DEPARTMENT OF ECONOMIC AND SOCIAL AFFAIRS
STATISTICS DIVISION
UNITED NATIONS

System of Environmental Economic Accounting

SEEA EEA Revision

Working Group 4: Individual Ecosystem Services

Discussion paper 6:

Defining and valuing carbon related services in the SEEA EEA

Version: 15 March 2019

Recommended citation:
Edens B., Elsasser P., Ivanov E. (2019). Discussion paper 6: Defining and valuing carbon related services in the SEEA EEA. Paper submitted to the Expert Meeting on Advancing the Measurement of Ecosystem Services for Ecosystem Accounting, New York, 22-24 January 2019 and subsequently revised. Version of 15 March 2019. Available at: https://seea.un.org/events/expert-meeting-advancing-measurement-ecosystem-services-ecosystem-accounting

Defining and valuing carbon related services in the SEEA EEA

Authors: Bram Edens, UNSD; Peter Elsasser, Thuenen Institute, Germany; Emil Ivanov, University of Nottingham, UK

The first version of this paper was circulated to the participants of the Expert Meeting on Advancing the Measurement of Ecosystem Services for Ecosystem Accounting, New York, 22-24 January 2019. Comments received during and immediately after the Expert Meeting have been addressed by the authors in an annex at the end of the paper.

Abstract

This issues paper provides an overview based on the existing Ecosystems Services (ES) literature of current issues around introducing carbon related ecosystem services (sequestration and storage), within an accounting framework. These issues cover definition and concept, measurement boundaries, including the alignment with IPCC reporting, whether sequestration should be considered as final or an intermediate service. The paper also provides a summary of the 4 main existing valuation approaches and evaluates the extent to which they align with accounting conventions such as the use of exchange values and market design. Finally, the paper also discusses several issues around how carbon sequestration may be recorded within the accounting framework. The paper goes beyond a mere description of the key issues and provides the following list of tentative recommendations:

Definition and concept:

- Carbon storage should not be seen as a distinct ecosystem service - the main service being carbon sequestration. Total carbon stored is a stock variable, which may be used as a condition indicator.
- The transaction model of the SEEA allows to see carbon sequestration as a final service (which differs from FEGS and CICES where sequestration is considered as an intermediate service or process); in fact NPP can be seen as the process (or intermediate service), with sequestration being seen as the ecosystem service.
- The definition and measurement of carbon sequestration should be aligned with / be complementary to IPCC guidelines as much as possible.
- Within an accounting framework, sequestration can be defined as: the removal of carbon from the atmosphere by ecosystems, by storing it in carbon pools (other than the atmosphere) for more than a year [unit: tC/ha/yr]
- Accordingly, the benefit can be defined as: reduced concentrations of carbon in the atmosphere.

Measurement:

- NECB (net ecosystem carbon balance) seems the most suitable metric to assess carbon sequestration.
- Look-up tables are the preferred mapping method in data-poor situations; new data sources on carbon fluxes (from Fluxnet) can help to reduce concerns of oversimplification.

- Scope should address contemporary and future sequestration that is occurring through both biotic (NPP) and abiotic elements, in terrestrial and aquatic ecosystems, hence excluding geological forms like oil and gas.

Valuation:

- We propose using ETS prices where they are available, and in countries with an ETS we recommend using these ETS prices also as "best available estimates" for those sectors which are not covered by the respective ETS.
- In countries without an ETS, the certificate prices of Clean Development Mechanism and/or Joint Implementation projects appear as most compatible approximations.
- Less preferably, abatement cost estimates could be utilized as an alternative.
- Taxes, prices of Voluntary Emission Reduction certificates and consumer preference studies seem unsuited for the SEEA context.
- It seems sensible to complement ETS based carbon valuations by an additional valuation based at a (global) SCC estimate (as this can be done easily), as long as this estimate comes from models that exclude consumer surplus and the applied discount rate is consistent with discount rates used elsewhere in the accounting system.

Recording / accounting treatment

- In terms of recording, it seems useful to record the use of carbon sequestration as intermediate consumption by those sectors emitting carbon during the accounting period.
- Adjustments need to be made to the National accounts in case carbon taxes are being recorded.
- Degradation costs (as a result of air emissions) can be defined in respect to changes in the CO_2 concentration of the atmosphere. Such costs are only recorded when emissions are beyond the sequestration taking place in the accounting period (for the country in question).
- There are a couple of boundary issues that need to be further discussed – especially in the context of linkages to air emission accounts (HWP; soil respiration; energy crops).

1 Introduction

One of the issues for the revision of the SEEA EEA is around the valuation of carbon sequestration and /or storage. While the debate initially focused on the proper price to value carbon, issues that emerged during the drafting of the Technical Recommendations in support of SEEA EEA (UN et al. 2017 - (TR in short) are: 1) whether there would be double counting when valuing sequestration and storage as two distinct services; 2) how to align carbon storage/ sequestration with UNFCCC reporting boundaries for AFOLU/LULUCF sector (IPCC 2006), that distinguish amongst others between short-lived and long-lived biomass on managed and un-managed land; 3) whether accumulated carbon should be treated as an environmental debt (and carbon stored as a liability) 4) and more fundamentally, whether carbon sequestration should be considered an ecosystem service at all (as argued in CICES V5.1, EEA 2018).

Within the environmental economics community, there has likewise been a long standing debate around the treatment of carbon emission in the national accounts (Hamilton 1996), and more recently in a wealth accounting context (Arrow et al., 2012). The Inclusive wealth report (IWR 2018) makes adjustments for carbon damages (often using similar valuation practices used for valuing sequestration and storage).

The policy relevance for agreeing on better standards is evident, in the wake of the Paris Agreement. There are also increasing demands for valuation of carbon damages from Corporate Sustainability Reporting practices.

Often, the issues related to the valuation of carbon are only discussed piecemeal, discussing only one or two of the issues mentioned above. This note intends to bring all issues at once to the table to discuss them in a more integrated way. The objective of this issues paper is to summarize the key issues, and where possible, provide suggested solutions.

The outline is as follows: in section 2 we discuss the description and measurement boundaries of the service and address the issue whether it should be considered as a final or intermediate service, and if there is one single or two distinct services. In section 3, we discuss how carbon sequestration can be measured, and also how future flows can be modelled. In Section 4, we discuss various valuation options for carbon. Section 5 discusses accounting treatments and recording.

It is hoped that helping to solve issues related to the valuation of carbon may also help solving related Ecosystem valuation issues on the research agenda.

Moreover, the comments received during the Expert Meeting on Advancing the Measurement of Ecosystem Services for Ecosystem Accounting, New York, 22-24 January 2019 have been addressed by the authors in an annex to the paper.

2 Description of the ecosystem service

2.1 Issue 1: one or two services?

According to the SEEA EEA (UN et al., 2013) ecosystem services are defined as:

ES: Contributions of ecosystems to benefits used in economic and other human activity (para 2.23)

During the development of the TR one of the key issues that emerged was whether carbon storage should be considered as a distinct ecosystem service in addition to carbon sequestration, or whether that would lead to double counting. The issue is described in the TR as follows: "Ecosystems may emit carbon dioxide, as well as other gasses such as methane or nitrous oxide. For example, carbon is emitted when peatlands are drained and forests cleared. While the emissions themselves are not ecosystem service flows, the loss of carbon from storage may be considered a reduction in the services provided by the associated ecosystem assets."

Before we go in more detail, it is useful to assess some of the ways the service has been described in the ES literature:

- In the Millennium Ecosystem Assessment, the description Climate regulation is used, described as follows.
  "Ecosystems influence climate both locally and globally. For example, at a local scale, changes in land cover can affect both temperature and precipitation. At the global scale, ecosystems play an important role in climate by either sequestering or emitting greenhouse gases." (MEA 2005).
- TEEB uses as description of the service Carbon sequestration and storage, described as:
  "Ecosystems regulate the global climate by storing and sequestering greenhouse gases. As trees and plants grow, they remove carbon dioxide from the atmosphere and effectively lock it away in their tissues. In this way forest ecosystems are carbon stores. Biodiversity also plays an important role by improving the capacity of ecosystems to adapt to the effects of climate change."
- Costanza et al. 1997 use climate regulation. "Regulation of global temperature, precipitation and other biologically mediated climatic processes at global or local levels."
- IPBES/NCP: regulation of climate. Climate regulation by ecosystems (including regulation of global warming) through: Positive or negative effects on emissions of greenhouse gases (e.g. biological carbon storage and sequestration; methane emissions from wetlands)
- CICES (EEA 2017): regulation of chemical composition of atmosphere (2.1.1.2)
- The 2006 IPCC Guidelines (IPCC 2006) speak about carbon emissions and removals (by sinks), or CO_2 uptake. The guidelines do not seem to use sequestration a lot, although sequestration is defined in the Glossary as: the process of storing carbon in a carbon pool.

While this if of course a highly selective list, it serves to demonstrate various aspects:
-the reviewed definitions do not appear to consider storage and sequestration as two distinct services. Indeed carbon sequestration and storage are used interchangeably in the literature METZ 2007.[1] In most general terms sequestration is defined as 'the process of increasing the carbon content of a carbon pool other than the atmosphere' PENMAN *et al.* 2003.
-name/description; climate regulation is frequently used in the name and description of the service, although it sometimes has a broader scope including also local scale regulation of temperature, or other molecules
-scope; two definitions specifically mention both sequestration and emissions (which in SEEA EEA are usually considered out of scope).

[1] A Google search indicated that "carbon sequestration" has 2,3 million hits versus 1 million for "carbon storage" versus 238 thousand hits for "climate regulation" (AND "ecosystem service" 88 vs 57 vs 37), for what it is worth..

Table 1: Hypothetical example

	unit: ton C		USD
Opening stock	1000		1000
sequestered (short-lived)	5		5
sequestered (trees)	5		5
harvest (trees)	-40		-40
Closing stock	970		970

It is obvious that carbon storage and sequestration are different things. Storage is a stock variable that measures the amount of carbon stored at a particular point in time at a particular area. Sequestration is a flow measure that measures the amount of carbon being added to a certain area (or carbon pool) during the accounting period considered (by default one year).

Carbon storage and carbon sequestration are sometimes valued using the same price of carbon. Assume for the time being that we have solved and agreed to how to put a price on carbon, and the price is 1 USD per tC (not tCO_2). This would result in the valuation presented in the right column of Table 1, assuming both are valued as price times quantity (p*q) - with q the number of tC stored or sequestered.

From the example, we immediately see that we would be double counting when we add both carbon sequestration and storage as ecosystem services using the same valuation per tC. It seems we are left with a number of options:[2]

Option 1: There is only one service, carbon sequestration

Option 2: There are two distinct services, sequestration and storage

Option 3: There is only one service, carbon storage

These 3 different perspectives on what constitutes the service imply also different views on what is the benefit being provided. The TR are not very precise in this regard: they mention as benefit of carbon sequestration "reducing the impacts of climate change" (5.54) but elsewhere the benefit is described as "climate regulation services through reduced concentrations of carbon dioxide in the atmosphere." (Table 5.2). Let us therefore discuss these 3 options in greater detail.

Ad Option 1) Considering sequestration as an ecosystem service has a strong intuitive appeal, it is a natural process that provides humanity with a clear benefit (at least in the current situation of global warming) that may be defined as:

<u>Benefit Option 1: reduced concentration of carbon dioxide in the atmosphere.</u>

[2] This example has wider ramifications, as for instance also in case of water, both storage (sometimes called water retention) and water provisioning (abstraction) are sometimes treated as distinct ecosystem services, likewise for soil (retention).

Practically speaking, a major advantage of considering sequestration as the service is data availability. With regard to physical units, emission/sequestration is being recorded e.g. in the national emission inventories of the UNFCCC member states, at least in principle[3]. With regard to carbon values, empirical information on prices as well as different kinds of costs again usually pertains to stock changes (i.e. emission and sequestration) rather than the stock values per se.

Ad Option 2) One way of seeing carbon storage as a distinct service would be to perceive carbon storage in analogy with "warehousing" (as described by ISIC 51) in the national accounts. There would be then the service of entering into storage (sequestration) and an additional service for keeping it stored. The amount of carbon stored would be a good physical indicator of the volume of the service provided (similar to tons of goods stored in inventories), the benefit could be defined as:

<u>Benefit(s) Option 2: total volume of carbon stored (and reduced concentration of carbon dioxide in the atmosphere</u>

The "warehousing" approach would argue that we should not value the service based on tons stored times a relevant carbon price, as we should not confuse the value of what is being stored with the service value of storing, which is about providing a safe / secure place. There would therefore be no double counting issue as in the hypothetical example above.

The disadvantage of this approach is however that it lacks an argument why we are concerned in the first place with carbon storage. A proponent of seeing carbon warehousing as a service needs an argument why carbon is singled out. For instance, why do we not value nitrogen storage or heavy metal storage in subsoil deposits. Second, it seems difficult to come up with a credible approach of placing a value on the warehousing value provided by forests etc.[4] Finally, the literature (with some exceptions) has not conceived of carbon sequestration and storage as 2 distinct services. WE therefore conclude that Option 2 is not a viable approach.

