean
36	ES-ES1	El Saler	ENF	17. needle-leaf trees	1. protected	39.3460	-0.3188	Mediterranean
37	ES-ES2	El Saler-Sueca	CRO	3. rice	14. annual crops	39.2756	-0.3153	Mediterranean
38	ES-LgS	Laguna Seca	OSH	24. Med. shrubs / scrub	2. unused (incl. abandoned)	37.0979	-2.9658	Mediterranean
39	ES-LJu	Llano de los Juanes	OSH	31. arid sparce veg.	2. unused (incl. abandoned)	36.9266	-2.7521	Mediterranean
40	ES-LMa	Las Majadas del Tietar	SAV	18. evergreen broadleaf trees	5. mixed (agroforestry)	39.9415	-5.7734	Mediterranean
41	ES-Ln2	Lanjaron-Salvage logging	OSH	24. Med. shrubs / scrub	2. unused (incl. abandoned)	36.9708	-3.4753	Mediterranean
42	ES-VDA	Vall d'Alinya	GRA	23. Alp. Shrubs	4. extensive grazing	42.1522	1.4485	Mediterranean
43	FI-Hyy	Hyytiala	ENF	17. needle-leaf trees	7. selective logging	61.8474	24.2948	Boreal
44	FI-Jok	Jokionen agricultural field	CRO	2. cereals	14. annual crops	60.8986	23.5135	Boreal
45	FI-Jok	Jokionen agricultural field	GRA	9. sown grass	17. intensive grazing/mowing	60.8986	23.5135	Boreal
46	FI-Kaa	Kaamanen wetland	WET	26. riverine/wetland needleleaf trees	2. unused (incl. abandoned)	69.1407	27.2950	Boreal
47	FI-Sii	Siikaneva fen	GRA	28. sedge/juncus veg.	1. protected	61.8327	24.1929	Boreal
48	FI-Sod	Sodankyla	ENF	17. needle-leaf trees	6. managed forest	67.3619	26.6378	Boreal
49	FR_fon	Fontainebleau	DBF	15. dec. broadleaf trees	6. managed forest	48.4764	2.7801	Atlantic
50	FR-Aur	Aurade	CRO	34. other annual crops	14. annual crops	43.5496	1.1061	Atlantic

51	FR-Avi	Avignon	CRO	34. other annual crops	14. annual crops	43.9161	4.8781	Mediterranean
52	FR-Bil	Bilos, Les Landes	ENF	17. needle-leaf trees	12. logging forestry	44.4939	-0.9559	Atlantic
53	FR-Bil	Bilos, Les Landes	ENF	17. needle-leaf trees	12. logging forestry	44.4939	-0.9559	Atlantic
54	FR-Gri	Grignon (after 6/5/2005)	CRO	34. other annual crops	14. annual crops	48.8442	1.9519	Atlantic
55	FR-Hes	Hesse Forest- Sarrebourg	DBF	15. dec. broadleaf trees	7. selective logging	48.6742	7.0656	Continental
56	FR-Lam	Lamasquere	CRO	34. other annual crops	14. annual crops	43.4965	1.2379	Atlantic
57	FR-LBr	Le Bray (after 6/28/1998)	ENF	17. needle-leaf trees	12. logging forestry	44.7171	-0.7693	Atlantic
58	FR-Lq1	Laqueuille (intensive)	GRA	9. sown grass	17. intensive grazing/mowing	45.6441	2.7370	Continental
59	FR-Lq2	Laqueuille extensive	GRA	9. sown grass	17. intensive grazing/mowing	45.6392	2.7370	Continental
60	FR-Pue	Puechabon	EBF	18. evergreen broadleaf trees	6. managed forest	43.7414	3.5958	Mediterranean
61	HU-Bug	Bugacpuszta	GRA	10. natural grass	4. extensive grazing	46.6911	19.6013	Pannonian
62	HU-He1	Hegyhatsal, HU	GRA	10. natural grass	17. intensive grazing/mowing	46.9559	16.6520	Pannonian
63	HU-Mat	Matra	GRA	10. natural grass	8. extensive mowing	47.8469	19.7260	Pannonian
64	IE-Ca1	Carlow1	CRO	2. cereals	14. annual crops	52.8588	-6.9181	Atlantic
65	IE-Ca2	Carlow2	GRA	9. sown grass	17. intensive grazing/mowing	52.8676	-6.9112	Atlantic
66	IE-Cla	Co.Laois	ENF	19. exotic needle-leaf forest	12. logging forestry	52.9500	-7.2500	Atlantic
67	IE-Dri	Dripsey	GRA	9. sown grass	17. intensive grazing/mowing	51.9867	-8.7518	Atlantic
68	IE-Kil	Killorglin-Glencar	WET	21. moorland/heath veg.	2. unused (incl. abandoned)	51.9684	-9.9003	Atlantic
69	IE-Wex	Wexford grassland	GRA	9. sown grass	17. intensive grazing/mowing	52.2982	-6.4998	Atlantic
70	IT-Amp	Amplero	GRA	9. sown grass	8. extensive mowing	41.9041	13.6052	Mediterranean
71	IT-Be1	Beano 1	CRO	1. C4 crops	15. annual fodder crops	46.0036	13.0256	Continental
72	IT-Be2	Beano 2	CRO	8. leguminous fodder	11. peren. fodder crops	46.0043	13.0278	Continental
73	IT-BCi	Borgo Cioffi	CRO	8. leguminous fodder	11. peren. fodder crops	40.5238	14.9574	Mediterranean
74	IT-BCi	Borgo Cioffi	CRO	1. C4 crops	15. annual fodder crops	40.5238	14.9574	Mediterranean
75	IT-BCi	Borgo Cioffi	GRA	9. sown grass	17. intensive grazing/mowing	40.5238	14.9574	Mediterranean
76	IT-Cas	Castellaro	CRO	3. rice	14. annual crops	45.0700	8.7175	Continental

