The treatment of global climate regulation service in SEEA EA and its potential for informing climate policy

21 October - 2021

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1. Introduction

Climate change and biodiversity loss are the defining challenges of this era. Addressing these challenges requires global agreement on goals, targets, but also data to monitor progress and inform accompanying policies. The System of Environmental Economic Accounting (SEEA), a statistical measurement framework that integrates environmental and economic data, has been developed to generate such information.

The SEEA takes a systems approach to measure the environment and its relationship with the economy, represented by flow and stock accounts in physical and monetary terms. It consist of two complementary frameworks. The SEEA Central Framework (SEEA CF – UN et al. 2014) takes the economic perspective and measures how the economy uses the environment using a series of accounts such as physical flow accounts, that measure the extraction of natural resources, their use by economic activities and the return of residuals back to the environment; asset accounts that measure the stock and changes in stocks of natural resources and monetary accounts, that measure the size of the environmental industries, environmental protection activities or environmental taxes / subsidies. Together these accounts provide relevant information for assessing, drivers, impacts and policy responses regarding climate change (Pizarro 2020). The SEEA Ecosystem Accounting (SEEA EA – UN et al. 2021) was recently adopted by the UN Statistical Commission at its last session in March 2021.[2] It complements the SEEA CF by taking an ecosystems perspective in which it represents the environment spatially as mutually exclusive areas, ecosystems described by their extent, condition and the ecosystem services they provide. These ecosystems are considered assets in the SNA sense as they are a store of value in their function of generating sets of ecosystem services that benefit the economy and society.. These services can be measured in both physical and monetary terms. Further, and using standard valuation techniques that is the net present value of expected future returns for each ecosystem service supplied by an ecosystem asset can be used to measure the stock of natural capital as well as its degradation or enhancement over time.

Climate change is one of the thematic accounts discussed in Chapter 13 of the SEEA EA. Thematic accounts are constructed by combining relevant accounts from both the SEEA Central Framework and Ecosystem Accounts as well as the System of National Accounts to respond to specific policy demands. The use of accounting rules, boundaries and classifications that are coherent allow for the integration of

[1] Thanks are for Alessandra Alfieri and Carl Obst who reviewed an earlier version of this draft. The views expressed in this paper are those of the author and do not reflect those of the United Nations or its member states.

[2] Specifically, the conceptual framework and chapters dealing with accounts in physical terms – extent, condition and ecosystem services - (Chapters 1-7) were recognized as a statistical standard, while the chapters on valuation were recognized as "statistical principles and recommendations for the valuation of ecosystem services and assets in a context that is coherent with the concepts of System of National Accounts for countries which are undertaking valuation of ecosystem services and/or assets" (https://unstats.un.org/unsd/statcom/52nd-session/documents/decisions/Draft-Decisions-Final-5March2021.pdf)

different data (UN et al. forthcoming). Chapter 13 provides a general structure for accounts for climate change, however, further work is required to further articulate those connections with the IPCC measurement framework especially in light of the Paris Agreement, the Katowice Rulebook, and ongoing discussions on Nationally Determined Contributions' reporting templates leading up to Conference of the Parties (CoP) 26 in Glasgow.

An example of the potential use of SEEA EA to support climate change policy is the SEEA carbon stock account, which can support the reporting of emissions for the LULUCF sector, given that it is spatially explicit and computed for different ecosystem types.[3] In addition, the SEEA EA defines a list of ecosystem services, including global climate regulation, which is at the heart of climate policy. Further, because of its characteristic of integrating economic and environmental data the SEEA has the potential to inform policy instruments such as REDD (Reduced Emissions from Deforestation and Forest Degradation) schemes and emerging carbon market mechanisms under Article 6 of the Paris Agreement, as well as supporting discussion of the connections between climate change policies and those related to biodiversity and securing co-benefits from nature.

The objective of this paper is to further investigate the potential of ecosystem accounts to inform climate policies. The focus of the paper will lie on the SEEA EA (not the CF), specifically on the treatment of what the SEEA EA calls the "global climate regulation service". The SEEA EA provides a novel framing of the global climate regulation service by considering two components: sequestration and retention.