Ad Option 3: A better analogy for carbon storage in the SNA would be the service provided when we store toxic waste somewhere remote as to avoid impacts on the population, e.g. "waste remediation" (i.e. ISIC 38). From this perspective, it makes more sense to define the benefit of carbon storage as:

<u>Benefit option 3: avoided release of carbon to the atmosphere.</u>

Seeing carbon storage as the main service appeals to a clear intuition. First of all, it is the storage of carbon that is important, the buffering it provides, less important is the actual amount sequestered (which fluctuates a lot anyway). For instance, when there would be 0 sequestration during a year, we would still like to see the say forest as providing us with a service. When valuing carbon storage, it would be logical to use an avoided damage coast approach (such as social cost of carbon). In case storage is seen as the main service, arguably it could be better described as climate regulation.

There are however also various drawbacks of seeing storage as a service:

[3] Problems might however be caused by different definitions and rules-of-thumb used in the emission inventories.
[4] Perhaps we would need to estimate the storage service in terms of replacement cost. This is easier said than done. Possibly, one could use the cheapest alternative of storing a likewise volume of bulk goods (e.g. water in reservoirs? but this will be contentious.

- A major practical disadvantage of this approach is that it would lead to additional quantification problems already concerning physical measurement, and even worse, to demarcation problems. Carbon is being stored in different repositories, e.g., in forests, in peatlands, in oceans, and in the earth crust (fossil fuels). A demarcation problem would be to define which of these repositories should be included; this could be tricky, as there are often no clear demarcations between different types of repositories (e.g. the gradient from peat to lignite to anthracite); excluding any of these might be quite arbitrary (specifically since a major part of the problem behind global warming is the emission of carbon from fossil repositories). As to quantification, measuring the total amount of C stored, including oceans and fossil repositories, might turn out practically impossible (as some repositories are still undetected today), and in other cases, irrelevant for accounting purposes (e.g. C stocks which are technically or economically inaccessible today [but might become accessible in the future due to technical progress]).
- Stored carbon can be seen as a stock but need not be an asset.[5] In fact, arguably, the stored carbon could be better seen as some sort of liability (posing risk of release) than as a proper asset.[6]
- A valuation approach that were to value all tC identical is problematic, as in most cases it would not be realistic that we would lose all carbon at the same time (i.e. perhaps we would degrade 10 % per year).
- Waste remediation is not valued in the SNA as the avoided damages of say radioactive waste leakage, but valued at cost (i.e. an input measure, not an output measure) (which is significantly lower).
- There are potentially double counting issues with the valuation of standing timber (when a stumpage price is used).[7]

Recommendations:

- Within an accounting context in which stocks and flows are rudimentary concepts, storage and sequestration should be clearly distinguished, despite being used interchangeably in the literature.
- We recommend that carbon sequestration should be considered as the (only) ecosystem service. The amount stored (as a result of sequestration or pre-existing) is a stock variable that may be included in the condition account and/or carbon account.

2.2 Issue 2: Final vs. intermediate vs process?

The TR (UN et al 2017) state clearly that “In the ecosystem accounting approach, **carbon sequestration is considered a final ecosystem service.**” i.e. an ecosystem service that generates a benefit for which there is a direct beneficiary (as distinct from an intermediate ecosystem service where the beneficiary

[5] I am indebted to Rocky Harris for making this point.
[6] NB: liabilities can only be of a financial nature in the SNA, so the word liability is used here not in an accounting sense.
[7] Indeed, as a rough estimate, timber consists of roughly 50 % of carbon.

would be another ecosystem unit). However, Table 5.2 of the TR seems less certain, when it says that sequestration is considered final only "as a matter of convention" as "final and intermediate effects are very hard to disentangle."

Moreover, it is relevant to point out that not everybody agrees that carbon sequestration is a final ecosystem service. Dixon and Landers (2013) argue that while carbon sequestration is definitely an ecosystem service, it should not be considered a final ecosystem service, but an intermediate service, as it is "not directly used or appreciated by individuals" .. "Moreover, most humans do not recognize or understand the importance of these entities.[8] To make things worse, the newest version of CICES V5.1 (EEA 2018) no longer considers carbon sequestration as an ecosystem service. "Carbon sequestration' is not an ecosystem service in V5.1, but regarded more as an ecosystem function. Nevertheless, it is acknowledged that it can be used as a proxy measure of the regulating effect that ecosystem can have in relation to one important constituent of the atmosphere."

This debate is complex as it is also contingent in part on the exact definition of final versus intermediate (and FEGS and TR have slightly different understanding here).[9] However, we do think that carbon sequestration should be considered as a (final) ecosystem service, not as a process due to a number considerations.

First of all, it is important to distinguish between the level of processes (in this case the process can be seen as primary productivity (see Section 3), which takes place regardless of human presence), and the level at which we situate ecosystem services, for which there should be beneficiaries.

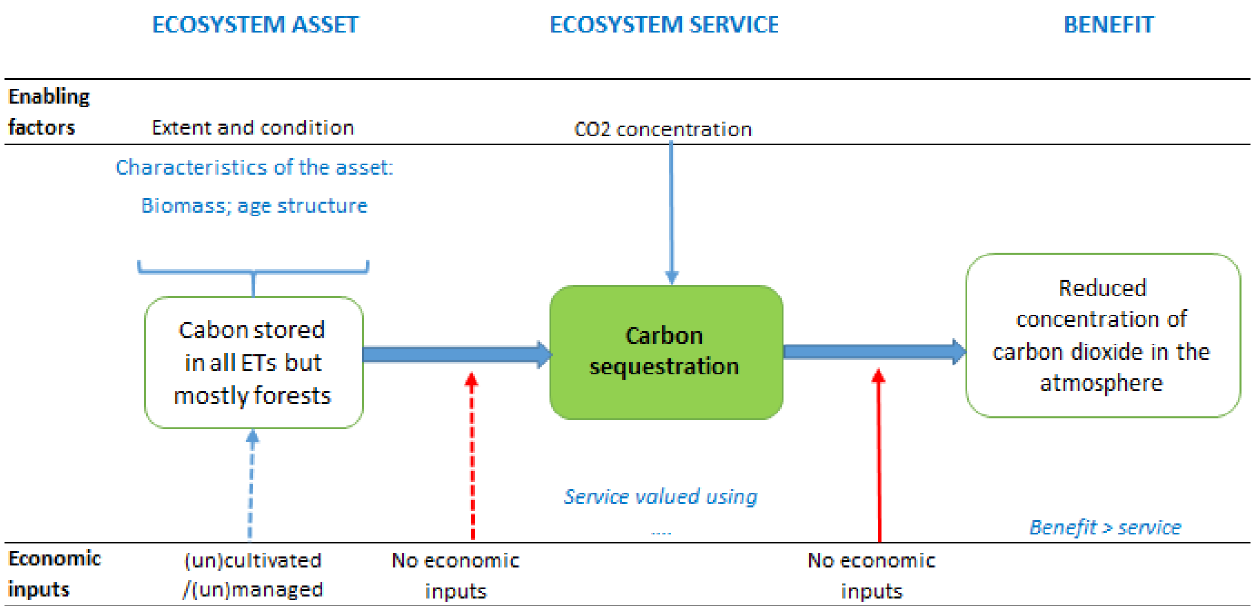
Second, it is important to be clear about the difference between benefit and social well-being. The TR state, "Carbon sequestration is one of the main ways through which ecosystems mitigate climate change. Hence, the corresponding benefit is reducing the impacts of climate change. Carbon sequestration comprises a flow of carbon from the atmosphere to the ecosystem, based on a variety of ecological processes" (ibid para 5.54). We prefer to define the benefit (i.e. the output) as "reduced concentration of carbon dioxide in the atmosphere", and not as 'climate regulation' or as 'reduced impacts of climate change' or as 'a stable climate' as these would be descriptions at the level of well-being. For instance, the output of the health industry is in the SNA (System of National Accounts) defined as medical services, not as improved health (which would be situated at the level of well-

[8] Dixon and Landers (2013) "Carbon sequestration is another process that is often asserted as an ecosystem service. Like biodiversity, we do not disagree that it is an ecosystem service in the general sense of the term. Carbon sequestration is certainly a vital process that contributes to the production and availability of many FEGS, but carbon sequestration is not a FEGS. We confidently hypothesize that the average person does not use, consume, or enjoy carbon sequestration; in fact, many people do not know what carbon sequestration is. However, many beneficiaries directly interact with weather (including temperatures) and the risks associated with the presence of particular environments (e.g., risk of flooding from sea level rise). Carbon sequestration and its impact on global climate change (among other processes and functions) are important, but intermediate to the supply of FEGS in an environment that a beneficiary directly uses, consumes, or enjoys."

[9] A related issue here may also be whether the atmosphere is considered an asset. If yes, then the situation strongly resembles the situation of pollination provided by one ecosystem to another, and sequestration would (in some cases) become an intermediate service, provided by ecosystems (say a forest) to the atmosphere.

being).[10] There are clearly well-defined benefits from sequestration, but these are arguably more indirect than in case of some other ecosystem services. Humans do not benefit directly from less carbon in the atmosphere (or more carbon in the soil), but they do benefit from a stable climate.

Figure 1: Logic chain of the service



Third, it is possible to anchor carbon sequestration into the transaction logic of the SEEA. For instance, we can connect the service being provided with the demand side for off-setting coming from released emissions from various sectors and related activities. This 'transaction model' of defining ES is what affirms carbon sequestration not only as a service, but also as a final ecosystem service, for which there are direct beneficiaries (we will get back to this topic in the section on recording).

Herewith, we propose the following logical chain:

Recommendation:

- Carbon sequestration should be considered a (final) ecosystem service,
- Define the benefit as reduced concentrations of carbon dioxide in the atmosphere as the benefit.

We will now discuss in greater detail the scope and measurement boundaries of carbon sequestration.

[10] Moreover, this would be consistent with services such as air filtration where the service is defined as (amount of tons removed), leading to benefit (reduced concentrations of say PM 2.5), which impacts human health and well-being (and allow us to value the service).

3 Measuring carbon sequestration

3.1 Scope and measurement boundaries

There are multiple published studies which applied carbon sequestration as an ES at various scales and contexts:

- at local – in forests below and aboveground biomass BRAUN *et al.* 2017; grasslands belowground biomass ACHARYA *et al.* 2012 and permanent crops SCANDELLARI *et al.* 2016
- at regional/national – with trade-offs between carbon sequestration and timber harvests in Austria SEIDL *et al.* 2007; crop/fodder production and carbon sequestration in Limburg province, the Netherlands REMME *et al.* 2014;
- and global – with climate regulation, food production, soil formation, water supply and flood control as driven by global geo-bio-chemical cycles WATANABE & ORTEGA 2011

There are multiple issues with the precise definition and scope of carbon sequestration, such as understanding how the service corresponds to the carbon cycling and storage processes. The following 3 equations apply (TR and IPCC 2006):

NPP (net primary production) = GPP (gross primary production) – plant respiration .

NEP (net ecosystem production) = NPP – soil respiration = GPP – ecosystem respiration

NECB (net ecosystem carbon balance) = Net Biome production (NBP) = NEP – Carbon loss from Disturbance/Land-clearing/Harvest

The following 5 scoping issues need to be resolved:

- NEP versus NPP (sometimes portrayed as a difference between "gross" and "net"); should emissions due to processes that may lead to carbon emissions by ecosystems different from plant respiration such as soil respiration or emissions due to soil subsidence be netted off?
- NECB (NBP) and Harvested wood products (HWP): should harvested timber be netted from carbon sequestration? In other words, should sequestration be equated with the effective change in carbon storage (of a particular ecosystem), in case of Table 1 -30 ton C, or as NPP / NEP.[11]
- Short-lived versus long-lived biomass: should we include all sequestration (NPP or NEP) (+15 in our example) or only sequestration leading to long-stored carbon (+5). The latter would be aligned with the IPCC guidelines (2006 IPCC) (and seems recommended in the TR[12])
- (Un)Managed lands; this is another boundary issue viz-a-viz climate change reporting. The IPCC Guidelines for instance only include emissions (and sinks) from managed lands (as the objective is to assess anthropogenic causes).[13] The definition of managed land need not align with the distinction between cultivated and non-cultivated lands in the SNA/SEEA CF.

[11] The IPCC guidelines consider HWP as a separate carbon pool. Hence they would report the removal of carbon from say a forest through harvesting, but this carbon would be added to HWP pool.

[12] Table 5.2 of the TR state: "Climate regulation / Carbon sequestration. Assessments of this service should only consider carbon stored long-term (i.e. at least several decades) in the ecosystem".

[13] IPCC Guidelines for AFOLU, Chapter 1 state: "For the AFOLU Sector, anthropogenic greenhouse gas emissions and removals by sinks are defined as all those occurring on 'managed land'. Managed land is land where human interventions and practices have been applied to perform production, ecological or social functions… while local and short-term variability in emissions and removals due to natural causes can be substantial (e.g., emissions from fire, see footnote 1), the natural 'background' of greenhouse gas emissions and removals by sinks tends to average

- Scope: do we only include sequestration taking place in specific ecosystem types (e.g. terrestrial, grasslands; forests etc.) or also within aquatic systems.

We believe there is value added to align the definition of carbon sequestration as much as possible with the IPCC guidelines both for issues of data availability (practical) as well as consistency. This implies to define carbon sequestration (or removal – as used in the IPCC guidelines) as:

- Carbon sequestration: the removal of carbon dioxide from the atmosphere by ecosystems, by storing it in carbon pools for more than a year [unit: tC/ha/yr]

This definition has a number of elements that are worth clarifying:

First of all, it would be consistent and complementary with carbon accounting by IPCC in the sense that a distinction is made between long-lived (durable) and short-lived forms of carbon sequestration. This would exclude annual crops and grasses, but perennial (e.g. energy) and permanent crops are included. The durable forms addressed by IPCC-AFOLU are the six carbon pools: above-ground biomass, below-ground biomass, dead wood, litter, soils and harvested wood.