77	IT-Col	Collelongo- Selva Piana	DBF	15. dec. broadleaf trees	6. managed forest	41.8494	13.5881	Alpine
78	IT-Cp2	Castelporziano 2	EBF	18. evergreen broadleaf trees	1. protected	41.7043	12.3573	Mediterranean
79	IT-Cpz	Castelporziano	EBF	18. evergreen broadleaf trees	1. protected	41.7052	12.3761	Mediterranean
80	IT-Ctv	Castelvetrano	CRO	14. olives	9. permanent crops	37.6442	12.8464	Mediterranean
81	IT-La2	Lavarone2	ENF	17. needle-leaf trees	6. managed forest	45.9542	11.2853	Alpine
82	IT-Lav	Lavarone (after 3/2002)	ENF	17. needle-leaf trees	6. managed forest	45.9562	11.2813	Alpine
83	IT-LMa	La Mandria	DBF	15. dec. broadleaf trees	6. managed forest	45.1526	7.5826	Continental
84	IT-Lec	Lecceto	EBF	18. evergreen broadleaf trees	6. managed forest	43.3036	11.2698	Mediterranean
85	IT-Mal	Malga Arpaco	GRA	10. natural grass	4. extensive grazing	46.1140	11.7033	Alpine
86	IT-MBo	Monte Bondone	GRA	10. natural grass	8. extensive mowing	46.0147	11.0458	Alpine
87	IT-Neg	Negrisia vineyard	CRO	12. fruit/nut perm. crops	9. permanent crops	45.7476	12.4467	Continental
88	IT-Noe	Sardinia/Arca di NoÞ	CSH	24. Med. shrubs / scrub	2. unused (incl. abandoned)	40.6061	8.1515	Mediterranean
89	IT-Non	Nonantola	MF	15. dec. broadleaf trees	7. selective logging	44.6902	11.0911	Continental
90	IT-Pia	Island of Pianosa	OSH	24. Med. shrubs / scrub	2. unused (incl. abandoned)	42.5839	10.0784	Mediterranean
91	IT-PT1	Zerbolo-Parco Ticino- Canarazzo	DBF	16. fast-growing (exotic) broadleaf trees	12. logging forestry	45.2009	9.0610	Continental
92	IT-Ren	Renon/Ritten (Bolzano)	ENF	17. needle-leaf trees	7. selective logging	46.5869	11.4337	Alpine
93	IT-Ro1	Roccarespampani 1	DBF	15. dec. broadleaf trees	12. logging forestry	42.4081	11.9300	Mediterranean
94	IT-Ro2	Roccarespampani 2	DBF	15. dec. broadleaf trees	12. logging forestry	42.3903	11.9209	Mediterranean
95	IT-SRo	San Rossore	ENF	17. needle-leaf trees	6. managed forest	43.7279	10.2844	Mediterranean
96	IT-Tor	Torgnon	GRA	10. natural grass	4. extensive grazing	45.8444	7.5781	Alpine
97	NL-Ca1	Cabauw	GRA	9. sown grass	17. intensive grazing/mowing	51.9710	4.9270	Atlantic
98	NL-Dij	Dijkgraaf	CRO	1. C4 crops	15. annual fodder crops	51.9921	5.6459	Atlantic
99	NL-Haarweg	Haarweg, NL	GRA	9. sown grass	17. intensive grazing/mowing	51.9707	5.6427	Atlantic
100	NL-Hor	Horstermeer	GRA	10. natural grass	2. unused (incl. abandoned)	52.2404	5.0713	Atlantic
101	NL-Lan	Langerak	CRO	34. other annual crops	14. annual crops	51.9536	4.9029	Atlantic
102	NL-Lel	Lelystad, NL	GRA	9. sown grass	17. intensive grazing/mowing	52.5242	5.5516	Atlantic

103	NL-Loo	Loobos	ENF	17. needle-leaf trees	6. managed forest	52.1666	5.7436	Atlantic
104	NL-Lut	Lutjewad	CRO	2. cereals	14. annual crops	53.3989	6.3560	Atlantic
105	NL-Vre	Vredepeel	CRO	4. tubers	14. annual crops	51.5317	5.8441	Atlantic
106	PL-Tcz	Tuczno	ENF	17. needle-leaf trees	6. managed forest	53.1930	16.0975	Continental
107	PL-wet	Polwet	WET	27. reed/rush veg.	2. unused (incl. abandoned)	52.7622	16.3094	Continental
108	PT-Esp	Espirra	EBF	16. fast-growing (exotic) broadleaf trees	12. logging forestry	38.6394	-8.6018	Mediterranean
109	PT-Mi1	Mitra (Evora)	EBF	18. evergreen broadleaf trees	5. mixed (agroforestry)	38.5406	-8.0001	Mediterranean
110	PT-Mi2	Mitra IV Tojal	GRA	9. sown C4 grass	17. intensive grazing/mowing	38.4765	-8.0246	Mediterranean
111	SE-Asa	Asa	ENF	17. needle-leaf trees	12. logging forestry	57.1723	14.8001	Boreal
112	SE-Deg	Degero	GRA	32. tundra/Alp. Grass	1. protected	64.1820	19.5567	Boreal
113	SE-Faj	Fajemyr	WET	21. moorland/heath veg.	2. unused (incl. abandoned)	56.2655	13.5535	Boreal
114	SE-Fla	Flakaliden	ENF	17. needle-leaf trees	12. logging forestry	64.1128	19.4569	Boreal
115	SE-Nor	Norunda	ENF	17. needle-leaf trees	7. selective logging	60.0865	17.4795	Boreal
116	SE-Kno	Knottasen	ENF	17. needle-leaf trees	12. logging forestry	60.9983	16.2173	Boreal
117	SE-Sk1	Skyttorp1 young	ENF	17. needle-leaf trees	12. logging forestry	60.1250	17.9181	Boreal
118	SE-Sk2	Skyttorp	ENF	17. needle-leaf trees	12. logging forestry	60.1297	17.8401	Boreal
119	SE-Sto	Stordalen Palsa Bog	WET	32. tundra/Alp. Grass	1. protected	68.3560028	19.0452	Boreal
120	SE-St1	Stordalen grassland	WET	32. tundra/Alp. Grass	1. protected	68.3541	19.0503	Alpine
121	UK-AMo	Auchencorth Moss- Scotland	WET	28. sedge/juncus veg.	4. extensive grazing	55.7925	-3.2436	Atlantic
122	UK-EBu	Easter Bush- Scotland	GRA	9. sown grass	17. intensive grazing/mowing	55.8660	-3.2058	Atlantic
123	UK-ESa	East Saltoun	CRO	34. other annual crops	14. annual crops	55.9069	-2.8586	Atlantic
124	UK-Gri	Griffin- Aberfeldy-Scotland	ENF	19. exotic needle-leaf forest	12. logging forestry	56.6072	-3.7981	Atlantic
125	UK-Ham	Hampshire	DBF	15. dec. broadleaf trees	7. selective logging	51.1535	-0.8583	Atlantic
126	UK-PL3	Pang/ Lambourne (forest)	DBF			51.4500	-1.2667	Atlantic
127	UK-Tad	Tadham Moor	GRA	10. natural grass	17. intensive grazing/mowing	51.2071	-2.8286	Atlantic
128	SL_Podgorski_grass	Podgorski Kras plateau	GRA	10. natural grass	4. extensive grazing	45.5502	13.9193	Continental