The outline of this paper is as follows. Section 2 provides some general context on the relevance of the SEEA CF and SEEA EA accounts to inform climate discussions. Section 3 discusses the background leading to the choice of global climate regulation service in the SEEA EA. Section 4 illustrates its measurement with a country application using the innovative tool, ARIES for SEEA Explorer, what is aligned with the SEEA EA. Section 5 then discusses possible policy implications, in particular regarding existing fiscal and monetary policy instruments such as emission permits, carbon taxes and REDD+ schemes. Section 6 discusses possible ramifications of the chosen approach for consideration of the atmosphere as an asset and Section 7 concludes with emphasizing the importance of ecosystem accounting in the context of the upcoming CoP 26 in light of its focus on Nature.

2. SEEA accounts and climate change

2.1 SEEA CF accounts

There are a number of SEEA CF accounts that provide relevant information for monitoring climate change policies: air emission accounts detail GHG emissions by economic activities; environmental protection expenditure accounts describe investments in mitigation technologies or adaptation costs; the environmental goods and services sector provide information of the magnitude of the environmental industry and in particular on the production of technologies that are environment friendly; and environmental taxes and subsidies accounts provide information on economic instruments having an environmental purpose or an environmentally damaging effect, for instance in the case of fossil fuel subsidies. The strength of the SEEA is that these accounts are fully integrated thus allowing for analyzing interlinkages and spillover effects of the economic instruments not only on the economy but also on the environment, thus allowing monitoring their performance in a broader sense. We focus in

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[3] The 2006 IPCC Guidelines have integrated the LULUCF (which stands for Land Use, Land-Use Change and Forestry) and Agriculture sectors, into the AFOLU sector (Agriculture, Forestry and Other Land Use). For the purposes of assessing linkages with SEEA, it is better to treat these two sections separately.

this section on the air emission accounts to illustrate the difference and similarities with the GHG emission inventories.

The differences and similarities between SEEA air emission accounts and GHG emission inventories are well understood (Eurostat 2015). Figure 1 illustrates in a schematic format the main differences. The SEEA CF essentially aligns information from emission inventories with standard economic data from the national accounts, using similar principles and classifications, in order to enrich its potential to inform economic policy. The integration with the national accounts facilitates analytical usage, for example, in the form of assessing emission intensities, calculating multipliers, carbon footprints, or performing structural decomposition analysis. Similar differences apply between the energy balances, which are used as input to the emission inventories, and energy accounts used as input in the air emission accounts.

Figure 1: Differences between air emission accounts and GHG emission inventories

Inventories	Accounts
Emissions are assigned to the country **where the emission takes place** ('territory' principle)	Emissions are assigned to the country **where the company or household causing the emission is based** ('resident' principle).
Emissions are assigned to **technical processes** (e.g. combustion in power plants, solvent use), according to main IPCC sectors: AFOLU, Energy (which includes Transport); Industrial Processes and Product Use (IPPU); Waste; Other	Emissions are classified by **economic activity** (using the NACE classification, as used in the system of national accounts). For example, emission from transport are allocated to the economic activity or households owning the vehicles.
Emissions from international **shipping and aviation** are not included in national totals. To ensure global completeness, these emissions should be reported separately (as p.m.)	Emissions from international **shipping and aviation** are included in national air emission accounts and assigned to the countries where the airline/shipping company is based, regardless of where the emission takes place.

Source: adapted from https://ec.europa.eu/eurostat/web/environment/air-emissions

Differences in the approaches are usually summarized in the form of bridge tables that allow one to go from the inventories to the accounts and vice versa[4]. Indicators from air emission accounts and GHG inventories are considered are both relevant and serve different policy purposes. For this reason, they are indicated as "dual indicators" in the UNECE set of core climate change related indicators (UNECE 2021). For example, the UNECE indicator set includes: 9a Total greenhouse gas emissions from the national economy, which is based on the SEEA and 9b Total greenhouse gas emissions from the national territory, which is based on emission inventories. There is considerable experience in a number of countries to compile both air emission accounts and GHG emission inventories, as well as in communicating the differences between the two approaches when releasing both figures.

2.2 SEEA EA accounts

In SEEA EA, the extent account provides the basic geospatial infrastructure that serves as a starting point for all the other ecosystem accounts in that it describes how various ecosystem types (e.g. tropical

[4] https://ec.europa.eu/eurostat/web/environment/air-emissions

forests or cropland) are distributed in the territory, a country, an administrative region, a river basin or any other spatial area. The SEEA EA uses the IUCN Global Ecosystem Typology (GET) as international reference classification and recommends reporting extent accounts at the level of Ecosystem Function Groups (EFGs). Generally, this level of reporting will have fewer classes than ideal for national level account compilation, it allows on balance for cross country comparisons. The extent account is commonly derived by overlaying various data layers, primarily land cover combined with additional layers such as elevation, temperature, aridity etc. The account provides the summary tabular information of underlying maps. As land cover is a key layer in deriving ecosystem extent, the extent account can in principle be linked to LULUCF categories (Forest land, Cropland, Grassland, Wetlands, Settlements and Other Land). Some countries have chosen to use their land cover map as proxy for ecosystem extent.