Second, since ecosystems capture and loose carbon simultaneously, through photosynthesis, respiration and other processes, sequestration is considered to be the net positive effect of these processes BRAUN *et al.* 2017. Practically, this implies that we would be using NECB as the best measure. IPCC guidelines recommend the stock-differencing method to assess carbon emissions and removals and specify that the difference equals NBP. This is in line with the dominant approach within the literature as multiple studies consider NECB (or NBP) as a measure of carbon sequestration, although this is sometimes reflected with different wordings, for example:

- CO_2 regulation defined as positive values of NBP of croplands and forest BRAUN *et al.* 2017
- Forest carbon sequestration with NBP TURNER *et al.* 2004
- Forest carbon sequestration with NECB and stock difference measurement GIELEN *et al.* 2013
- In the absence of harvest, forest carbon sequestration is often assessed with NEP BLACK *et al.* 2007; BABST *et al.* 2014; KNOHL *et al.* 2003
- Carbon sequestration of crop-rotations assessed with NBP AUBINET *et al.* 2009
- Grasslands carbon sequestration, measured with NCS (net carbon storage) which considers all inflows and outflows of carbon SOUSSANA *et al.* 2010; SENAPATI *et al.* 2014
- Farm-scale carbon sequestration with NECB BYRNE *et al.* 2007;
- Carbon sequestration of permanent crops with NECB SCANDELLARI *et al.* 2016
- Carbon sequestration assessed on the basis of woody biomass growth and soil carbon measurements SAHLE *et al.* 2018

Third, it is proposed here to use the ecosystem asset definition applied in the SEEA EEA (so sequestration in all ecosystems would be in scope), rather than restricting the scope towards managed land only. The IPCC and SEEA have different goals. IPCC wants to exclude unmanaged areas because of its focus on human interferences, whereas SEEA EEA wants to include it because of its focus on ES & their services. It is important to note that the carbon transfer may be a mechanical, physical or biological process. Mostly biological processes taking place in ecosystems are considered an ecosystem service in

out over time and space. This leaves the greenhouse gas emissions and removals from managed lands as the dominant result of human activity.”

the literature and are further specified as persistent increase of their carbon storage (Hutchinson, Campbell, and Desjardins 2007) in biomass, soil, litter etc., although this persistence varies widely in time. The biological form of sequestration is not limited to capturing carbon (in the form of CO_2) directly from the atmosphere (through photosynthesis) but also indirectly, for example, from manure turning into humus compounds in the soil (Alexander et al. 2015). Physical (i.e. abiotic) processes of carbon sequestration taking place in the ecosystems are of interest as well and should be retained within the scope of this discussion. The temporal distinction of current/future and past geological processes allows to exclude oil and gas from this scope.

Recommendations:

- Based on the above overview NECB (or an equivalent metric, such as NBP and NCS) can be affirmed as the most suitable metric for defining and estimating carbon sequestration as a final service. However, this definition would be valid provided that the assessment covers multiple years to separate short-lived from durable forms of biomass growth. The alternative definition would be to measure/assess the durable forms, e.g. woody biomass and soil organic carbon directly as in SAHLE *et al.* 2018; GIELEN *et al.* 2013 and estimate their temporal change, whereby a positive difference counts as the final ecosystem service (and a negative difference, i.e. an emission, as a final disservice). The literature overview also implies that in absence of timber harvests, forest NEP can be applied as a measure of carbon sequestration, however there are other processes albeit of smaller magnitude which decrease the carbon retained within the ecosystem, for example carbon losses through erosion. This is why NEP would be more appropriately viewed as an intermediate service, similarly to NPP.

3.2 Practical measurement

There are essentially two basic approaches to analyze the supply of carbon sequestration by ecosystems (see TR p.91). The first is to derive sequestration by comparing changes in stocks of carbon over time (this is called the stock-difference method in IPCC guidelines), for instance on the basis of forest inventories and soil carbon measurements. Below and above ground carbon stocks in various forms need to be included in such assessments. This approach may be called an indirect method, as sequestration can be derived as a residual.

The second approach is to estimate carbon sequestration directly (called Gains-Loss method in IPPC guidelines) and involves the quantification of all key inflows and outflows of carbon per ecosystem unit, to estimate NECB or an equivalent metric (e.g. NBP or NCS).

The first approach is commonly applied in the existing carbon accounting mechanisms addressing IPCC's categories of managed land, and also a subject of intense research on biomass mapping in support of REDD+ RODRIGUEZ-VEIGA *et al.* 2017. Modelling NECB or NBP is a more complex process with fewer examples: PECKHAM *et al.* 2013; TURNER *et al.* 2015; GOVIND *et al.* 2011 etc, yet novel data sources and model advances need to be explored for the wider scope of SEEA-EEA

Since there is no proven best method to quantify and map carbon sequestration directly, several possibilities exist:

a) Carbon sequestration rates in specific ecosystem types can be derived from literature and from IPCC guidelines on stock inventory estimates for the LULUCF and used to produce look-up tables. The estimation therefore essentially is the product of numbers of hectares times a coefficient. This method is widely applied in ecosystem services studies SAHLE *et al.* 2018; MOKONDOKO *et al.* 2018, KIM *et al.* 2018, despite being criticized for oversimplification AKUJÄRVI *et al.* 2016.

b) More detailed carbon cycling modelling can be developed, starting with NPP (or GPP) which can also be modelled using the Normalized Difference Vegetation Index (NDVI) that is easily produced from most optical remote sensing instruments. However, care needs to be taken that the relationship between NDVI and NPP is well established for the ecosystems involved, and that accuracy levels are calculated based on sample points.

c) The direct flux measurements from FLUXNET: "a global network of micrometeorological tower sites that use eddy covariance methods to measure the exchanges of carbon dioxide, water vapor, and energy between terrestrial ecosystems and the atmosphere can be applied to calibrate and validate carbon cycling models to map carbon sequestration. More than 500 tower sites around the world are operating on a long-term basis. The overarching goal of the FLUXNET data collection at ORNL DAAC is to provide information for validating remote sensing products for net primary productivity, evaporation, and energy absorption."[14]

Recommendation:
However, all things considered, country-wide estimation of carbon sequestration needs spatial modelling for which the look-up table approach can be applied in data-poor situations ., despite its criticism for oversimplification.[15] Detailed process-based modelling would be the preferred mapping approach where SEEA-EEA experimentation is more advanced.
These recommendations apply mostly to terrestrial vegetated ecosystems (including forests, croplands, grasslands and wetlands etc. but excluding water bodies). Measuring and modelling the equivalent processes in aquatic ecosystems, and also the abiotic forms of carbon sequestration (such as dissolution in the ocean) can build on the more robust lessons from bio-sequestration on land, but will likely remain subject to larger uncertainties.

3.3 Measuring future flows of ecosystem services

The capacity of an ecosystem to continue to sequester carbon will depend on a range of factors, such as the current stock of timber, species composition, forest age structure, as well as management regime. For instance a growing forest sequesters more carbon than an old forest (that is in equilibrium). There are clearly also very large differences in the amount of carbon stored in forests.

[14] https://daac.ornl.gov/cgi-bin/dataset_lister.pl?p=9

[15] An often used model based on the look-up approach is INVEST, which has a specific module on carbon sequestration, the InVEST Carbon Storage and Sequestration model. "This module estimates the current amount of carbon stored in a landscape and values the amount of sequestered carbon over time. First it aggregates the biophysical amount of carbon stored in four carbon pools (aboveground living biomass, belowground living biomass, soil, and dead organic matter) based on land use/land cover (LULC) maps provided by users." User's guide: http://data.naturalcapitalproject.org/nightly-build/invest-users-guide/html/carbonstorage.html

The projection of future ES flows of sequestration therefore requires biophysical modelling. It is important that the modelling assumptions are consistent with assumption made when modelling other services. As the TR state, "if estimates of carbon sequestration services are made assuming that a forest can sequester carbon over an infinite timeframe, while for the same ecosystem asset, estimated rates of timber provisioning are made assuming the forest is depleted within a limited time frame with no regeneration (e.g. 30 years), then the two estimates of expected service flows should be considered internally inconsistent. In many cases, it is likely that asset lives for provisioning services involving harvest or extraction will provide an upper bound to the asset lives and should therefore be applied in estimation of all expected ecosystem service flows."

4 Valuation of the ecosystem service

4.1 Different possible valuation approaches and their conceptual links

The benefit of the Ecosystem service "carbon sequestration" is that it removes carbon dioxide (CO_2) from the atmosphere, and therefore avoids the respective damages caused by global warming. Hence, a straightforward approach to monetizing the value of one unit of CO_2 sequestered by an ecosystem is to determine the value of the damages that this unit might cause otherwise, i.e. the "social cost of carbon"[16] (as far as it is possible to determine such damages in advance). This is the "damage cost" approach to valuation. If applied to different CO_2 quantities, this results in a demand-type value curve: As global warming damages increase progressively with the amount of carbon emitted, the benefits of one additional unit of carbon sequestered depend on the present greenhouse gas (GHG) load in the atmosphere – as long as GHG loads (and global temperatures) are low, marginal benefits of sequestration are low, too (or possibly even negative); but once GHG loads become dangerously high, the benefits of a sequestered carbon unit increases accordingly. Therefore, marginal benefits of carbon sequestration *decrease* with the quantity already sequestered (at least in theory and under ceteris-paribus-conditions: that is, if there are no other emissions).

An alternative cost based approach is to determine how costly it would be for an economy to avoid the emission of an additional unit of carbon, or alternatively, to release it from the atmosphere by technical or by nature-based measures ("abatement cost approach"). Obviously such costs again depend on the quantity of emissions that are to be avoided: reducing emissions by a small amount only may be quite cheap, simply because the economy can choose the cheapest available options for emission reductions first. However, if more emissions have to be avoided, more expensive options have to be applied, too. Therefore, marginal avoidance costs *increase* with increasing amounts of emissions reduction, as is typical for a supply curve. This renders it possible to link the damage cost approach to the avoidance cost approach: If an economy acted fully rationally, and if it had all necessary information available, then it would be most efficient for this economy to reduce its emissions just until marginal avoidance costs equaled the marginal damage costs caused by this last emitted unit. At this quantity, damage cost and avoidance cost approach yield exactly the same result. (Other cost based approaches exist which can be

[16] The social cost of carbon may be defined as "the monetary value of the first partial derivative of global, net present welfare to current carbon dioxide emissions" (TOL 2018:10). Thus it is conceptually equal to a PIGOU tax on carbon dioxide emissions.

considered as variants of the damage cost or the avoidance cost approach; they can be linked to these approaches in a similar manner).

If the rights to emit carbon are restricted and compliance markets for emission certificates are established (as is the case in the European Union and in several other countries), the prices paid in these markets are another source of value information. Again, they can be theoretically linked to cost concepts. In a perfect market, the buyer of a certificate will increase his demand as long as certificates are cheaper than his individual options for emission reduction; and vice versa, the seller will increase his supply as long as the price of one certificate is higher than the cost which the abandonment of the respective emission right causes to him. Thus, the equilibrium price in a (perfect) emission market theoretically reveals the marginal avoidance costs of the market partners; and if the reduction target for the whole market is set at an efficient quantity, prices reveal marginal damage costs, too, as above.

Lastly, the value of emission reductions and/ or carbon sequestration can be determined by analyzing consumers' preferences for this service, i.e. a population's stated or revealed willingness-to-pay (WTP). Under idealized assumptions, the marginal WTP of a rational decision maker (politician or citizen) for a unit of emissions reduction will just equal the damages that this marginal unit would otherwise cause. This links the WTP approach to the damage cost approach; the links to the other cost based approaches are again as described above.

Unfortunately, all of these approaches to carbon valuation suffer from specific problems, when it comes to practical application. Therefore, there is no unequivocal valuation approach to carbon valuation. We will therefore discuss the available options in more detail, including their specific advantages and disadvantages for use in the SEEA framework.

4.2 Damage cost approach (social cost of carbon)

Estimates of the social cost of carbon (SCC) usually rely on Integrated Assessment Models (IAMs). An IAM uses multiple functional relations between natural and economic processes to predict future climate scenarios and their impact on economic output (typically GDP is a central indicator). About 20 such Integrated Assessment Models exist at global scale. These focus either at detailed process analyses, or, at a more aggregate level, at benefits and costs of climate change (WEYANT 2017). Of the latter, three models are widely used for estimates of the social cost of carbon: DICE (Dynamic Integrated Climate-Economy model) (NORDHAUS 2017), PAGE (Policy Analysis of the Greenhouse Effect)[17] (HOPE 2011), and FUND (Climate Framework for Uncertainty, Negotiation and Distribution) (ANTHOFF & TOL 2014). Structurally, these models differ in various respects:

- in their complexity and basic structure (e.g., DICE focuses on GDP at global level only and distinguishes just a market from a nonmarket sector, while FUND distinguishes 16 world regions and 14 sectors),
- in the way how they include uncertainty and possible catastrophic risks (e.g. whether or not they include possible tipping points, and/or extreme events like the melting of the Greenland ice sheet),

[17] The "Stern Report" (STERN 2007), for instance, has used PAGE as its modelling base. All three models are used by an interagency working group in the USA to develop an official SCC for use in regulatory analyses (METCALF & STOCK 2017).