129	SL_Podgorski_shrub	Podgorski Kras plateau	OSH	22. Temp. shrubs	2. unused (incl. abandoned)	45.5427	13.9172	Continental
130	IT_Bolzano	Bolzano	CRO	12. fruit/nut perm. crops	9. permanent crops	46.3500	11.2667	Alpine
131	IT-peach	Bernalda - peach	CRO	12. fruit/nut perm. crops	9. permanent crops	40.3914	16.7011	Mediterranean
132	ES-Balsablanca	Balsablanca	GRA	31. arid sparce veg.	1. protected	36.9395	-2.0339	Mediterranean
133	IE_A	Glenvar	GRA	10. natural grass	17. intensive grazing/mowing	55.1592	-7.5823	Atlantic
134	IE_B	Lanesborough	GRA	10. natural grass	17. intensive grazing/mowing	53.6569	-7.9470	Atlantic
135	Lei-30M	Leinefelde, Dün, 30yr	DBF	15. dec. broadleaf trees	7. selective logging	51.3369	10.3686	Continental
136	Lei-62M	Leinefelde, Dün, 62 yr	DBF	15. dec. broadleaf trees	7. selective logging	51.3300	10.3553	Continental
137	Lei-141M	Leinefelde, Dün, 141yr	DBF	15. dec. broadleaf trees	7. selective logging	51.3281	10.3678	Continental
138	Mühl-38	Mühlhausen, 38yr	DBF	15. dec. broadleaf trees	7. selective logging	51.1947	10.3056	Continental
139	Mühl-55	Mühlhausen, 55yr	DBF	15. dec. broadleaf trees	7. selective logging	51.1936	10.3100	Continental
140	Mühl-85	Mühlhausen, 85yr	DBF	15. dec. broadleaf trees	7. selective logging	51.1981	10.3197	Continental
141	Mühl-102	Mühlhausen, 102yr	DBF	15. dec. broadleaf trees	7. selective logging	51.1919	10.3203	Continental
142	Mühl-171+10	Mühlhausen, 171yr	DBF	15. dec. broadleaf trees	7. selective logging	51.1900	10.3069	Continental
143	Lang-I	Langula, 190/122/45	DBF	15. dec. broadleaf trees	7. selective logging	51.1289	10.3706	Continental
144	Lang-II	Langula, 180/123/39	DBF	15. dec. broadleaf trees	7. selective logging	51.1425	10.3711	Continental
145	Lang-III	Langula, 178/168/87	DBF	15. dec. broadleaf trees	7. selective logging	51.1758	10.3378	Continental
146	Hai-I	Hainich NP, 230/147/51	DBF	15. dec. broadleaf trees	1. protected	51.0800	10.4625	Continental
147	Hai-II	Hainich NP, 178/131/48	DBF	15. dec. broadleaf trees	1. protected	51.0783	10.4539	Continental
148	Hai-III	Hainich NP, 202/153/74	DBF	15. dec. broadleaf trees	1. protected	51.0792	10.4519	Continental
149	NL-Stein	Stein	GRA	9. sown grass	17. intensive grazing/mowing	52.0187	4.7788	Atlantic
150	NL-Oukup	Oukup	GRA	9. sown grass	17. intensive grazing/mowing	52.0337	4.7804	Atlantic
151	grazing FR-Lusi	Lusignan	GRA	9. sown grass	17. intensive grazing/mowing	46.4170	0.1209	Atlantic
152	mowing FR-Lusi	Lusignan	GRA	9. sown grass	17. intensive grazing/mowing	46.4142	0.1206	Atlantic
153	UK-Cross-grazed	Crossens Marsh grazed	WET	29. salt marsh veg.	4. extensive grazing			Atlantic
154	UK-Cross-ungrazed	Crossens Marsh ungrazed	WET	29. salt marsh veg.	2. unused (incl. abandoned)			Atlantic

155	ES-Ras	Rascafría	DBF	15. dec. broadleaf trees	7. selective logging	40.9369	-3.8638	Mediterranean
156	IT-Peg	Mt Peglia	ENF	17. needle-leaf trees	7. selective logging	42.7810	12.2125	Mediterranean
157	IT-Casal	Casalotti	ENF	17. needle-leaf trees	7. selective logging	41.9019	12.3564	Mediterranean
158	ES-Pob	Natural Park of Poblet (Tarragona	ENF	17. needle-leaf trees	7. selective logging	41.3518	1.0405	Mediterranean
159	ES-Cov	Covaleda (soria)	ENF	17. needle-leaf trees	7. selective logging	41.9334	-2.8169	Mediterranean
160	IT-Cansiglio	Cansiglio	DBF	15. dec. broadleaf trees	6. managed forest	46.0417	12.4125	Alpine
161	IT-Forni	Forni	ENF	17. needle-leaf trees	6. managed forest	46.5869	12.8097	Alpine
162	FI-lim-grass	Linnansuo-grass	CRO	27. reed/rush veg.	10. peren. energy crops	62.5547	30.4951	Boreal
163	FI-lim-peat	Linnansuo-peat	WET		16. peat extraction	62.5488	30.4917	Boreal
164	HU-Kis	Kiskun-Sag	OSH	22. Temp. shrubs		46.8644	19.4150	Pannonian
165	ES-Garraf	Garraf	OSH	24. Med. shrubs / scrub		41.3022	1.8181	Mediterranean
166	IT-Capo	Capo Caccia	CSH	24. Med. shrubs / scrub		40.6091	8.1515	Mediterranean
167	NL-Old	Oldebroek	CSH	21. moorland/heath veg.		52.4050	5.9289	Atlantic
168	DK-Mols	Mols	CSH	21. moorland/heath veg.		56.2301	10.5718	Continental
169	UK-Clocaenog	Clocaenog	CSH	21. moorland/heath veg.		53.0553	-3.4653	Atlantic
170	DE-meh-grazed	Mehrstedt - grazed	GRA	10. natural grass	4. extensive grazing	51.2833	10.6479	Continental
171	IT-Nuria	Mount Nuria	DBF	15. dec. broadleaf trees	7. selective logging	42.3698	13.0770	Mediterranean
172	IT_Catania_orange	Catania - orange	CRO	13. subtrop./citrus perm crops	9. permanent crops	37.4759	14.9760	Mediterranean
173	IT-Orange2	Scordia-orange	CRO	13. subtrop./citrus perm crops	9. permanent crops	37.2787	14.8839	Mediterranean
174	IT-Ferrandina	Ferrandina-olive	CRO	14. olives	9. permanent crops	40.4847	16.4681	Mediterranean
175	IT-Bologna_apple	Cadriano-Bologna-apple	CRO	12. fruit/nut perm. crops	9. permanent crops	44.5381	11.3820	Continental
176	SL-Gornji Grad	Gornji Grad forest	ENF	17. needle-leaf trees	7. selective logging	46.2978	14.8636	Continental
177	DE-Kan	Kannenbruch	DBF	15. dec. broadleaf trees	6. managed forest	53.7843	10.6049	Continental
178	IT-POPFACE	POPFACE	DBF	16. fast-growing (exotic) broadleaf trees	13. short-rotation copice	42.3721	11.8068	Mediterranean
179	UK-Har-clear		ENF	19. exotic needle-leaf forest	12. logging forestry			Atlantic
180	UK-Har-7		ENF	19. exotic needle-leaf forest	12. logging forestry			Atlantic