A second ecosystem account that is important in the context of informing climate change is the carbon account (see Table 1). The carbon account is a stock account in physical units that describes stocks and changes therein (due to carbon uptake and emissions) during the accounting period for the chosen accounting area (e.g. the country or province). Carbon accounts are systematically described in the SEEA EEA (Section 4.4) – which specified an accounting structure distinguishing between various carbon pools.[5] It is important to note here that the carbon account is comprehensive: all carbon stored (and changes) are recorded, regardless of whether the land is managed or not, and whether the emissions and other changes in stock are due to natural or human causes. The rows in Table 1 below detail possible additions and reductions in the stock.

Table 1: Carbon account structure (tonne CO2e)

	Geocarbon					Biocarbon			Carbon in the economy			Carbon in the oceans	Carbon in the atmosphere	Total
	Oil	Gas	Coal	Limestone and marl	Other	Terrestrial	Freshwaters and saline wetlands	Marine	Inventories	Fixed assets, consumer durables	Waste	Total	Total	
Opening stock														
Additions to stock														
Unmanaged expansion														
Managed expansion														
Discoveries														
Reclassifications														
Imports														
Reductions in stock														
Unmanaged contraction														
Managed contraction														
Reclassifications														
Exports														
Catastrophic losses														
Net carbon balance														
Closing Stock														

Source: SEEA EA (UN et al. 2021).

[5] Geocarbon (e.g,. stored in oil and gas), biocarbon (stored in various ecosystems), as well as accumulation in economy and atmosphere (see Australia (Ajani and Comisari 2014) and the Netherlands () for examples of comprehensive carbon accounts following these principles).

A third SEEA EA account that is relevant for climate change is the ecosystem services account, that describes which ecosystem services are supplied by \ecosystem types and used byeconomic units, including households\. The SEEA EA contains a reference list of 27 ecosystem services, including what is now described as "global climate regulation services" defined as:

> *"the ecosystem contributions to the regulation of the chemical composition of the atmosphere and oceans that affect global climate through the accumulation and retention of carbon and other GHG (e.g., methane) in ecosystems and the ability of ecosystems to remove carbon from the atmosphere."*

This definition is the result of a long discussion on the treatment of carbon related ecosystem services during the SEEA EA revision process, that is discussed in the next section.

A fourth account relevant for climate change is the ecosystem condition account, which allows to monitor changes arising from the impacts of climate change – e.g. loss of soil moisture in agriculture, changes in species diversity and abundance. Changes in condition may affect the generation of (future) ecosystem services (e.g. water supply) and thereby necessitate adaptation of economic activities.

3. The conceptual framing of carbon related services in an accounting context.

In the SEEA community, there has always been wide-spread agreement on the importance of measuring ecosystem services in physical units reflecting an actual contribution by ecosystems to people. For services related to crops, water and recreation this has been relatively straightforward. However, a contentious issue has been how to properly reflect carbon related ecosystem services in an (ecosystem) accounting system: as two separate services (sequestration and storage) or as a single service (and if so which one). In short, how to best describe and measure in non-monetary terms the contribution of ecosystems to people as it concerns mitigating the effects of climate change.

The dominant view in the ecosystem services literature (see the earlier issue paper on this topic by Edens et al. 2019) is to see ecosystems as providing a single "sequestration" ecosystem service (sometimes described as "climate regulation" as in the Millennium Ecosystem Assessment (MA 2005), or as "carbon sequestration and storage" in The Economics of Ecosystems and Biodiversity study (TEEB). In the most general terms, sequestration in those contexts can be defined as 'the process of increasing the carbon content of a carbon pool other than the atmosphere' (Penman et al. 2003) – so it contains both the element of uptake as well as storage. [6] Also important to note is that sequestration goes beyond the ecological process of primary productivity by which carbon is sequestered – and which is considered a functional characteristic of ecosystems described in the ecosystem condition account[7] .