- in the climate variables considered (e.g. whether or not storm event probabilities are included),
- in the functional form of the damage function, in the elements included in this damage function, and their possible interactions (e.g., whether or not costs due to increased infectious disease risks and mortality of humans are included),[18]

and other details (for a more detailed comparison, see DIAZ & MOORE 2017).

Conceptually all of the models are based on very long time projections of the economies' development, of the respective emissions, and of the damages caused by the latter: DICE and PAGE both simulate up to the year 2200, FUND even up to 2300/3000. Such very long time projections inevitably require a plethora of assumptions: As they try to forecast the costs of carbon in the future, they need to assume how productivity will develop, what role new technologies will play and how these will be diffused, how prices will develop in energy and other markets, and ultimately, how market prices in the future can be discounted in order to determine the present value of economic costs and benefits. As a result, SCC estimates based at such projections differ considerably. According to a recent survey, most published estimates suggest a cost of carbon between $20/tC and $400/tC (TOL 2018),[19] depending on the preferred rates of discount and risk aversion. (For a graphical comparison of results at different levels of temperature change see DIAZ & MOORE 2017, fig.2). Given the different structures of the models and the many uncertainties associated with the assumptions used as input data, valuation results may even vary by one or two orders of magnitude (WEYANT 2017:122, quoting ROSE *et al.* 2014).

However, all models agree that damages increase over time, as GHGs accumulate in the atmosphere. The most striking damages will hence occur in a more distant future. Estimates of the SCC are therefore not constant over time; the SCC is expected to grow progressively, with a growth rate estimated at about 2-3 % per year (TOL 2018). While this is merely a matter of (expected) facts, another temporal discontinuity of SCC estimates is rather due to the development of our knowledge about facts: As new information about the physical and economic consequences of global warming becomes available, it will eventually be integrated into an IAM. Therefore, an SCC estimate for a specific year calculated today will not be identical to an estimate calculated in the year 2025, even if both use the same IAM.

There is also broad agreement that damages will be distributed unevenly across the world. This is due to different reasons: The world's wealth is not distributed evenly over world regions and countries; and the vulnerability of countries to natural catastrophes is unequal, too (e.g. flat islands will suffer more from sea level rise than mountainous regions). Therefore, an SCC estimate which comprehends various countries, or even the world as a whole, needs aggregation rules in order to sum up damages which affect different goods in different and possibly incommensurable societies. Such an aggregation cannot be neutral; it inevitably involves implicit value judgements.

The mentioned properties of Integrated Assessment Models are relevant for a possible utilization of carbon damage cost estimates in a SEEA context.

---

[18] According to WEYANT, benefit-cost-IAMs "can be so highly aggregated in terms of economic costs and benefits that it is not even clear which impacts have been included and whether interactions between those impacts are being considered" (WEYANT 2017:124).

[19] This roughly translates to a range between ~$5/t$CO_2$ and more than $100/t$CO_2$ (the exact conversion factor is [12.0107+2*15.9994/12.0107 ≈ 3.664, according to the respective molar masses of C and O).

- A convenient property of an SCC estimate which is aggregated to one single number (i.e. the monetary value of global GDP loss) is that it corresponds well with the economic nature of the sequestration service, which is a global public good. However, this does not mean that the *value* of this public good is homogenous across the world. First, damages of global warming (and hence, the benefits of avoiding them) are distributed unevenly. Second, purchasing power distribution is uneven, too. Even if the aggregation rule for global GDP accounts for different purchasing power, the "global" SCC estimate is dominated heavily by a few richer countries – only 3 % of all countries contribute more than 50 % to global GDP (WORLD BANK 2015:154). This implies that damages in poorer countries contribute less than proportionally to the global SCC estimate, and the "global" SCC is statistically not representative for the damage costs in the vast majority of the world's countries. This thwarts existing results which indicate that negative impacts of global warming will be substantially greater in poorer (as well as hotter and lower lying) countries (TOL 2018). A further related problem is that within such poorer countries, comparisons of carbon values to national wealth measures will be heavily skewed.[20] In other words, a globally uniform SCC estimate might turn out quite misleading in various respects. Even if it was not, it would not yield much relevant information beyond the physical quantity of carbon emitted and sequestered in any country, since it implies merely a multiplication of this physical quantity with a constant.
- Regionalised estimates of the SCC might avoid these problems. However, another problem still remains, that is that some of the damages captured by some of the current IAMs are alien to national accounting principles (like e.g. increased human disease and morbidity risks in FUND). Including such values in comprehensive damage estimates seems sensible in general; but in a national accounting framework, it would require human capital to be recognized as an asset, which is currently not the case.
- The problem just mentioned is a conceptual one. Other problems exist which pertain to data reliability, i.e. the fuzziness of the current SCC estimates. Several national institutions therefore provide official recommendations for practical use (e.g., the Interagency Working Group in the USA (IWG 2016), the Department of Energy and Climate Change in the UK (DECC 2009),[21] and the Federal Environmental Agency in Germany (UBA 2018)). Even these recommendations vary by one order of magnitude and more.[22] Inevitably such recommendations are not influenced by pure empiricism only; rather, the selection of results to be included in such recommendations also reflects the personal convictions of the involved experts. In other words, the numbers do not reveal just what carbon sequestration is worth to society, but rather what experts think it *should* be worth. Moreover, experts' convictions need not be the same in different institutions and countries, which implies that SCC recommendations issued by different institutions will not be comparable (and hence not be usable for comparisons between countries in a SEEA framework).

[20] As an example, an SCC of \$42/tCO_2 (as advocated by the U.S. Interagency Working Group as a central estimate for 2020; *IWG 2016*) would exceed the average monthly income in the 9 poorest states of the world, for a single ton of CO_2 sequestered.

[21] The DECC has abandoned recommending social costs of carbon for valuation purposes due to "the considerable uncertainty that exists surrounding estimates of the SCC" (DECC 2009). Their revised approach recommends (forecasted) carbon prices for sectors under the EU-ETS, and marginal abatement costs otherwise.

[22] For example, the value recommended by IWG 2016 (\$42/tCO_2 for 2020 at a discount rate of 3%) does not compare well to the one recommended by UBA 2018 (EUR 180/tCO_2 for 2016 at a discount rate of 1%, with an additional sensitivity analysis for an SCC of EUR 640 at 0%; the latter is explicitly being advocated for intergenerational justice reasons).

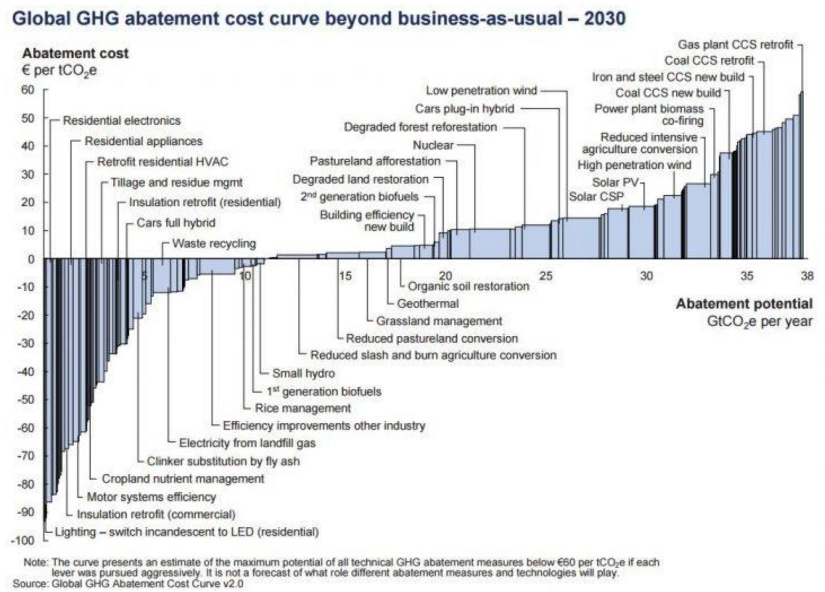
SEEA

- Possibly the major argument against applying SCC estimates for valuation in a national accounting framework is the enormous number of assumptions behind any such estimate, and the large influence of these assumptions. Specifically this applies to the choice of the discount rate. Due to the very long time horizons which have to be respected in carbon damage valuation, any SCC estimate is a direct function of the discount rate applied in estimation. As there is not much empirical guidance for determining how future events should be discounted, SCC estimates may be considered as mainly arbitrary (PINDYCK 2017). Even worse, they are susceptible to political manipulation, keeping in mind the many international and intertemporal distribution issues which are implicit in the aggregation of damages across different regions and different times into a single number.

4.3 Abatement cost estimates

Abatement costs can be defined as the costs incurred by an economy for avoiding the emission of a specific amount of carbon, or for capturing it by biological or technical means. Abatement cost functions can be estimated in a top-down fashion (i.e. by modelling the reduction of economic output as emissions are gradually reduced, again using Integrated Assessment Models); or alternatively in a bottom-up manner (i.e. by assessing the abatement potentials of economic activities, estimating the costs of those potentials, and sorting them according to cost) (CLINE 2011). Several such abatement cost functions have been constructed at global scale (e.g. MCKINSEY & COMPANY 2009, 2010), but also for specific economies (e.g. 15 country studies by McKinsey, 2007-2010;[23] 25 major economies in CLINE 2011) and for specific sectors (e.g. VALATIN 2012 on UK forestry, VERMONT & DE CARA 2010; DE CARA & JAYET 2011 on agriculture). Fig. # shows the global curve by MCKINSEY & COMPANY 2009 as an example.

[23] See https://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/greenhouse-gas-abatement-cost-curves



Like with avoidance cost or replacement cost estimates, such cost curves are only valid as long as the respective alternatives are low-cost alternatives (this is by definition the case when using such a curve), and if the alternative would actually be implemented in case of a loss of an ecosystem service (which might be difficult to prove). Generally abatement cost curves have been criticized for lacking transparency in their methodology and underlying assumptions, for their limited treatment of uncertainty and intertemporal dynamics, and for possible double counting as well as for non-consideration of interactions (e.g. Kesicki & Ekins 2012).

The curve depicted here shows that the net abatement costs of various interventions even are negative, i.e. the benefits seem to outweigh the costs (for example by switching to LED lighting in houses, as shown in the figure). The persistence of negative costs seems weird and needs explanation, as they seem to present business opportunities which rational actors would immediately have seized ("no regret options"). In fact such negative costs are caused by barriers which actually prevent "no regret options" to be implemented (like e.g. lack of information about saving possibilities, lack of market access, lack of liquidity, etc.), but which are not considered in the construction of the curve. Since such barriers indicate the presence of unobserved transaction costs, it can be concluded that the presented curve underestimates total abatement costs, at least in its left part. Carbon values estimated by such a curve would therefore likely be biased downwards.

For utilizing abatement cost curves in a SEEA framework, several issues would have to be addressed:

- Costs presented in a marginal abatement cost curve are annualized. The applied discount rate may be however much lower than the rate of return typically required by investors. For consistency reasons, unique discount rates would have to be applied for national accounting.
- Abatement cost curves are time dependent, i.e. they are valid for a specific year only. If a specific emissions reduction goal has to be realized sequentially, then an annual emissions trajectory must be defined (including time-specific abatement costs).

- Additionally, abatement cost curves are by their nature country dependent, and even location dependent. This requires determining different abatement cost curves for different countries, and complicates international comparability of accounts. A further practical obstacle is that abatement cost curves are so far only available for some countries, but not for all.
- Beyond this, it needs to be considered how a national (or even local) abatement cost estimate is linked to market exchange possibilities: In the presence of markets, abatement costs can be balanced between different locations (which would turn down costs on average); without such market exchange, they cannot. Again this raises comparability issues.
- In any case it would be necessary to specify the quantity for which the respective abatement cost should be calculated. This might turn out speculative rather than empirical in such (developing) countries where emission reduction obligations are not bindingly quantified. But even in countries with quantified reduction obligations ambivalences might arise in cases where the reduction goals agreed in the UNFCCC framework diverge from “internal” (politically set) reduction goals.[24]

4.4 Observed market prices

There are different kinds of markets where economic agents can trade greenhouse gases (GHG; usually in units of carbon dioxide equivalents, CO_2e): mandatory cap-and-trade systems (“compliance markets”); voluntary carbon markets; and as a special case, the ”flexible mechanisms” introduced by the Kyoto Protocol (intergovernmental Emissions Trading, the Clean Development Mechanism, and Joint Implementation; UNFCCC 1997). In general, all these markets turn emission rights into a scarce resource by limiting their permissible amount. Furthermore they provide a set of rules that define which emitters are subject to the market, and how their emissions are measured and registered (including rules about the kind of greenhouse gases included, and the sources and sinks to be accounted for). As these rules differ between the individual markets, the respective certificates are not generally exchangeable, and prices may differ substantially.

By far the highest amount of certificates is being traded in mandatory cap-and-trade systems. It is important to note that carbon values based at market prices in a cap-and-trade-system have to be interpreted slightly differently from values based at avoided damages. While avoided damage costs directly indicate what nature contributes to human wellbeing, market prices rather indicate what nature contributes to a politically specified goal (which is intended to serve human wellbeing). That is, prices also reflect characteristics of the institutional setting of the respective market beyond the pure value of the ecosystem service. First and foremost, prices reflect the scarcity of emission allowances as induced by the cap. Although an “ideal” (efficient) policy would specify this cap exactly at the optimal quantity of emissions, where marginal avoidance costs (and thus, prices) equal marginal damage costs (see above), real life policies might fail in meeting the optimal quantity. In this case, prices will be biased downwards if a cap allows more than the optimal quantity of emissions, and vice versa.