181	UK-Har-21		ENF	19. exotic needle-leaf forest	12. logging forestry			Atlantic
182	UK-Har	Harwood	ENF	19. exotic needle-leaf forest	12. logging forestry	55.21272222	-2.0375	Atlantic
183	CZ-Zab	Zabcice	CRO	1. C4 crops	15. annual fodder crops	49.0219	16.6156	Continental
184	UK-Wyw	Wytham Woods	DBF	15. dec. broadleaf trees	1. protected	51.7743	-1.3379	Atlantic
185	UK-Moor	Moor House	WET	21. moorland/heath veg.	1. protected	54.6908	-2.3639	Atlantic
186	NL-Haa	Haastrecht	GRA	9. sown grass	17. intensive grazing/mowing	52.0036	4.8056	Atlantic
187	DE-Hart	Hartheim	ENF	17. needle-leaf trees	7. selective logging	47.9344	7.6006	Continental
188	FR-LCS	Le Cape Sud	CRO	1. C4 crops	15. annual fodder crops	44.4106	-0.6373	Atlantic
189	FI-Huh	Huhus	ENF	17. needle-leaf trees	6. managed forest	62.8681	30.8181	Boreal
190	DK-MkA	Morke E-AR	CRO	9. sown grass	17. intensive grazing/mowing	56.3813	10.3946	Continental
191	DK-MkG	Morke E-PG	GRA	9. sown grass	17. intensive grazing/mowing	56.3818	10.4031	Continental
192	DK-MkR	Morke E-RG	CRO	2. cereals	14. annual crops	56.3818	10.4006	Continental
193	DK-SkA	Skjern W-AR	CRO	2. cereals	14. annual crops	55.9378	8.4466	Atlantic
194	DK-SkG	Skjern W-PG	GRA	9. sown grass	17. intensive grazing/mowing	55.9412	8.4474	Atlantic
195	DK-SVA	Store Vildmose N-AR	CRO	4. tubers	14. annual crops	57.2331	9.8444	Continental
196	DK-SVG	Store Vildmose N-PG	GRA	9. sown grass	17. intensive grazing/mowing	57.2331	9.8444	Continental
197	DK-SVR	Store Vildmose N-RG	CRO	9. sown grass	17. intensive grazing/mowing	57.2331	9.8444	Continental
198	IT-Olive2	Follonica	CRO	14. olives	9. permanent crops	42.9440	10.7724	Mediterranean
199	FI-Alkkia	Alkkia	ENF	17. needle-leaf trees	12. logging forestry	62.1834	22.7842	Boreal
200	CZ-ST	Štítná	DBF	15. dec. broadleaf trees	6. managed forest	49.0360	17.9699	Continental
201	ES-Ln1	Lanjaron-Non intervention	OSH	24. Med. shrubs / scrub	2. unused (incl. abandoned)	36.9678	-3.4768	Mediterranean
202	DE-Leegmoor	Leegmoor	WET	28. sedge/juncus veg.	3. restored (actively)	53.0008	7.5564	Atlantic
203	CH-Agro	Agroscope research farm	GRA	9. sown grass	17. intensive grazing/mowing	46.7678	7.1078	Continental
204	PL-Minikowo	Minikowo	GRA	10. natural grass	8. extensive mowing	53.1497	17.7192	Continental
205	PL-Frydrychowo	Frydrychowo	GRA	10. natural grass	17. intensive grazing/mowing	53.0003	17.9569	Continental
206	EE-RCG-F	Lavassaare - grass fertilized	CRO	27. reed/rush veg.	10. peren. energy crops			Boreal

207	EE-RCG-C	Lavassaare - grass control	CRO	27. reed/rush veg.	10. peren. energy crops			Boreal
208	EE-BP	Lavassaare - peat	WET	30. peat moss	2. unused (incl. abandoned)			Boreal
209	BE-POPFULL	POPFULL	DBF	16. fast-growing (exotic) broadleaf trees	13. short-rotation copice	51.1122	3.8506	Atlantic
210	DE-RuR	Rollesbroich	GRA	9. sown grass	17. intensive grazing/mowing	50.6219	6.3041	Continental
211	DE-Mooseurach	Mooseurach	ENF	17. needle-leaf trees	12. logging forestry	47.8094	11.4578	Continental
212	DE-RuS	Selhausen Juelich	CRO	34. other annual crops	14. annual crops	50.8659	6.4472	Atlantic
213	DE-Breitfilz-heath	Breitfilz bog heath	WET	26. riverine/wetland needleleaf trees	3. restored (actively)	47.7939	11.4434	Continental
214	DE-Breitfilz-meadow	Breitfilz bog meadow	GRA	10. natural grass	8. extensive mowing	47.7940	11.4434	Continental
215	DE-Zrk	Zarnekow	WET	27. reed/rush veg.	3. restored (actively)	53.8759	12.8890	Continental
216	IT-SR2	San Rossore 2	ENF	17. needle-leaf trees	6. managed forest	43.7320	10.2910	Mediterranean
217	IT-CA1	Castel d'Asso 1	DBF	16. fast-growing (exotic) broadleaf trees	13. short-rotation copice	42.3804	12.0266	Mediterranean
218	IT-CA2	Castel d'Asso 2	CRO	1. C4 crops	15. annual fodder crops			Mediterranean
219	IT-CA2	Castel d'Asso 2	CRO	2. cereals	14. annual crops			Mediterranean
221	IT-CA3	Castel d'Asso 3	DBF	16. fast-growing (exotic) broadleaf trees	13. short-rotation copice	42.3800	12.0222	Mediterranean
222	IT-Vinyard	Sardinia	CRO	12. fruit/nut perm. crops	9. permanent crops	39.3619	9.1239	Mediterranean
223	IT-Cardoon	CREA-SCA Research Unit experimental farm	CRO	11. perenneal energy crops	10. peren. energy crops	41.0181	17.0181	Mediterranean
224	UK-Forsinard	Forsinard	WET	30. peat moss	2. unused (incl. abandoned)	58.3703	-3.9644	Atlantic
225	IE-Bellacorick-wet	Bellacorick rewetted	WET	28. sedge/juncus veg.	3. restored (actively)	54.1250	-9.5562	Atlantic
226	IE-Bellacorick-dry	Bellacorick drained	WET	28. sedge/juncus veg.	18. drained	54.1280	-9.5560	Atlantic
227	FI-Maaninka	Maaninka	CRO	11. perenneal energy crops	10. peren. energy crops	63.1636	27.2342	Boreal
228	DK-Norrea - barley	Nørrea - barley	CRO	2. cereals	14. annual crops			Continental
229	DK-Norrea - reed canary	Nørrea - reed canary	CRO	27. reed/rush veg.	10. peren. energy crops			Continental
230	UK-Penglais	Penglais	CRO	11. perenneal energy crops	10. peren. energy crops	52.4214	-4.0706	Atlantic
231	IE-Misk	TERC-Miskantus	CRO	11. perenneal energy crops	10. peren. energy crops	52.2898	-6.5240	Atlantic
232	IE-ReedCanary	TERC-Reed canary grass	CRO	11. perenneal energy crops	10. peren. energy crops	52.2928	-6.5271	Atlantic