[6] The 2006 IPCC Guidelines (IPCC 2006) speak about carbon emissions and removals (by sinks), or CO2 uptake. The guidelines do use the word sequestration a lot, but sequestration is defined in the Glossary as "the process of storing carbon in a carbon pool." There does not seem to be specific guidance on how long the carbon should be expected to remain stored.

[7] Various carbon-related processes take place in ecosystems, which can be summarized in the following equations. 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.

There is however an immediate problem with sequestration so defined that arises in an accounting context: what to record in situations of (net) carbon emissions for a specific carbon pool or ecosystem type? This is the case of peatlands that emit more than sequester due to soil subsidence or biomass harvest for energy generation. Accounting records transactions and the supply and use of negative amounts goes against basic accounting principles.

The solution to simply record a 0 service in case of net-emissions seems unsatisfactory as there is a clear physical flow (that is recorded in LULUCF inventories) and it would introduce an asymmetrical treatment.

An initial issues paper was drafted in early 2018 (Edens et al. 2018) to take stock of various carbon-related issues from an accounting perspective such as the definition of the service, its measurement, (monetary) valuation, and the recording of the service in accounts. This issues paper proposed to see the service as a single service - carbon sequestration - defined as the net uptake of carbon (Net Ecosystem Carbon Balance - NECB) by ecosystems. To address the issue of negative NECB for certain ecosystems, it proposed to record negative NECB as part of degradation costs. To make this work, the idea was (i) to introduce the atmosphere as an environmental asset, characterized by a condition, with CO2 concentration as one of the main indicators of this condition (its condition could also be described by additional variables such as PM 2.5 concentration etc.), and (ii) to record degradation costs if and only if there would be a deterioration of the physical condition of the asset (i.e. when the CO2 concentration increases), where the deterioration was allocated to the agent responsible for the emissions. For example, if there were CO2 emissions from burning fossil fuel but an equivalent net uptake by forests (so no net change in CO2 concentration of the atmosphere), the accounts would record an ecosystem service flow provided by forest[8], and no degradation costs. However if emissions were larger than the (net) uptake (during the accounting period), degradation costs would be recorded that could be charged to the emitter thereby reducing its net value added.

While this proposal allowed for a comprehensive recording of emissions and concurred with a "polluter pays perspective", this proposal was criticized for a number of reasons. First of all, for providing wrong policy incentives: e.g. replacing rainforest by faster growing bamboo would show as an increase in ecosystem services in the accounts. Second, by being poor accounting: e.g. it would lead to an asymmetrical treatment of a symmetrical physical process (net uptake as a service versus degradation costs in case of net emissions). More fundamentally, in line with the capital theory that underpins accounting in general, in order to introduce the atmosphere as an asset, one would first need to specify the capital services it provides.

Some experts involved in the discussions went back to the drawing board and discussed/developed a number of alternatives, among which two were discussed at greater length.

The first alternative was the idea to see the atmosphere as an asset providing a sink function/service for carbon emissions. The idea to see the environment as providing sink functions (in addition to resource functions) was prominent in the SEEA 2003. However, this approach would have major drawbacks. First of all, it would be counterintuitive in the sense that the higher the CO2 or PM 10 concentrations, the more valuable the atmosphere would become, and thus seemingly incentivizing pollution. This is a more

[8] The carbon sequestration flow could be recorded as intermediate consumption by the emitting economic activity or as final consumption by general government. In case of net uptake, the carbon sequestration flow could be recorded as an export.

generic issue with defining remediation services, that also arises when defining services such as water quality amelioration. Relatedly, how would one conceive of degradation / enhancement of the atmosphere? Second, it would not fit into the scope of ecosystem accounts (as the atmosphere is largely abiotic; nor is dilution an active process)..

The second alternative was what became known in the SEEA community as the carbon retention proposal. This approach conceives a service being provided by ecosystems in terms of avoiding the release of carbon i.e. retaining carbon. This proposal draws its inspiration from ecosystem services such as sediment retention, which measure the amount of sediment retained by vegetation, for instance by comparing soil erosion rates of current vegetation type with erosion rate of barren land.

In its simplest form, the carbon retention proposal is to (i) estimate carbon stocks in ecosystem assets, (ii) multiply this by a suitable carbon price, and (iii) turn this into an annual service flow by multiplying this value by a suitable rate of return (to create an annuity). Figure 1 provides a basic illustration of the idea, for a discount rate of 5%, an opening stock for the accounting period t0 (say the year 2020) of 10 tons of carbon stored in the ecosystem and an assumed price of 1$/tC. This results in a carbon retention service flow of 10*1*0.05 = 0.50 $ in t0. Likewise, assuming the carbon stored increases during the accounting period to 11 tons, we would find a retention service flow in the next period of 0.55 $.