[24] E.g., Germany’s formal reduction target for 2020 (as compared to 1990) is -20% according to the second Kyoto period in combination with the EU burden sharing rules; internally the federal government has committed itself to reduce emissions by -40 % until 2020 (WISSENSCHAFTLICHE DIENSTE 2018).

Currently about 20 different GHG emissions trading systems are in force worldwide, which cover nearly 15% of global emissions (ICAP 2018): one supranational (the EU-ETS)[25], several national ones (in South Korea, Australia, New Zealand, Kazakhstan, Switzerland, and recently forthcoming, China), and subnational ones in parts of the USA, Canada, and Japan. Similar systems are under development in further countries (ZECHTER *et al.* 2017; WORLD BANK & ECOFYS 2018). This trend can be expected to continue, as Article 6 of the Paris Agreement lays the ground for strengthening pricing mechanisms in the future (UNFCCC 2015). Indeed 88 of the UNFCCC Parties have already signaled their intention to use carbon pricing (through markets or taxes) as a tool for meeting their emission targets (WORLD BANK & ECOFYS 2018:18).

Prices in the world's various ETS markets differ significantly and are fairly volatile. When comparing these prices to the damage cost estimates presented above, it seems obvious that market price levels are considerably lower. For example, in 2017 the average prices in the various ETSs covered a range from about 1 US$/t CO_2e in Chinese pilot markets to about 18 US$/t CO_2e in the Korean ETS. New Zealand's ETS and the Swiss ETS were in between, with about 13 and about 7 US$/t CO_2e, respectively (ZECHTER *et al.* 2017). For the first half of 2018, moderate price increases of about 1-3 US$/t CO_2e have been reported in these markets (WORLD BANK & ECOFYS 2018). In the same time, the EU-ETS price rose from about 6 US$/t CO_2e to about 16 US$/t CO_2e, later fluctuating around 22 US$/t CO_2e (20 €/t CO_2e) (from September to December 2018, cf. Figure 2).

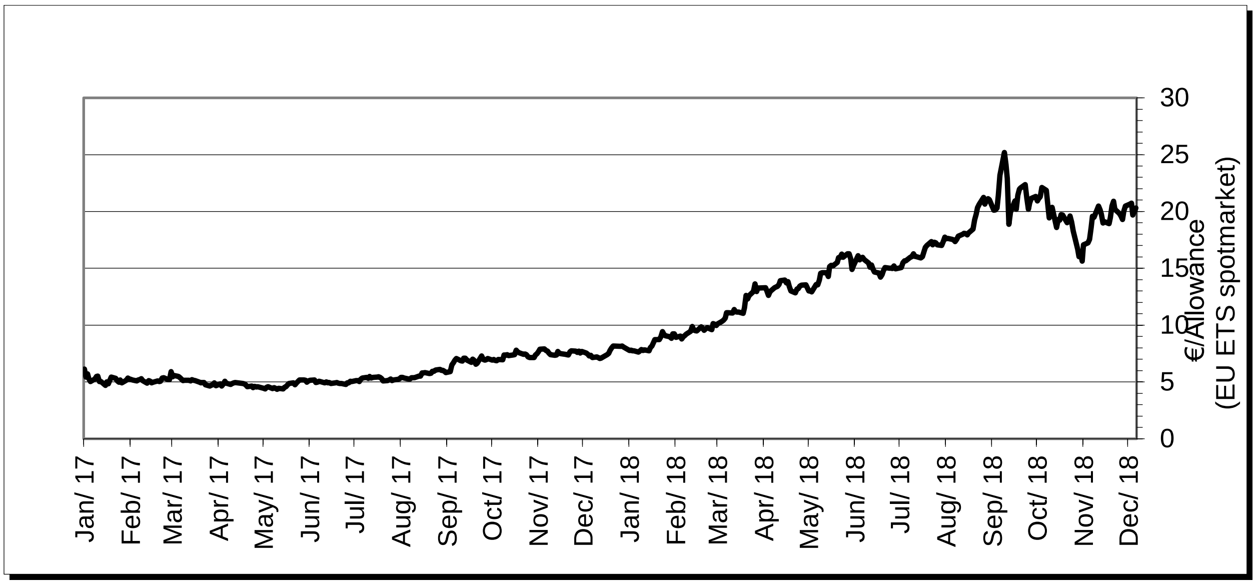


Figure 2: Price development in the EU-ETS between January 2017 and December 2018 (source: EEX[26], daily EU Emission Allowances [secondary market])

Such regional and temporal price differences reflect differences in the respective economic situation and the institutional setting around each market, and their changes over time: Market prices for carbon are indirectly influenced by complimentary policies which affect emissions (like e.g. regulations on renewables and energy efficiency, or the respective tax regimes) as well as by direct measures intended

[25] The EU-ETS includes all 28 EU Member States plus Iceland, Liechtenstein and Norway.
[26] European Energy Exchange, http://www.eex.com/en/market-data/environmental-markets/spot-market/european-emission-allowances

to counteract market imbalances (like e.g. the Market Stability Reserve scheduled for the EU ETS from 2019 onwards; cf. HEPBURN *et al.* 2016). A special measure for stabilizing carbon market prices is a "price floor" as introduced by the UK government in 2013. As long as the EU-ETS price falls below a pre-specified minimum (i.e. the price floor), an additional levy (called the Carbon Support Price) has to be paid by UK energy generators, which tops up the EU ETS allowance price to the carbon floor price target. The price floor was initially intended to rise every year until 2020 to a price of £30/tCO_2, but is frozen at a price of £18/tCO_2 (~23 US$/t$CO_2$) since 2016, to limit competitive disadvantages faced by business in the UK and reduce energy bills for the respective consumers (HIRST & KEEP 2018).

None of the existing emissions trading systems covers all GHG emissions of the respective economies. For instance, the EU-ETS is restricted to power stations of more than 20 MW and other installations in specific sectors, but excludes, e.g., the transportation sector, private households, agriculture and forestry. Altogether it covers about 40% of the respective countries' total GHG emissions, or about 2 bn t CO_2e/a. The Chinese ETS, in contrast, only covers emissions in the power sector as yet (which make up about 30% of total emissions, or 4.5 bn t CO_2e/a). Only one of the currently existing ETSs includes the forest sector, too, which is the ETS of New Zealand (accounting for emissions as well as carbon sequestration; cf. HAMRICK & GALLANT 2017a). As it is a political decision how emission rights will be allocated between "inside" sectors (which are covered by the respective ETS) and the "outside" sectors, "inside" and "outside" sectors need not face the same scarcity of emission rights – particularly when reduction goals differ explicitly, as is the case in the EU-ETS.[27]

Two other price-related instruments may be shortly mentioned which must be distinguished from compliance markets, i.e. carbon taxes, and purchases of carbon offsets in voluntary markets:

- First, a carbon tax is a governmental instrument which also uses price signals for reducing carbon emissions. Therefore taxation and market instruments are sometimes subsumed under the term "carbon pricing", and in several countries they are applied in combination (ZECHTER *et al.* 2017).[28] However, both instruments reveal different kinds of value information: While market prices reveal the market participants' reactions to a (politically determined) quantity restriction, taxes just are the result of a political decision – which may have been influenced by reallocation as well as by revenue targets as well as other political motives. Therefore, tax rates per carbon unit are not well suited for informing about the empirical value of this unit (even though it may seem convenient that carbon tax information might be available also from sectors and countries which are not subject to an ETS).[29]

[27] According to EU regulation 2018/842, sectors "outside" the ETS must reduce their emission by 30 % until 2030 in comparison to 2005, while the reduction goal for the "inside" sectors is 43 % (EU 2018).

[28] The bulk of these carbon taxes is significantly higher than prices in the various ETSs, with a range up to 139 US$/tCO2 in the case of the Swedish carbon tax (cf. ZECHTER *et al.* 2017).

[29] There are several further problems. First, using carbon tax values for accounting purposes would induce additional classification problems, as some countries tax carbon emissions directly and explicitly (e.g. Australia, Mexico, Sweden, Slovenia), while other countries apply different names and slightly different concepts, but with similar effects (e.g. the German energy taxes). Second, the widespread presence of tax exemption rules might preclude the calculation of effective (mean) tax rates. Third, the assumption that tax rates (for emissions) can be simply reversed to the opposite case of carbon sequestration might be questionable, as this would imply that decision makers are indifferent between earning taxes and paying subsidies.

- Second, voluntary carbon markets provide emission offsets to citizens and organisations wishing to contribute to climate protection goals even in the absence of a compliance market. Usually such offsets are verified by third parties according to specific standards, which differ with regard to the requirements to be fulfilled, verification methodology, etc. Voluntary markets are much smaller than the mandatory cap-and-trade systems described above, in terms of traded volumes as well as of realized prices. For 2016, the overall volume of carbon offsets has been estimated at about 63 million tons of CO_2e, which is about 0.0002 % of annual worldwide emissions. Prices were highly variable and ranged from less than \$0.50/tCO_2e to more than \$50/tCO_2e, the differences being attributable to project location, verification standard, project type, and other characteristics (HAMRICK & GALLANT 2017b). The average price was estimated at about US\$ 3.0/tCO_2e – again much lower than most ETS prices, let alone SCC estimates. As participation in these markets is voluntary, it can be expected that price estimates from these markets will be downwards biased due to the lack of demand revealing incentives (i.e. the free rider problem). This renders them unsuitable for accounting purposes in the SEEA framework.

Empirical market-based carbon values which are better comparable to ETS prices are available from the flexible mechanisms of the Kyoto protocol. The Clean Development Mechanism might be most interesting here since it specifically addresses developing countries that do not have quantified reduction obligations, and usually do not operate an ETS.[30] Volumes and prices of the respective allowances, however, are low. Stock exchange data report prices below 1 €/tCO_2 ever since 2013.[31] For afforestation and reafforestation projects, slightly higher prices up to 6 US\$/tCO_2 have been reported in the past (GOLDSTEIN *et al.* 2014). It should be noted that these prices do not reveal domestic demand, but demand from international trading partners who are subject to an obligatory emissions reduction regime.

For a possible utilization of market prices from compliance markets for carbon valuation in a SEEA context, several points need discussion:

- A major advantage of ETS market prices is that they provide a market based exchange value that is aligned with the SNA (and SEEA) exchange value notion. Beyond this, many transactions concerning carbon are already recorded in the national accounts. This is the case in those countries which are subject to an Emissions Trading System (but also in countries which apply carbon taxation).[32]
- It is argued that market price levels in almost all existing ETSs have been (and possibly still are) „too low“, as compared to an efficient price level (e.g. STIGLITZ *et al.* 2017), and indeed they are considerably lower than most of the SCC estimates. Whether or not this is a problem for carbon accounting depends on the interpretation of carbon values. If they are to be interpreted primarily as

[30] Payments for REDD+ could be an additional information source specifically about forest carbon in developing countries. Yet, these payments do not reflect empirical carbon values alone, as they are also influenced by distributive aims. Moreover they refer to a different baseline situation: Agents in an ETS have to pay for every ton of carbon they emit (which implicitly refers to a baseline of “no emissions”); whereas under REDD+ the baseline is “emissions as usual”, and agents get paid if they emit less than the baseline allows.

[31] https://www.carbonplace.eu/info-commodities-CER; https://www.eex.com/en/market-data/environmental-markets/spot-market/green-certified-emission-reductions

[32] This complicates matters, as the original national accounts may have been influenced by both ETS prices (for the sectors covered by the ETS) and carbon taxes, which may differ considerably. However, separating both influences is an accounting problem, not a valuation problem per se.

welfare indicators, then the utilization of ETS prices most probably will lead to downwards biased results, as they underestimate the value carbon sequestration contributes to human societies. If on the other hand a reflection of current policies and their interplay with economic success is in the foreground, then ETS prices seem better suited, as they reveal the outcome of actual market exchanges (which may be affected by specific market failures in the case of climate policy, but also by other market failures in other policy domains which still are captured in national accounts).[33]

- A related problem is that carbon prices may differ between countries if these countries belong to different ETSs, which might appear as an artifact (e.g., differences of carbon prices between Austria and Switzerland might be caused by different market designs rather by different inherent carbon values).[34] However, this also holds for many other goods and services that are within the current SNA. Moreover, the SNA makes perfectly clear that it values transactions irrespective of whether the underlying markets are perfect or competitive.
- Perhaps the most significant problem is that ETS prices do not apply to countries which have no ETS, and even in countries with an ETS these prices do not necessarily apply to those sectors which are not covered by the respective ETS. Closing those gaps requires additional assumptions, which inevitably will be hypothetical to some degree. There are several options for doing so: ETS prices could be interpreted as estimates of carbon values outside the respective market, too (which essentially interprets the existing ETS as a proxy market for those sectors which are not covered by this ETS, and posits that a value broadly similar to the ETS price would arise in a hypothetical additional market); prices could be imputed using abatement cost estimates;[35] and finally, missing ETS prices could be substituted by taxes, SCC estimates, or prices of project certificates (e.g. from voluntary or CDM projects).
    - *a)* Interpreting ETS prices as universal value estimates beyond the limits of a specific ETS would be clearly inaccurate from a theoretical point of view, as pointed out above. Practically speaking however, in a country participating in an ETS the respective carbon prices likely yield the least biased estimates, even for those activities which are not covered by this ETS (i.e. in the “outside” sectors), and probably they are the most comparable ones. (This argument does however not hold for countries which are generally not subject to an ETS, as the choice of a suitable reference ETS would be arbitrary for these countries).
    - *b)* For countries without an ETS, imputing ETS prices using abatement cost estimates appears as a less arbitrary solution. Still, it would be necessary to determine a “correct” price estimate along the (quantity-dependent) abatement cost curve (i.e. a hypothetical cap). Two possibilities exist for doing so: for a preassigned quantity of emissions reduction, the least cost option could be identified; as an alternative, for a specified activity the corresponding