233	FI-Hyy-clear		ENF	17. needle-leaf trees	12. logging forestry			Boreal
234	FI-Hyy-12		ENF	17. needle-leaf trees	12. logging forestry			Boreal
235	FI-Hyy-75		ENF	17. needle-leaf trees	12. logging forestry			Boreal
236	FI-Var-fjell	Varrio	GRA	32. tundra sparce vegetation	1. protected	67.7260	29.6020	Boreal
237	FI-Var	Varrio	ENF	17. needle-leaf trees	1. protected	67.7569	29.6160	Boreal
238	FI-Lom	Lompolojänkkä	WET	28. sedge/juncus veg.	2. unused (incl. abandoned)	67.9972	24.2092	Boreal
240	FI-Ken	Kenttärova	ENF	17. needle-leaf trees	6. managed forest	67.9872	24.2431	Boreal
241	FI-Sam	Sammaltunturi	GRA	33. tundra sparce vegetation	2. unused (incl. abandoned)	67.9739	24.1158	Boreal
242	FI-Kns	Kalevansuo	ENF	17. needle-leaf trees	6. managed forest	60.6468	24.3562	Boreal
243	IT-Kiwi	Ravenna Kiwi	CRO	12. fruit/nut perm. crops	9. permanent crops	44.3064	12.1567	Continental
244	UK-London	Urb-London	URB	19_urban	19. urban	51.5120	-0.1162	Atlantic
245	UK-Swindon	Urb-Swindon	URB	19_urban	19. urban	51.5847	-1.8005	Atlantic
246	IT-Florence	Urb-Florence	URB	19_urban	19. urban	43.7744	11.2551	Continental
247	FI-Helsinki	Urb-Helsinki	URB	19_urban	19. urban	60.2047	24.9639	Boreal

Annex 2. Database of carbon budget with site-average values

Site_code	Ecosystem	SOC (at 30cm)	AGB	SRE	GPP	RE	NEP	Wood_ growth	NPP	Hay	Grazed biom.	Anim. prod.	Food Crop	Straw	En. crop	Timber	CH_4	feed_ seed	manure	DOC	NECB
AT-Neu	40.grass	5890	449	-1792	1568	-1586	-36			317									284		
BE-Bra	36.NF	8990	8550	-411	1285	-1186	99	130	590							1850				10	240
BE-Dor	40.grass				2226	-2085	141		710	8	312	3					12	26	22	7	161
BE-Lon	21.crop	4670			1391	-1034	357						405	156				5	17		-26
BE-Vie	39.DBF_EBF	16000	11592		1755	-1271	470														
CH-Cha	40.grass	5550 – 6940			2651	-2630	91			349		20							332		47
CH-Dav	36.NF	10100	10905		1212	-988	190	107	513												
CH-Fru	40.grass	5800			2121	-1758	319			311		65							138	5	146
CH-Oe1-int	40.grass		490	-1988	1884	-1550	334			368									68		134
CH-Oe2	21.crop				1343	-1346	-3						261						54		-18
CH-Lae	39.DBF_EBF	9000	18927		1900	-1177	600	369	763												
Cr-Ja	39.DBF_EBF	7700	6900	-879	1531	-1047	484	484	812							474					449
CZ-BK1	36.NF				1554	-746	807														
CZ-BK2	43.exten_grass				1134	-1179	-36														
CZ-wet	51.wetland_reed				1172	-1038	137														
DE-Akm	51.wetland_reed				1139	-1024	108														
DE-Geb	21.crop	7200			1064	-859	200		669				252	126					122		-56
DE-Gri	40.grass				1529	-1379	185			147									0		-34
DE-Hai	39.DBF_EBF	9200	20476	-877	1633	-1053	588	194	662											5	286
DE-Kli	21.crop	9700 (60cm)			1327	-1149	151		645				223	213					113	13	-251
DE-Lnf	39.DBF_EBF	4400	19500				501	630	996							540					-46

DE-Lkb	35.dist_forest				425	-699	-274														
DE-Meh	34.BF_NF_young	7550 (60cm)	155		989	-950	25													3	25
DE-Obe	36.NF				1706	-1411	278														
DE-Seh	21.crop				1284	-976	305						313	189				8	0		-224
DE-SfN	37.org_NF				890	-837	53										5				
DE-Spw	39.DBF_EBF				1689	-1189	492														
DE-Tha	36.NF		15041		1962	-1374	594	150	567							1808					452
DE-Wet	36.NF	8700	9797		1530	-1442	88	369	791											26	171
DK-Eng	43.exten_grass				807	-705	105														
DK-Lva	21.crop						31												1450		1075
DK-Lva	40.grass				1593	-1342	282			296									1383		1479
DK-Ris	21.crop				1262	-989	273		610				256	206				5	0		-159
DK-Sor	39.DBF_EBF	9800 (60cm)	9885	-752	1957	-1780	187	300	708							533				25	150
ES-Amo	48.sparce				147	-363	-155														
ES-ES1	36.NF				1415	-1156	258														
ES-ES2	23.crop_rice				1268	-616	652		928				402					5	0		300
ES-LgS	47.MED_shrub				425	-313	104														
ES-LJu	48.sparce				161	-145	12														
ES-LMa	43.exten_grass				1074	-946	129														
ES-Ln2	35.dist_forest		0				-105									1652					
ES-VDA	43.exten_grass		515	-494	606	-559	47												0		
FI-Hyy	38.BOR_NF	6560 (50cm)	4770	-634	1104	-895	209	110	428							504				1	
FI-Jok	22.org_crop	56000 (peat)			603	-790	-187		419				126								-336
FI-Jok	41.org_grass	56000 (peat)			782	-855	-73		581	373									0		-452
FI-Kaa	37.org_NF	1 m peat			263	-241	22										4			8	11