Table 2: Illustration of carbon retention service

5%		t0	t1
	Stock (tC)	10	11
	Price	1	1
	Retention	0.50	0.55
present value		$9.92	
present value		$10.92	
		$1.0	

The retention approach recognizes that the retained carbon stocks provide a benefit, namely of avoided damages. So, in physical terms, the amount stored is a “proxy” for the service flow provided; in monetary units, the service flow is the annual annuity, with higher (lower) annuity flows reflecting higher (lower) levels of ecosystem service provision.

To give an example, suppose we have a forest that is being logged for timber, and as a result it has (net) declining carbon stocks between periods t1 and t2. In the accounts we would then record the following transactions / flows:

1) the carbon retention service - which is lower in t2 compared to t1 as the carbon stock declines (and hence the level of the annual annuity / return).
2) a timber provisioning service in the period the logging takes place.
3) in the asset account, we record a degradation cost equal to the change in NPV of (future) carbon retention services. In its simplest form, this would be the total reduction in stored carbon times carbon price. In a more complex / dynamic model, one could take into account the expected future carbon stored that will change due to different regrowth pattern.

A nice property of the retention framing is that where sequestration leads to permanent storage (shown in Table 2 as the stock going from 10 to 11 and assuming no further changes), the change in present value is also 1 i.e. equal to what one would record using a basic sequestration approach. However, in the carbon retention framing, such a sequestration event leading to permanent storage would be recorded as ecosystem enhancement (in the monetary ecosystem asset account), not as sequestration.

The appeal of the retention framing is that it provides the 'right' signals to policy makers;

- if an ecosystem loses carbon, we have lower retention services;
- ecosystems with high carbon stocks (e.g. tropical rainforests) would get high retention values (even though oftentimes they have low sequestration - as they are in equilibrium / old growth); sending the signal that they are worth conserving;
- the accounts would not incentivize say replacing rainforest with fast growing bamboo.
- the focus on storage aligns well with REDD+ schemes (as discussed later);

During the various consultations on SEEA EA it became apparent that while the retention framing had broad support, it also had some limitations. First, it was not clear whether all carbon stored should be included in the retention service – it was argued that only those stocks which are at risk of release should be included.[9] Second, while there are policies focused on retention, there are also policies and technologies focused on carbon sequestration (e.g. carbon capture and storage; or the possibility of carbon farming).

In the end the compromise solution found in the SEEA EA was to consider global climate regulation as a single service, consisting of two components: sequestration and storage. An analogy can also be drawn with "warehousing" (as described by ISIC 51) in the national accounts (Edens et al. 2019) by distinguishing two elements: 1) entering into storage (sequestration) and 2) keeping it stored (retention). The SEEA EA states:

> *"In principle, carbon retention and carbon sequestration components should be measured for all ecosystem assets. In practice, it is likely that different ecosystem assets will provide different contexts for measurement. In stable ecosystems, carbon retention will be the primary component while in those ecosystems where there is clear expansion in the stock of carbon, then carbon sequestration may be the focus of measurement. Of high relevance will be ecosystems whose stock of carbon is at risk of emission, for example due to land use practices (e.g., draining of peatlands, deforestation) or extreme events (e.g., fires). In these cases there may be little carbon sequestration and the focus of measurement should be placed on measuring carbon retention."*[10]

The SEEA EA (6.112-6.113) specifies a few measurement boundaries when it comes to carbon retention:
-stocks are limited to carbon stored in above ground and below ground (including seabed) living and dead biomass in all ecosystems and soil organic carbon.
- in the case of peatlands and relevant organic carbon rich soils, only the carbon stored to a maximum of 2 meters below the surface should be included.
- inorganic carbon stored in freshwater, marine and subterranean ecosystems is excluded from scope.
- carbon stored in fossil fuel deposits should not be considered an ecosystem service
- storage of carbon in harvested wood products should not be considered an ecosystem service

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[9] The retention framing is similar to the way other regulating services are conceived. For example, sediment retention, is usually estimated based on a comparison between the amount of soil erosion occurring in the current state with a counterfactual scenario of bare soil i.e. the absence of vegetation.

[10].

- carbon stored in stocks of cultivated biological resources (e.g., crops, livestock) should not be included in the measurement of carbon retention due to its short rotation cycle.