[33] Accordingly, changes of SCC estimates over time could be interpreted as reflecting changes in knowledge about damages, at least ideally (i.e. as far as they are not simply effects of ideology-based influences); whereas changes in market prices reflect policy changes in the first place (e.g. the introduction of more restrictive market rules).
[34] The question of whether it is sensible to value climate regulation by prices which depend on national circumstances has already been discussed before (see damage cost section): The fact that climate regulation is a global public good does not necessarily imply that the value of this public good is homogenous across the world.
[35] DECC 2009 argues in favor of using abatement cost estimates in cases where price information is missing. However, this recommendation applies to carbon valuation in a single country. In a multi-country environment, possible inconsistencies between abatement cost estimates in different countries must additionally be considered.

abatement costs could be determined (e.g. using nationally standardized afforestation costs when the sequestration value of afforestation activities is in question).[36]

c) Instead of abatement costs, average certificate prices of CDM or JI projects lend themselves to substituting for ETS prices in "non-ETS-countries", keeping in mind that these certificates are specifically designed for countries without emission reduction obligation (or respectively, for activities beyond such obligations), and that they are conceptually well compatible with ETS prices.

d) Other options (taxes, SCC estimates, prices from voluntary markets) are less suitable as price substitutes, and should thus not be combined with compliance prices. Conceptually, they all differ very much from such prices; and empirically, their respective levels deviate so heavily from price levels that this might strongly bias comparisons between sectors and/or countries.[37]

4.5 Consumer preference studies

Finally, laboratory or survey experiments about the values individuals place on carbon are a theoretically appealing information source for valuing the benefits of carbon sequestration: Ultimately it is the benefit of the individuals which constitutes social welfare, and moreover, the individual is the only authority being competent to assess his or her benefits appropriately. In the case of carbon however, there is a caveat: In contrast to other ecosystem services which are directly experienced by consumers, the benefits of carbon abatement affect people only indirectly via the avoided damages, and benefits arise mostly in the future. The associated cognitive burdens might render valuation experiments for carbon less reliable than for other consumer goods and services.

Indeed, value estimates from available case studies cover a very wide range even within one single country. As an example, average willingness-to-pay (WTP) estimates of 11 valuation experiments among German residents from the last decade[38] range from less than 10 €/tCO_2 (DIEDERICH & GOESCHL 2014; SCHWIRPLIES *et al.* 2017) to far more than 250 €/tCO_2 (HACKBARTH & MADLENER 2013; UEHLEKE 2016). International studies fall within the same boundaries (BROUWER *et al.* 2008; ALBERINI *et al.* 2018).

While these results may serve to affirm the plausibility of value ranges established with other approaches (particularly with regard to the damage cost approach), their vagueness again restricts their usability for accounting purposes. Additional problems include:

- A conceptual issue: WTP estimates often include consumer surplus values which do not belong to the exchange value concept of national accounting (even though price equivalents could be derived from WTP based demand curves).

[36] Both options are not unusual in national accounting.

[37] However, SCC and prices from voluntary markets could be interpreted, respectively, as upper and lower bounds.

[38] Cf. RAJMIS *et al.* 2009; ACHTNICHT 2011, 2012; HACKBARTH & MADLENER 2013; LÖSCHEL *et al.* 2013; DIEDERICH & GOESCHL 2014; HOLM *et al.* 2015; HACKBARTH & MADLENER 2016; UEHLEKE 2016; LENGWENAT 2017; SCHWIRPLIES *et al.* 2017

- A consistency issue: Any valuation experiment of public goods must insinuate a hypothetical market condition which needs not be consistent with that of other experiments, or with the structure of actual markets.[39]
- A methodological issue: Valuation results are often very dependent on functional forms and other elements of statistical analysis methods applied.
- A representativeness issue: The available case studies are not statistically representative for the world population as a whole.

We therefore do not recommend valuing carbon sequestration as an ecosystem service with approaches based on individual preference studies, particularly not in the SEEA context.

Recommendation for monetary valuations in the SEEA context

- Based on the discussions above, we recommend using ETS prices where they are available, and in countries with an ETS we recommend using these ETS prices also as "best available estimates" for those sectors which are not covered by the respective ETS. In countries without an ETS, the certificate prices of Clean Development Mechanism and/or Joint Implementation projects appear as most compatible approximations. Less preferably, abatement cost estimates could be utilized as an alternative for these cases. Taxes, prices of Voluntary Emission Reduction certificates and consumer preference studies seem unsuited for the SEEA context.
- Estimates of the Social Cost of Carbon based on damage costs would have to be interpreted differently from exchange values based on ETS prices. However, an alternative calculation based at a single "universal" SCC estimate can be easily provided, as this requires just a multiplication of a physical value with a constant. It might therefore seem sensible to complement ETS based carbon valuations by an additional valuation based at a (global) SCC estimate (As a sensitivity analysis). However, valuing carbon sequestration in the SEEA context solely by damage cost estimates would appear unreliable, as the approach yields only imprecise results and thus is very susceptible to manipulation.
- When an approach based at long-time forecasts is chosen (like e.g. an SCC estimate, or an abatement cost estimate using Integrated Assessment Modeling), it is important to be consistent with other valuation methods, in particular when it comes to the choice of discount rate and rates of return. Worded differently, using an SCC estimate, likely places restrictions on what discount rates and rates of return can be used in other NPV / resource rent calculations (or vice versa). It would important to choose a best estimate (e.g. median or mean) outcome from an existing IAM model that is aligned with accounting conventions (e.g. excluding human health costs) such as the DICE model, with its focus on lost production.

[39] Moreover, many of the available case studies have valued abatement policies (rather than carbon per se), so that results may have been influenced by elements of these policies, too.

5 Accounting treatments – the role of carbon emissions

So far we have only looked at carbon sequestration as a service being provided by ecosystems to humanity, the supply side. It is important however to also consider the use side of the service being provided. Indeed, due to the transaction based nature of the accounting system (supply equals use), as soon as we consider something an ecosystem service, it is important to think about the user(s) of the service, or how the service would be recorded in an accounting setting.

One option would be to simply record the service as being used by households, or as being exported – stressing the global nature of carbon. However, it may be worthwhile to make a connection with air emissions being generated by economic activity, for the following reasons:

1. There may be issues of double counting here as degradation costs (for instance in earlier applications of SEEA and in corporate sustainability reporting) are often also assigned based on a valuation of tC;
2. The understanding of carbon sequestration and/or storage is inherently linked to the development of the concentration of GHG emissions in the atmosphere, which are directly linked to carbon emissions. This was also made explicit in the definitions of NCP and MEA.

5.1 Recording of the use of sequestration

Table 2: Recording of carbon sequestration

	Ecosystem	Isic A	Inv.	Hh cons.	Total
Supply					
Sequestration	10				10
Product X		200			200
Use					
Sequestration		10			10
Product X				200	200
Value added (gross)	10	190			**200**
degradation (CNC)					
Value added (net)	10	190		**200**	

Making a connection with the industries causing emissions has a lot of potential in terms of providing a generic solution. Suppose we have a very simple imaginary economy in which a single industry produced a product (valued 200) which is consumed by households. The value added of this economy is hence 200. We see in Table 2 that supply equals use of the product, we also see that the sum of value added (in this case consisting of the single producing sector) equals the sum of final demand equals the total income generated (all 3 being 200), reflecting the basic structure of the SNA. Suppose now also that this economy has air emissions of 10 (due to soil fossil fuels being burned), with exactly the same amount being sequestered (as defined earlier – i.e. as NECB).

Following the TR's recommendations for extended supply – use tables we have however added an additional sector "ecosystems". We can now impute an ecosystem a service flow between the ecosystem (as supplier) and the industry responsible for emitting (as user). As we see in Table 2, this has no effect on the total value added of our economy (which remains 200), but it now recognizes two sectors (the ecosystem and the producing industry) as generating the value added. This recording treatment has made the contribution of the ecosystem to the economy visible.

It has the effect of suppressing the value added of the industry causing the emissions (e.g. polluter pays principle). The reduction in value added could be compensated in the distribution of income accounts, ensuring that net income remains equal (and of course ecosystems usually do not have bank accounts).

5.2 Degradation

Now, to continue our hypothetical example, suppose that we have a situation in which 20 tons of carbon are being emitted, of which only 10 tons are being sequestered. This results in the CO2 concentration to increase. How should we treat this in an accounting sense?

Table 3: Recording of carbon sequestration and degradation

	Ecosystem	Isic A	Inv.	Hh cons.	Total
Supply					
Ecosystem service A	10				10
Product X		200			200
Use					
Ecosystem service A		10			10
Product X				200	200
Value added (gross)	10	190			200
degradation (CNC)		10			
Value added (net)	10	180		**190**	

In this situation, it makes sense to again impute the same sequestration flow (as in situation 1), but what to do with the additional emissions? It seems logical to record this as a degradation cost (a consumption of natural capital) charged to the industry causing the emissions. The degradation cost would be set equal to the additional 10 tons not being sequestered (we keep the intermediate consumption of 10 tC as above).

The effect this would have is that the total output (and GVA) of the economy would be the same, but net value added would be reduced, with the amount of the degradation that has taken place during the accounting period. The intuitive appeal of the proposal is that it would be aligned with seeing degradation as occurring when there are actual changes in the condition of an asset (in this case of the atmosphere as an asset due to increased CO2 concentration). This degradation costs could be recorded in the capital account as giving rise to an environmental liability. So far we have only discussed a single country, but the treatment can easily be generalized to a multi-country setting. Countries would be recording degradation costs for those emissions that they cannot sequester within their own borders (see Table 2).

So, what would happen in case emissions are less then sequestration taking place? In this case the total amount of sequestration would be seen as output of ES, part would be intermediately consumed by economic activities responsible for the emissions. The remainder would be treated as an investment reducing the environmental liability of the country in question.[40]

It becomes clear that degradation costs are only assigned when emissions go over and above amounts actually being sequestered. In case of natural (i.e. non man-made) disasters such as forest fires, the additional emissions would be recorded as increasing the environmental liability of the country in question. In case a plantation were to deforest a certain stretch of land, the resulting additional emissions would be charged as costs.

Recommendation:

- Recording the use of sequestration service in relation to the air emissions generated allows a treatment of degradation that is intuitive; emitters use imputed ES that they intermediately consume, hence reducing their net value added and income, providing an appropriate signal about their economic contribution;
- We only record degradation when there is an actual adverse change in condition of an underlying asset (in this case increased concentrations in the atmosphere).
- Finally, it allows for a consistent treatment of allocating responsibilities (internationally) for built up degradation in the form of registering an environmental liability (or environmental debt), that will be reduced by investment when sequestration is higher than emissions.

5.3 Boundary issues

While these examples may provide generic solutions for recording of carbon sequestration, there are a couple of boundary issues to consider, that may require more discussion.

- Short-lived biomass (e.g. energy crops / wood); as our proposal is to align carbon sequestration with IPCC definitions where it leads to long term storage, in situations in which short-lived biomass is used say for energy an inconsistency may arise with the air emission accounts.
- In situations in which NECB is negative (e.g. in case of emissions due to soil respiration), these emissions would be recorded in the air emission accounts. It seems desirable in case total emissions exceed the actual sequestration within a country's borders to apportion the degradation costs proportionally (e.g. based on output). This requires however to have separate estimates about soil respiration. Recording these as separate flows has the advantage that it provides additional insight that may be of great policy relevance (e.g. emissions from peatland ecosystems that could be reduced by changing water drainage regime). Likewise, it is recommended (in case this is possible) to have separate estimates (ideally, in the form of maps), of the different metrics NPP and soil respiration, for instance in case there are net emissions (e.g. soil subsidence).

[40] The treatment of an export seems less practical.

- HWP (harvested crop and wood products) are treated separately (after being removed from the ecosystems) as a carbon pool within the IPCC guidelines. The alignment with IPCC definitions implies that sequestration in an ecosystem would be net of harvest of wood products. As discussed in section 5, this is not ideal in case connections are made with air emission accounts. Suppose 40 ton are taken up from the atmosphere each year (by growth of biomass), 40 tons are emitted each year (say by burning coal), but that 40 is also harvested in the form of timber used for housing. The NECB measure would record 0 sequestration in this case, while we do have air emissions. It may seem desirable to add the carbon stored in HWP as being sequestered (and hence intermediate consumed by emitting industries).

It seems some additional flows (that may be described specifically e.g. as energy crops sequestration or HWP sequestration) may be useful to add to the system.

6 Annex – key issues raised during discussion with author responses

Presentation:
-A key issue of importance, given that both CICES and other frameworks question this, is whether carbon sequestration should be considered as a (final) ecosystem service, rather than a process.