FI-Sii	52.wetland_sedge.peat	2 - 4 m peat			376	-339	37										9				36
FI-Sod	38.BOR_NF	3100	3000		513	-562	-49														
FR_fon	39.DBF_EBF	4796	8854		1881	-1188	685														
FR-Aur	21.crop				1057	-907	194		653				206					2	0		-27
FR-Avi	21.crop				1176	-1019	157		823				197	149				5	0		-110
FR-Bil	35.dist_forest		2760		727	-996	-290														
FR-Bil	34.BF_NF_young				1950	-1615	335														
FR-Gri	21.crop	10500 (60cm)			1230	-822	408		682				338						60	13	-117
FR-Hes	39.DBF_EBF	10070 (160cm)	6248	-619	1454	-964	490	418	758							1632					
FR-Lam	21.crop				1298	-1041	297		917				311	256				4	132		-113
FR-LBr	36.NF		7008		1702	-1424	284														
FR-Lq1	40.grass	23100			1594	-1495	99				227	2					10		0	3	87
FR-Lq2	40.grass	23100			1514	-1440	74				115	1					5			3	69
FR-Pue	39.DBF_EBF		5424		1285	-1063	231	80													
HU-Bug	43.exten_grass				848	-794	123				30						1		0		68
HU-He1	40.grass				1012	-1022	-10												0		
HU-Mat	40.grass				892	-798	94														
IE-Ca1	21.crop			-1245	907	-715	189		657				270					6		3	-78
IE-Ca2	40.grass		680	-1166	1653	-1444	212			374	135						5		0	20	-79
IE-Cla	34.BF_NF_young	2200 (50 cm)	6162	-989	2235	-1379	856	896	1569							2041				3	866
IE-Dri	40.grass				1738	-1442	277		540	153		39					13	54		7	184
IE-Kil	46.moors				288	-232	56										5				
IE-Wex	40.grass				1486	-1343	144			250											
IT-Amp	40.grass	5420	125	-1305	1303	-1089	214			78									0		
IT-Be1	21.crop	4840			1310	-902	408		1015												-48

IT-Be2	21.crop	4840			1568	-1020	549		1088												-177
IT-BCi	21.crop				1845	-1525	320														
IT-BCi	21.crop				1762	-1441	347		1225										86		-385
IT-BCi	40.grass				1662	-1413	270														
IT-Cas	23.crop_rice				1344	-977	367						256	99			22		22		34
IT-Col	39.DBF_EBF	14700	12768		1258	-722	535	363	642												
IT-Cp2	39.DBF_EBF				2006	-1405	604														
IT-Cpz	39.DBF_EBF				1878	-1481	395														
IT-Ctv	24.crop_perm				2625	-1373	1253						294								958
IT-La2	36.NF	11800			2103	-1070	1028														
IT-Lav	36.NF	11800		-773	1970	-775	1048														
IT-LMa	39.DBF_EBF	7400	7800		1337	-463	832	360													
IT-Lec	34.BF_NF_young		5000		1300	-1060	240	334													
IT-Mal	43.exten_grass				1083	-640	360				53						2		0		358
IT-MBo	40.grass	8120	286	-1743	1419	-1355	64			62									0		
IT-Neg	24.crop_perm						814	98	814				153								
IT-Noe	47.MED_shrub				1077	-926	162														
IT-Non	34.BF_NF_young	5370			1494	-943	551														
IT-Pia	47.MED_shrub				1050	-820	230														
IT-PT1	34.BF_NF_young	5230 (down to 1m)		-439	1523	-829	694									4090					
IT-Ren	36.NF		6843	-1015	1472	-713	709														
IT-Ro1	34.BF_NF_young	8600	691		1560	-1310	242	161													
IT-Ro2	34.BF_NF_young	7400	2408		1516	-777	739	315													
IT-SRo	36.NF		9700		1919	-1477	437	370													
IT-Tor	43.exten_grass	2800			861	-780	83														
NL-Ca1	40.grass				1466	-1458	8														

NL-Dij	21.crop			-715	1982	-1652	332		1015				450	310				0	51		-102
NL-Haarweg	40.grass				1722	-1470	251												0		
NL-Hor	51.wetland_reed		434		1331	-1036	316										32				262
NL-Lan	21.crop				1847	-1576	271											0	27		
NL-Lel	40.grass				1084	-940	143			229	90						7		92		33
NL-Loo	36.NF	7700	4260		839	-1215	434	124	687											24	399
NL-Lut	21.crop				1335	-904	451		1008									6	0		-356
NL-Vre	21.crop						486		1110				850						433		69
PL-Tcz	36.NF				2182	-1457	737														
PL-wet	51.wetland_reed				856	-600	256														
PT-Esp	34.BF_NF_young		5164	-778	1576	-1146	430									4850					
PT-Mi1	43.exten_grass				792	-767	26														
PT-Mi2	40.grass				941	-875	66			93									0		
SE-Asa	38.BOR_NF	11500	6763		1317	-1013	287	259	544												
SE-Deg	52.wetland_sedge.peat	3 - 4 m peat		-140	373	-291	82		154											18	24
SE-Faj	46.moors	5m peat			544	-495	49														
SE-Fla	38.BOR_NF	3610	3513		1006	-1000	6	154	379												
SE-Nor	38.BOR_NF	thin org layer	11410		1238	-1326	-65		779							1932					
SE-Kno	38.BOR_NF	2930	2550		1203	-1235	-32	120	381												
SE-Sk1	35.dist_forest		211		529	-706	-177														
SE-Sk2	38.BOR_NF		6063		1232	-953	279														
SE-Sto	52.wetland_sedge.peat	up to 3 m peat	68				50										13			3	44
SE-St1	52.wetland_sedge.peat																				
UK-AMo	52.wetland_sedge.peat	60 cm peat		-529	1075	-1028	48										0				
UK-EBu	40.grass	11925			1756	-1538	218		878	49		9					4		25	16	163