The argument (that in part was in the paper) is as follows:
-CS is a final service because consumers demand it. Demand in an economic sense does only exist if there is scarcity, i.e. since CS has stopped being a free good. Whether something is a free good or not is not a property of the good, but rather an issue of the people demanding it. CS may have been a free good in the past, but today this is obviously no longer the case. If it was, we would not have any kind of carbon markets, no policy regulations, etc.
-A necessary condition in order for an ecosystem service to be considered “final” as mentioned in the meeting was that there should be a clear policy. This is obviously the case for carbon sequestration;
-NPP will always happen (regardless of us human beings)-> it is only by our emission (enabling factor) that CS as a service can exist-> important to link to emissions;
-Suppose we would be in 1750 – pre-industrial revolution – NPP would take place, but we would not consider this as providing an ecosystem service, because there was at that point in time no climate change problem. In other words, in order for a service to be considered a service there needs to be scarcity.
-This scarcity is arising due to carbon emissions. This implies that the transaction i.e. the demand for the service should be linked to emitters.

The following key issues was raised during the discussion, with responses from the authors.

- Important to link the accounting to IPCC, at least to do a cross walk.

This was indeed the point of departure of the paper

- There was general support for the position that we only need to record a single service and not two (with one or two exceptions). Terminology – agree technically has to be called carbon sequestration, but those who use carbon storage may mean the same thing

Valid point – this is however mostly a semantical issue, as the WG supported that there should be only one carbon related service that we need to measure, and that it is a flow (not a stock). Alternatives would be to label the service "carbon sequestration and storage".

- Problem of logic chain – on the left side, carbon stored should not be considered as an asset.

Agree - the left side of the logic chain has been corrected, this was a language issue.

- In case of non-SNA benefits, the benefit and the service should be the same. Removing carbon and reducing concentration are the same thing.

Whether the service and the benefit should be the same for non-SNA services is a fundamental issue that cuts across many ecosystem services. The advantage would be that we would not need to record two different types of transactions (one for services and one for benefits – with separate valuations). Regardless of how this will be eventually resolved, this would not have major implications for the recommendations of the paper itself.

The revised logic chain is in the Annex. The revised chain also makes clear that a stable climate should be assessed at the level of well-being.

- Regarding the proposal to attribute the use of carbon sequestration to the polluters. This seems counterintuitive, as the main beneficiaries is society as large, who is benefiting from a stable climate. In the Dutch SUT, therefore carbon sequestration was allocated to the government sector.
- Question to whom to allocate resembles the discussion of allocation to consumers or producers (as in carbon footprint accounting). Also akin to the discussions on water quality amelioration service (e.g. purchase of remediation service)
- Good to have more clarity of sequestration, but the issue of emissions should be considered as well. Have to bring emissions into the picture in order to have a complete carbon accounting and communicate to audience

While something can be said for recording the service as going to government consumption (and potentially to exports in case more carbon is sequestered then emitted), there are also clear advantages to record this as intermediate consumption by emitters.
-the emitters are responsible for the existence of the scarcity and therefore (as argued above) for the fact that we conceive of carbon sequestration as a service (and not a process).
-recording CS as service intermediately consumed, would follow the polluter pays principle, as it would suppress the value added of the activities concerned.

- Not clear what is being degraded (Atmosphere?) If this is the case, can we treat atmosphere as an asset?

Exactly, this point is perhaps not elaborated in full in the latest version of the paper (but it was in earlier drafts). We believe that a consistent and comprehensive treatment of both sequestration and emission /degradation can be obtained as follows:

-first of all, we introduce the atmosphere as an asset, that can be characterized by a condition, with CO2 concentration as one of the main indicators of this condition (could be also things like PM 2.5 concentration etc.).
-we wish to only record degradation costs, when there is a deterioration of the condition of the asset (i.e. when the CO2 concentration increases).
-it is clear that the proposed recording fulfils the latter criteria. Consider two situations:

1. *Energy use from coal / oil etc. leading to carbon emissions.*
    a. *If NECB > 0 recording is straightforward, we would record intermediate consumption of CS by the emitters. If emissions would be larger than NECB, we record degradation (as concentration in the atmosphere i.e. its condition would increase). If NECB = emissions, we would not record degradation costs, which is logical as there would be also no change in condition of the asset.*
2. *Energy from harvested timber.*
    a. *If NECB > 0, CS is recorded*
    b. *If NECB = 0 (i.e what is being harvested is sequestered) -> there will be no CS recorded (and no degradation costs). There will be CO2 emissions recorded in the air emission account, but the implication would be that they would have a 0 price.*
3. *(net) Emissions from land clearing (AFOLU) -> NECB < 0 recorded as degradation costs for the sector causing the land clearing.*

- Emissions (from energy use, but also from LULUCF are clearly a disservice. Not accounting for them is a problem, but it is also not necessarily clear how to deal with these in the context of ecosystem accounting.

See above, our proposals are able to accommodate disservices / degradation costs.

- Netting off of Harvested Wood Products is problematic. This has little to do with ecosystem services.

Agree that this is not ideal, as HWP usually would not lead to emissions. This is however necessary if we want to remain consistent with the IPCC guidelines. At minimum we would like to recommend however that HWP are described in the carbon account as a distinct carbon pool.

- Timing of the benefit. Is there a problem with lagged benefits? If carbon sequestration is happening in this period, should the benefit also happen in this year? If not happen in this year, this could mean that there is no transaction.

No, this is not a problem for accounting per se, as lagged benefits also occur in many other sections of the economy (think of the health sector). Indirect benefits don't need to occur at the transaction time point or within the same period.

- Is there is a threshold on carbon sequestration to hit in order to have services?

This is a good question, as this relates to the notion of condition and reference state. In pre-industrial times, there was also NPP, but we would not want to have recorded it back then as a service as there was no scarcity. Perhaps the CO2 concentration in the pre-industrial situation (say 1750) could be used as reference level.

- It would be problematic if the accounts imply that plantation is sequestering more carbon than an old grove forest, as this would lead to old grove forests being converted.

In our proposal, conversion of an old grove forest would lead to negative NECB (assuming all else equal) and recorded as a degradation costs (according to polluter pays principle). This cost would be recorded in the accounting period in which the conversion takes place, so the recommendations do lead to proper policy implications. It is the case however, that after this period with degradation costs, it would likely be the case that NECB plantation > NEBC old grove forest.

- Avoiding degradation and deforestation (e.g. through REDD + schemes) is one of the main policies and carbon sequestration should be put in the context. Should the stored carbon not be rather treated as a liability (than an asset)?
- Raise a lot of issues of what is the ownership of asset.

This is an excellent point that requires more thought. REDD(+) schemes assume as a baseline that deforestation is taking place, and credits are generated when deforestation rates are slowed down or reversed. So compared to the situation described in the paper two features are equal, one feature is different. The 2 things which are equal are the unit considered [t CO2e], and the definitions and measurement rules used for determining the respective amounts (using NECB). What's different is the reference: In our approach (like elsewhere in this context) the reference/baseline is "zero emissions", that is, any positive amount of emissions will be counted as an emission, and any sequestration as the same thing but with the opposite sign. In contrast, under REDD the reference is each individual country's allowed baseline emission. In other words, this is merely a matter of the allocation of property rights, i.e. a distributive and political issue, not a matter for accounting; what matters for accounting is just the difference between the baseline and zero (i.e. a country's allowed amount of emissions).

One issue that needs to be further looked at is the following; those countries which finance REDD, have transferred a limited amount of emission rights to REDD receiving countries. This transfer has a monetary value and is recorded (like other financial transfers for development aid) in the national accounts. These transactions may need to be reclassified depending on the accounting treatment chosen for the SEEA EEA.

- Social cost of carbon, seems hardly related to ecosystems

This is another good reason why using SCC should not be used as preferred valuation method.

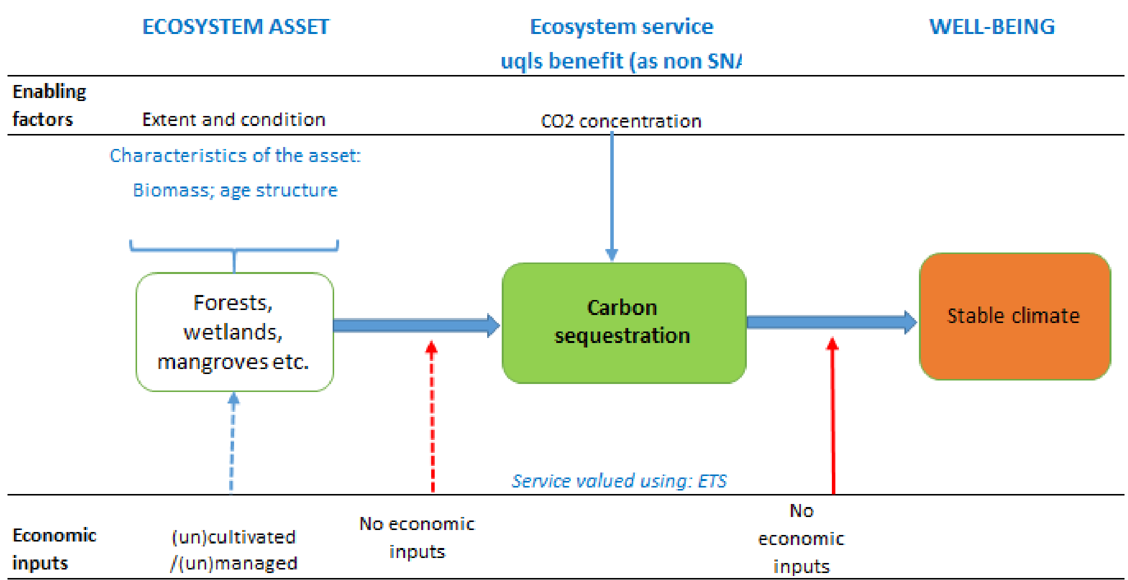
- Accounting only work in gross term, then do netting. If we start using net measure, may create issue for accounting system.

Agree that it would be preferable to record all physical flows in gross terms, but this may not be realistic for a large number of countries.

Other suggestions that were made are:

- Problem of the term “reduced”. Could use another term, lowering

- Duration of one year is too short to assess whether CS has taken place.
- Should allocate the emitters to other countries like US and China
- Mangroves – a lot of carbon stored there and there is opportunity to account for these
- Good to make accounting compatible to IPCC, more effort can be made about it.
- Treatment of abiotic is a bit problematic. It is not in the ecosystem climate and we got not control on that process.
- Valuation - Timber price – important thing to consider, given that carbon is one of the main components of timber. Payment cost – can also reflect the cost of carbon
- The EU JRC does not do explicit modelling of carbon sequestration, but rather uses proxies. It is important though to decide on what constitutes the actual flow of carbon sequestration.
- Fluxes should also be considered.



Notes NECB is proposed as key metric to assess carbon sequestration

Literature

Acharya, B.S.; Rasmussen, J.; Eriksen, J. (2012): Grassland carbon sequestration and emissions following cultivation in a mixed crop rotation. *Agriculture, Ecosystems & Environment* **153** (Supplement C), 33-39

Achtnicht, M. (2011): Do environmental benefits matter? Evidence from a choice experiment among house owners in Germany. *Ecological Economics* **70** (11), 2191-2200

Achtnicht, M. (2012): German car buyers' willingness to pay to reduce CO2 emissions. *Climatic Change* **113** (3), 679-697

Akujärvi, A.; Lehtonen, A.; Liski, J. (2016): Ecosystem services of boreal forests – Carbon budget mapping at high resolution. *Journal of Environmental Management* **181**, 498-514

Alberini, A.; Bigano, A.; Ščasný, M.; Zvěřinová, I. (2018): Preferences for Energy Efficiency vs. Renewables: What Is the Willingness to Pay to Reduce CO2 Emissions? *Ecological Economics* **144** (Supplement C), 171-185

Anthoff, D.; Tol, R.S.J. (2014): *The Climate Framework for Uncertainty, Negotiation and Distribution (FUND), Technical Description, Version 3.9*. http://www.fund-model.org/Fund-3-9-Scientific-Documentation.pdf. 26 pp.

Aubinet, M.; Moureaux, C.; Bodson, B.; Dufranne, D.; Heinesch, B.; Suleau, M., . . . Vilret, A. (2009): Carbon sequestration by a crop over a 4-year sugar beet/winter wheat/seed potato/winter wheat rotation cycle. *Agricultural and Forest Meteorology* **149** (3), 407-418

Babst, F.; Bouriaud, O.; Papale, D.; Gielen, B.; Janssens, I.A.; Nikinmaa, E., . . . Frank, D. (2014): Above-ground woody carbon sequestration measured from tree rings is coherent with net ecosystem productivity at five eddy-covariance sites. *New Phytologist* **201** (4), 1289-1303

Black, K.; Bolger, T.; Davis, P.; Nieuwenhuis, M.; Reidy, B.; Saiz, G., . . . Osborne, B. (2007): Inventory and eddy covariance-based estimates of annual carbon sequestration in a Sitka spruce (Picea sitchensis (Bong.) Carr.) forest ecosystem. *European Journal of Forest Research* **126** (2), 167-178

Braun, D.; Damm, A.; Paul-Limoges, E.; Revill, A.; Buchmann, N.; Petchey, O.L., . . . Schaepman, M.E. (2017): From instantaneous to continuous: Using imaging spectroscopy and in situ data to map two productivity-related ecosystem services. *Ecological indicators* **82**, 409-419

Brouwer, R.; Brander, L.; Van Beukering, P. (2008): “A convenient truth”: air travel passengers’ willingness to pay to offset their CO2 emissions. *Climatic Change* **90** (3), 299-313

Byrne, K.A.; Kiely, G.; Leahy, P. (2007): Carbon sequestration determined using farm scale carbon balance and eddy covariance. *Agriculture, ecosystems & environment* **121** (4), 357-364

Cline, W.R. (2011): *Carbon Abatement Costs and Climate Change Finance*. Washinton: Peterson Institute for International Economics. Policy Analyses in International Economics, 256 pp.

De Cara, S.; Jayet, P.-A. (2011): Marginal abatement costs of greenhouse gas emissions from European agriculture, cost effectiveness, and the EU non-ETS burden sharing agreement. *Ecological Economics* **70** (9), 1680-1690

DECC (ed.) (2009): *Carbon Valuation in UK Policy Appraisal: A Revised Approach*. Department of Energy and Climate Change, 128 pp.

Devaux, J. (2015): Unpaid ecological costs: initial attempts to estimate the increase in the ecological debt for the natural assets of "climate", "air" and "continental aquatic environments". *La Revue du CGDD* (December 2015), 85-92

Diaz, D.; Moore, F. (2017): Quantifying the economic risks of climate change. *Nature Climate Change* **7**, 774

Diederich, J.; Goeschl, T. (2014): Willingness to Pay for Voluntary Climate Action and Its Determinants: Field-Experimental Evidence. *Environmental and Resource Economics* **57** (3), 405-429

EU (2018): Regulation (EU) 2018/842 of the European Parliament and of the Council of 30 May 2018 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement and amending Regulation (EU) No 525/2013 [Verordnung (EU) 2018/842 des Europäischen Parlaments und des Rates vom 30. Mai 2018 zur Festlegung verbindlicher nationaler Jahresziele für die Reduzierung der Treibhausgasemissionen im Zeitraum 2021 bis 2030 als Beitrag zu Klimaschutzmaßnahmen zwecks Erfüllung der Verpflichtungen aus dem Übereinkommen von Paris sowie zur Änderung der Verordnung (EU) Nr. 525/2013]. *Official Journal of the European Union* **L 156/26 (19.6.2018)**, 26-42

Gielen, B.; De Vos, B.; Campioli, M.; Neirynck, J.; Papale, D.; Verstraeten, A., . . . Janssens, I.A. (2013): Biometric and eddy covariance-based assessment of decadal carbon sequestration of a temperate Scots pine forest. *Agricultural and Forest Meteorology* **174-175**, 135-143

Goldstein, A.; Gonzales, G.; Peters-Stanley, M. (2014): *State of the Forest Carbon Markets 2014: Turning over a New Leaf*. Washington DC: Ecosystem Marketplace. Forest Trends, 87 pp.

Govind, A.; Chen, J.M.; Bernier, P.; Margolis, H.; Guindon, L.; Beaudoin, A. (2011): Spatially distributed modeling of the long-term carbon balance of a boreal landscape. *Ecological Modelling* **222** (15), 2780-2795

Hackbarth, A.; Madlener, R. (2013): Consumer preferences for alternative fuel vehicles: A discrete choice analysis. *Transportation Research Part D: Transport and Environment* **25**, 5-17

Hackbarth, A.; Madlener, R. (2016): Willingness-to-pay for alternative fuel vehicle characteristics: A stated choice study for Germany. *Transportation Research Part A: Policy and Practice* **85**, 89-111

Hamrick, K.; Gallant, M. (2017a): *State of the Forest Carbon Markets 2017: Fertile Ground*. Washington DC: Ecosystem Marketplace. Forest Trends, 79 pp.

Hamrick, K.; Gallant, M. (2017b): *State of the Voluntary Carbon Markets 2017: Unlocking Potential*. Washington DC: Ecosystem Marketplace. 42 pp.

Hepburn, C.; Neuhoff, K.; Acworth, W.; Burtraw, D.; Jotzo, F. (2016): The economics of the EU ETS market stability reserve. *Journal of Environmental Economics and Management* **80**, 1-5

Hirst, D.; Keep, M. (2018): *Carbon Price Floor (CPF) and the price support mechanism*. House of Commons Library. Briefing Paper 05927, 25 pp.

Holm, T.; Latacz-Lohmann, U.; Loy, J.-P.; Schulz, N. (2015): Abschätzung der Zahlungsbereitschaft für CO_2-Einsparung – Ein Discrete-Choice-Experiment [Estimation of the Willingness to Pay for CO2 Savings – A Discrete Choice Experiment]. *German Journal of Agricultural Economics* **64** (2), 63-75

Hope, C. (2011): *The PAGE09 Integrated Assessment Model: A Technical Description*. University of Cambridge: Judge Business School. Working Paper Series 4/2011, 44 pp.

ICAP (ed.) (2018): *Emissions Trading Worldwide: Status Report 2018*. Berlin: International Carbon Action Partnership, 104 pp.

IWG (ed.) (2016): *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis - Under Executive Order 12866* -. Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, 35 pp.

Kesicki, F.; Ekins, P. (2012): Marginal abatement cost curves: a call for caution. *Climate Policy* **12** (2), 219-236

Kim, Y.S.; Latifah, S.; Afifi, M.; Mulligan, M.; Burk, S.; Fisher, L., . . . Jenness, J. (2018): Managing forests for global and local ecosystem services: A case study of carbon, water and livelihoods from eastern Indonesia. *Ecosystem Services* **31**, 153-168

Knohl, A.; Schulze, E.-D.; Kolle, O.; Buchmann, N. (2003): Large carbon uptake by an unmanaged 250-year-old deciduous forest in Central Germany. *Agricultural and Forest Meteorology* **118** (3-4), 151-167

Lengwenat, E. (2017): *Zahlungsbereitschaft für freiwillige CO_2-Kompensationen. Ein Experiment auf Messen und Veranstaltungen in Deutschland [Willingness to pay for voluntary carbon offsetting. An experiment at fairs and events in Germany]*. TU München: Fakultät für Wirtschaftswissenschaften/WDV Medien Verlag. Dissertation, 167 pp.

Löschel, A.; Sturm, B.; Vogt, C. (2013): The demand for climate protection—Empirical evidence from Germany. *Economics Letters* **118** (3), 415-418

McKinsey & Company (ed.) (2009): *Pathways to a Low-Carbon Economy. Version 2 of the Global Greenhouse Gas Abatement Cost Curve*. McKinsey & Company, 189 pp.

McKinsey & Company (ed.) (2010): *Impact of the financial crisis on carbon economics: Version 2.1 of the global greenhouse gas abatement cost curve*. McKinsey & Company, 12 pp.

Metcalf, G.E.; Stock, J.H. (2017): Integrated Assessment Models and the Social Cost of Carbon: A Review and Assessment of U.S. Experience. *Review of Environmental Economics and Policy* **11** (1), 80-99

Metz, B. (2007): Special report on carbon dioxide capture and storage. *http://www. ipcc. ch/pub/reports. htm*,

Mokondoko, P.; Manson, R.H.; Ricketts, T.H.; Geissert, D. (2018): Spatial analysis of ecosystem service relationships to improve targeting of payments for hydrological services. *PLoS ONE* **13** (2),

Nordhaus, W.D. (2017): *Scientific and Economic Background on DICE models*. URL: https://sites.google.com/site/williamdnordhaus/dice-rice (9.11.2018)

Peckham, S.D.; Gower, S.T.; Perry, C.H.; Wilson, B.T.; Stueve, K.M. (2013): Modeling harvest and biomass removal effects on the forest carbon balance of the Midwest, USA. *Environmental Science and Policy* **25**, 22-35

Penman, J.; Gytarsky, M.; Hiraishi, T.; Krug, T.; Kruger, D.; Pipatti, R., . . . Tanabe, K. (2003): Good practice guidance for land use, land-use change and forestry. *Good practice guidance for land use, land-use change and forestry.*,

Pindyck, R.S. (2017): The Use and Misuse of Models for Climate Policy. *Review of Environmental Economics and Policy* **11** (1), 100-114

Rajmis, S.; Barkmann, J.; Marggraf, R. (2009): User community preferences for climate change mitigation and adaptation measures around Hainich National Park, Germany. *Climate Research* **40** (1), 61-73

Remme, R.P.; Schröter, M.; Hein, L. (2014): Developing spatial biophysical accounting for multiple ecosystem services. *Ecosystem Services* **10**, 6-18

Rodriguez-Veiga, P.; Wheeler, J.; Louis, V.; Tansey, K.; Balzter, H. (2017): Quantifying forest biomass carbon stocks from space. *Current Forestry Reports* **3** (1), 1-18

Rose, S.; Turner, D.; Blanford, G.; Bistline, J.; de la Chestnaye, F.; Wilson, T. (2014): *Understanding the Social Cost of Carbon: A Technical Assessment*. Palo Alto, CA: Electric Power Research Institute. 184 pp.

Sahle, M.; Saito, O.; Fürst, C.; Yeshitela, K. (2018): Quantification and mapping of the supply of and demand for carbon storage and sequestration service in woody biomass and soil to mitigate climate change in the socio-ecological environment. *Science of the Total Environment* **624**, 342-354

Scandellari, F.; Caruso, G.; Liguori, G.; Meggio, F.; Palese Assunta, M.; Zanotelli, D., . . . Tagliavini, M. (2016): A survey of carbon sequestration potential of orchards and vineyards in Italy. *European Journal of Horticultural Science* **81** (2), 106-114

Schwirplies, C.; Dütschke, E.; Schleich, J.; Ziegler, A. (2017): *Consumers' willingness to offset their CO_2 emissions from travelling: A discrete choice analysis of framing and provider contributions*. Karlsruhe: Fraunhofer ISI. Working Paper Sustainability and Innovation S 05/2017, 38 pp.

Seidl, R.; Rammer, W.; Jäger, D.; Currie, W.S.; Lexer, M.J. (2007): Assessing trade-offs between carbon sequestration and timber production within a framework of multi-purpose forestry in Austria. *Forest Ecology and Management* **248** (1), 64-79

Senapati, N.; Chabbi, A.; Gastal, F.; Smith, P.; Mascher, N.; Loubet, B., . . . Naisse, C. (2014): Net carbon storage measured in a mowed and grazed temperate sown grassland shows potential for carbon sequestration under grazed system. *Carbon Management* **5** (2), 131-144

Soussana, J.-F.; Tallec, T.; Blanfort, V. (2010): Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. *Animal* **4** (3), 334-350

Stern, N. (ed.) (2007): *The Economics of Climate Change: The Stern Review*. Cambridge: University Press, 712 pp.

Stiglitz, J.E.; Stern, N.; Duan, M.; Edenhofer, O.; Giraud, G.; Heal, G., . . . Winkler, H. (eds.) (2017): *Report of the High-Level Commission on Carbon Prices*. Washington D.C.: World Bank, 61 pp.

Tol, R.S.J. (2018): *The impact of climate change and the social cost of carbon*. University of Sussex: Department of Economics. Working Paper Series 13-2018, 22 pp.

Turner, D.P.; Guzy, M.; Lefsky, M.A.; Ritts, W.D.; Van Tuyl, S.; Law, B.E. (2004): Monitoring Forest Carbon Sequestration with Remote Sensing and Carbon Cycle Modeling. *Environmental Management* **33** (4),

Turner, D.P.; Ritts, W.D.; Kennedy, R.E.; Gray, A.N.; Yang, Z. (2015): Effects of harvest, fire, and pest/pathogen disturbances on the West Cascades ecoregion carbon balance. *Carbon Balance and Management*,

UBA (ed.) (2018): *Methodenkonvention 3.0 zur Schätzung von Umweltkosten (Methodische Grundlagen und Kostensätze)*. Dessau-Roßlau: Umweltbundesamt, 61 pp.

Uehleke, R. (2016): The role of question format for the support for national climate change mitigation policies in Germany and the determinants of WTP. *Energy Economics* **55**, 148-156

UNFCCC (1997): *Kyoto Protocol to the United Nations Framework Convention on Climate Change*. 23 pp.

UNFCCC (2015): *Paris Agreement (FCCC/CP/2015/10/Add.1)*. 16 pp.

Valatin, G. (2012): *Marginal abatement cost curves for UK forestry*. Edinburgh: Forestry Commission. Research Report, 16 pp.

Vermont, B.; De Cara, S. (2010): How costly is mitigation of non-CO_2 greenhouse gas emissions from agriculture?: A meta-analysis. *Ecological Economics* **69** (7), 1373-1386

Watanabe, M.D.B.; Ortega, E. (2011): Ecosystem services and biogeochemical cycles on a global scale: Valuation of water, carbon and nitrogen processes. *Environmental Science and Policy* **14** (6), 594-604

Weyant, J. (2017): Some Contributions of Integrated Assessment Models of Global Climate Change. *Review of Environmental Economics and Policy* **11** (1), 115-137

Wissenschaftliche Dienste (2018): *Sachstand: Aktuelle Klimaschutzziele auf internationaler, europäischer und nationaler Ebene - Nominale Ziele und Rechtsgrundlagen [Current climate protection targets at international, European and national level - nominal targets and legal basis]*. Deutscher Bundestag. WD 8 - 3000 - 009/18, 26 pp.

World Bank (ed.) (2015): *Purchasing Power Parities and the Real Size of World Economies: A Comprehensive Report of the 2011 International Comparison Program*. Washington D.C.: World Bank, 305 pp.

World Bank; Ecofys (eds.) (2018): *State and trends of carbon pricing 2018 (May)*. Washington D.C.: World Bank, 58 pp.

Zechter, R.H.; Kossoy, A.; Oppermann, K.; Ramstein, C.S.M.; Klein, N.; Wong, L., . . . Child, A. (2017): *State and trends of carbon pricing 2017 (English)*. Washington D.C.: World Bank Group. 100 pp.