UK-ESa	21.crop				2018	-1779	238														
UK-Gri	34.BF_NF_young	49000	4349		1956	-1368	588	448													
UK-Ham	39.DBF_EBF	8700	5800	-723	2039	-1541	498		689							922					
UK-PL3																					
UK-Tad	41.org_grass	1.8 m peat			1564	-1395	169			203	25	1									-59
SL_P_grass		16700	313	-1248			-353														
SL_P_shrub	45.shrub	17200	3842	-1296	1642	-1387	255														
IT_Bolzano	24.crop_perm		880	-801	1346	-943	403	45	905				418						36		69
IT-peach	24.crop_perm		1721	-431	1074		398	113	721	74			114	69					197		412
ES-Balsablanca	48.sparce				356	-245	111														-119
IE_A	41.org_grass				1500	-1498	2			181							5			16	-148
IE_B	41.org_grass				2089	-2322	-233			351							10			46	-663
Lei-30M	39.DBF_EBF	7793	3433				653	448	920												
Lei-62M	39.DBF_EBF	8237	14652				340	332	643												
Lei-141M	39.DBF_EBF	6949	14483																		
Mühl-38	39.DBF_EBF	8881	4430																		
Mühl-55	39.DBF_EBF	10431	11593																		
Mühl-85	39.DBF_EBF	8817	13313																		
Mühl-102	39.DBF_EBF	10914	19809					340													
Mühl-171+10	39.DBF_EBF	9972	13171																		
Lang-I	39.DBF_EBF	7495																			
Lang-II	39.DBF_EBF	8164						310													
Lang-III	39.DBF_EBF	9700	18454																		
Hai-I	39.DBF_EBF	9015	19771																		
Hai-II	39.DBF_EBF	10245	18271																		
Hai-III	39.DBF_EBF	12220	23952																		

NL-Stein	41.org_grass				1600	-1750	8			470											-462
NL-Oukup	41.org_grass				1550	-1750	-122			325	125						35		142		-465
grazing FR-Lusi	40.grass				1741	-1511	231					74					15			1	141
mowing FR-Lusi	40.grass				1720	-1243	476			453										1	23
UK-Cross-grazed	52.wetland_sedge.peat	4740 (15 cm)	150				-420		244												
UK-Cross-ungrazed	52.wetland_sedge.peat	3690 (15 cm)	350				-333		503												
ES-Ras	39.DBF_EBF		6715					242													
IT-Peg	36.NF		10226													6905					
IT-Casal	34.BF_NF_young		9380													4623					
ES-Pob	36.NF											1				5095					
ES-Cov	36.NF		8249													4240					
IT-Cansiglio	39.DBF_EBF						220		390												
IT-Forni	36.NF						440		625												
FI-lim-grass	22.org_crop	85 cm peat			591	-483	100								133						-25
FI-lim-peat	70.peat					-381	-381														
HU-Kis	45.shrub		141	-151	210	5	4	55	105											5	-2
ES-Garraf	47.MED_shrub		278	-440	450	5	-70	61	225											3	-73
IT-Capo	47.MED_shrub		261	-1067					186												
NL-Old	46.moors		389	-320	392	5	-18	40	196											7	-26
DK-Mols	46.moors		221	-520	798	5	51	216	399											2	49
UK-Clocaenog	46.moors		1825	-580	1074	3	148	79	537											22	126
DE-meh-grazed	43.exten_grass	7850 (60cm)	169		1334	-1257	66				59	2								4	7
IT-Nuria	39.DBF_EBF		23391					498								2958					
IT_C_orange	24.crop_perm			-505			285		700				281								115
IT-Orange2	24.crop_perm				1640	-990	650														

IT-Ferrandina	24.crop_perm			577			156		732				139								
IT-Bologna_apple	24.crop_perm			-228			637	128	786				227								410
SL-Gornji Grad	36.NF		13417					363								1595					
DE-Kan	39.DBF_EBF				1619	-1270	349	398	775												
IT-POPFACE	34.BF_NF_young				2207	-955	1252	1073	1452												
UK-Har-clear	35.dist_forest				765	-1208	-443														
UK-Har-7	34.BF_NF_young				1261	-1253	8														
UK-Har-21	34.BF_NF_young				1970	-1350	620														
UK-Har	34.BF_NF_young		6243		1712	-1090	622														
CZ-Zab	21.crop				1670	-1247	423														
UK-Wyw	39.DBF_EBF				2030	-1890	265	140													
UK-Moor	46.moors	up to 8 m peat			891	-718	173														
NL-Haa	41.org_grass				1906	-2050	-144														
DE-Hart	36.NF				1011	-839	172														
FR-LCS	21.crop				1420	-1260	160														
FI-Huh	38.BOR_NF			497	916	-785	181		551												
DK-MkA	41.org_grass				1856	-2320	-464			240							0				-720
DK-MkG	41.org_grass				2102	-2538	-437			340							4				-790
DK-MkR	22.org_crop				1747	-3111	-1365						330								-1670
DK-SkA	22.org_crop				2074	-3330	-1255						260								-1530
DK-SkG	41.org_grass				2511	-2893	-382			300											-690
DK-SVA	22.org_crop				846	-1201	-355						350				0				-700
DK-SVG	41.org_grass				2156	-2838	-682			350							2				-1040
DK-SVR	41.org_grass				2238	-3057	-819			330											-1150
IT-Olive2	24.crop_perm				1027	-631	402						180								
FI-Alkkia	37.org_NF		3465		1156		-50		472												

CZ-ST	39.DBF_EBF				2197	-2038	159														
ES-Ln1	47.MED_shrub				290	-245	77														
DE-Leegmoor	52.wetland_sedge.peat				850	-778	71										14				58
CH-Agro	40.grass				2042	-1973	68					82									
PL-Minikowo	41.org_grass				1583	-2266	-681			140											-821
PL-Frydrychowo	41.org_grass				2042	-2327	-286			253											-540
EE-RCG-F	22.org_crop				433	-512	-79		170						170		0			4	-96
EE-RCG-C	22.org_crop				125	-326	-201		46						46		0			4	-215
EE-BP	70.peat						-170										0			4	-180
BE-POPFULL	34.BF_NF_young				1281	-1185	96	250	493						250		15			5	
DE-RuR	40.grass				1730	-1625	106			210											
DE-Mooseurach	37.org_NF				1717	-1932	-215														
DE-RuS	21.crop				1768	-1216	544														
DE-Breitfilz-heath	37.org_NF	between 2 and 5 m peat			775	-864	-89										4				-92
DE-Breitfilz-meadow	41.org_grass	between 2 and 5 m peat			1101	-1181	-80			46							4				-130
DE-Zrk	51.wetland_reed	up to 10m			700	-811	-109														
IT-SR2	36.NF				2071	-1985	363														
IT-CA1	34.BF_NF_young	1403			1231	-911	317														
IT-CA2	21.crop				884	-806	74				265						3				
IT-CA2	21.crop				1206	-850	344						164								
IT-CA2		1603			1045	-828	209				265		164				3				
IT-CA3	34.BF_NF_young	1169			1158	-748	392								102						
IT-Vinyard	24.crop_perm				1189	-993	195														
IT-Cardoon	21.crop				1504	-1064	440								449						-29
UK-Forsinard	52.wetland_sedge.peat				575	-461	114										4			10	99

IE-Bellacorick-wet	52.wetland_sedge.peat	50 cm peat			374	-284	90										8				
IE-Bellacorick-dry	52.wetland_sedge.peat	50 cm peat			189	-279	-90										0				
FI-Maaninka	21.crop				1265	-1006	259								323						
DK-Norrea - barley	22.org_crop				1509	-1392	117										0				
DK-Norrea - reed canary	22.org_crop				1619	-1864	-246								540		0				
UK-Penglais	21.crop	3250			1483		206								218						
IE-Misk	21.crop				1327	-1255	72														72
IE-ReedCanary	21.crop				1569	-1212	358								252						232
FI-Hyy-clear	35.dist_forest				323	-709	-386														
FI-Hyy-12	38.BOR_NF				928	-904	24														
FI-Hyy-75	38.BOR_NF				940	-617	323														
FI-Var-fjell	48.sparce	2500		-58	200		-1														
FI-Var	36.NF						130														
FI-Lom	52.wetland_sedge.peat	2.5 m peat					22										15				
FI-Ken	38.BOR_NF		1438				2														
FI-Sam	48.sparce						5														
FI-Kns	37.org_NF				986	-749	237	175													
IT-Kiwi	24.crop_perm		300		1158	-849	309						133								
UK-London	18_URB						-12720														
UK-Swindon	19_Sub.URB						-1745														
IT-Florence	18_URB						-8270														
FI-Helsinki	19_Sub.URB						-1760														

Annex 3: Classifications applied to define ecosystem units

plant functional traits	**Dominant species**	**IGBP class**
1. C4 crops	corn, sorghum	CRO
2. cereals	wheat, barley, oats, rye	CRO
3. rice	rice	CRO
4. tubers	sugar beet, potatoes	CRO
5. vegetables	tomato, cucumber, pepper, cabbage	CRO
6. oil crops (annual)	sunflower, rapeseed	CRO
7. leguminous crops	peas, beans, lentils	CRO
8. leguminous fodder	alfalfa, clover	CRO
9. sown grass	ryegrass, mixed grass-clover	GRA
10. natural grass	Festuca	GRA
11. perennial energy crops	miscantus, cardoon	CRO
12. fruit/nut perm. crops	apple, peach, cherry, almonds, vines, kiwi, raspberry etc	CRO
13. subtrop./citrus perm crops	orange, avocado	CRO
14. olives	olives	CRO
15. dec. broadleaf trees	oak, beech, ash, sycamore, birch	DBF
16. fast-growing (exotic) broadleaf trees	eucalypt, black locust, ex. poplar	DBF
17. needle-leaf trees	spruce, pine, fir, larch, yew	ENF
18. evergreen broadleaf trees	holm oak, cork oak	EBF
19. exotic needle-leaf forest	Sitka spruce, Douglas fir	ENF
20. ruderal vegetation	nettle, brambles	GRA
21. moorland/heath veg.	heather	CSH
22. Temp. shrubs	hawthorn, blackthorn, briars	CSH
23. Alp. Shrubs	junipers, vaccinium, mugo pine	CSH
24. Med. shrubs / scrub	wild olive, lentisc, brooms	CSH-OSH

25. riverine/wetland broadleaf trees	alder, willow, poplar	DBF
26. riverine/wetland needle-leaf trees	mugo pine	WET
27. reed/rush veg.	reed, rush, reed canary grass	WET
28. sedge/juncus veg.	heath, juncus, heather	WET
29. salt marsh veg.	salicornia	BSV
30. peat moss	peat moss	GRA
31. arid sparse veg.	dwarf palm, esparto grass, lentisc	GRA
32. tundra/Alp. grass	vaccinium, sedge, festuca	GRA
33. tundra sparse vegetation	crowberry, lichen	GRA

Annex 4: Ecosystem classifications for mapping fluxes and harvests

Ecosystem types for fluxes		**Ecosystem types for harvests**	
21.CRO	Annual and perennial crops	21.CRO	Non-Atlantic annual and perennial crops
22.CRO_org	Annual and perennial crops on organic soils	22.CRO_ATL	Atlantic annual and perennial crops
23.CRO_rice	Rice	23.CRO_rice	Rice
24.CRO_perm	Permanent crops	24.CRO_perm	Permanent crops
25.CRO_mix	Mixed annual perm. crops	25.CRO_mix	Mixed annual perm. crops
26.CRO_nat	Crops and natural veg.	26.CRO_nat	Crops and natural veg.
34.FOR_young	Young forest (2 - 24 years)	32.FOR_prot	Protected forests
35.FOR_dist	Disturbed forest (0 - 1 years)	34.FOR_young	Young forest (2 - 24 years)
36.ENF	Evergreen needle-leaf forest	35.FOR_dist	Disturbed forest (0 - 1 years)
37.ENF_org	Evergreen needle-leaf forest on org. soils	36.ENF	Evergreen needle-leaf forest
38.ENF_BOR	Boreal evergreen needle-leaf forest	38.ENF_BOR	Boreal evergreen needle-leaf forest
39.DBF_EBF	Deciduous and evergreen broadleaf forests	39.DBF_EBF	Deciduous and evergreen broadleaf forests
31.FOR_mix	Mixed forests	31.FOR_mix	Mixed forests
40.GRA	Grazed and mowed grasslands	40.GRA	Non-Atlantic grazed and mowed grasslands
41.GRA_org	Grazed and mowed grasslands on org. soils	41.GRA_ATL	Atlantic grazed and mowed grasslands
43.GRA_ext	Natural and extensively used grasslands	43.GRA_ext	Natural and extensively used grasslands
45.OSH	Open shrubland	45.OSH	Open shrubland
46.CSH_moor	Moors	46.CSH_moor	Moors
47.SH_MED	Mediterranean shrublands	47.SH_MED	Mediterranean shrublands
48.sparce	Sparse vegetation	48.sparce	Sparse vegetation
51.WET_reed	Wetlands with reed	51.WET_reed	Wetlands with reed
52.WET_sedge.peat	Wetlands with sage and peat moss	52.WET_sedge.peat	Wetlands with sage and peat moss