Regarding carbon sequestration, the SEEA EA specifies (6.114):
-The net ecosystem carbon balance (NECB) to be an appropriate metric;[11]
-In case NECB is zero or negative, the level of service supplied by an ecosystem will be zero.

The SEEA EA also clarifies that in situations where carbon stocks for an ecosystem asset are declining, the sequestration component of the service is zero, and we are only measuring retention. It is the author's view that in situations of net increases in carbon, there is a risk of double counting. Some have argued that double counting can be avoided when only using opening stocks to assess the retention component (see INEGI (2021) for such an application). Another point of view would be to argue that as the risk of release of carbon in such management contexts is low, the retention price would effectively be 0. These issues will be further addressed in the development of guidelines. Measurement guidelines will also need to further detail the precise scope of carbon pools (e.g. maximum depth; treatment of short-cyclic carbon).

3.3 Monetary valuation

The SEEA EA states the following when it comes to valuation (Para 9.31):

> *"A specific market concerns observed prices from emission trading systems which may be used to estimate prices for global climate regulation services. The number of countries with such trading systems is increasing, as is the quantity of carbon being traded and hence these markets may provide suitable price data. If the trading system is not considered sufficiently mature, an alternative is to use data on the marginal costs of abatement, which is more widely available, or data on the social cost of carbon when derived from models that are consistent with the exchange value concept, i.e. limited to an assessment of the effects on measures of output."*

It is emphasized, in line with SNA principles, that prices should be economically significant, and therefore one should take into account the depth and maturity when using prices from carbon markets. A possibility here would be to compare the price in relevant markets with prices commonly considered to be required to meet the "well below 2°C" goal to assess the significance test. According to World Bank Carbon Price Report (World Bank 2021) "Experts say prices of USD 40-80/tCO2e are needed to meet the 2°C goal.".

The same World Bank report notes that "A majority of carbon prices still remain far below the USD 40–80/tCO2e range needed in 2020 to meet the 2°C temperature goal of the Paris Agreement24 — only 3.76% of global emissions are covered by a carbon price at and above this range".

The SEEA EA approach opens up for using different prices for the two main components, retention and sequestration, although further discussion on this topic is required. This would be because sequestration and storage require different processes with different opportunity costs regulated in different markets.

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[11] It is important to also provide further guidance whether at what scale NECB should be assessed: at the level of individual ecosystem assets or at the level of ecosystem types or carbon pools.

Finally, it would be advisable to compare monetary valuation using different assumptions. This would allow to compare existing markets with for instance the social coat of carbon (SCC), which by itself may provide relevant information about the efficiency of markets. In case of the use of SCC, it is common to model these as increasing over time, showing the expected increasing importance of the benefits of avoiding emissions increases.

4. Example

The ARIES for SEEA Explorer, developed by researchers at the Basque Centre for Climate Change (BC3), is an integrated, open-source modelling platform for environmental sustainability.[12] ARIES stands for Artificial Intelligence for Environment and Sustainability. The Explorer allows to compile a basic set of ecosystem accounts (land cover; ecosystem extent; forest condition; selected ecosystem services) for any area in the world for a chosen accounting period using global data sets and default models.[13] ARIES applies machine reasoning to generate the "most appropriate" data and model for the specified user request (area + accounting period). ARIES has also functionalities for expert users to upload national data and customize models.

With ARIES it is possible to calculate a basic carbon stock account and thereby obtain values for the climate regulation ecosystem service anywhere on Earth in a matter of minutes. Table 1 shows the result for Senegal (from 1995-2015) for carbon stored (physical units), broken down by ecosystem type.

Table 3: Carbon storage in Senegal by ecosystem type (1995, 2015)

Million tons carbon	Intertidal forest shrubland	Coastal saltmarsh reedbed	Cropland	Urban industrial ecosystem	Tropical subtropical savanna	Seasonally dry tropical shrubland	Rocky pavement lavaflow scree	Tropical subtropical lowland rainforest	Tropical subtropical dry forest thicket	Other desert semidesert	Episodic arid floodplain	Tropical flooded forest peat forest	**Total**
Quantity at start of 1995 (tons C storage)	106	32	703	4	11	759	1	2	598	383	37	4	2,640
Quantity at start of 2015 (tons C storage)	106	33	714	7	11	710	0	1	651	377	37	4	2,652
Net change	**0**	**1**	**11**	**3**	**0**	**-49**	**0**	**-1**	**53**	**-6**	**0**	**0**	**12**

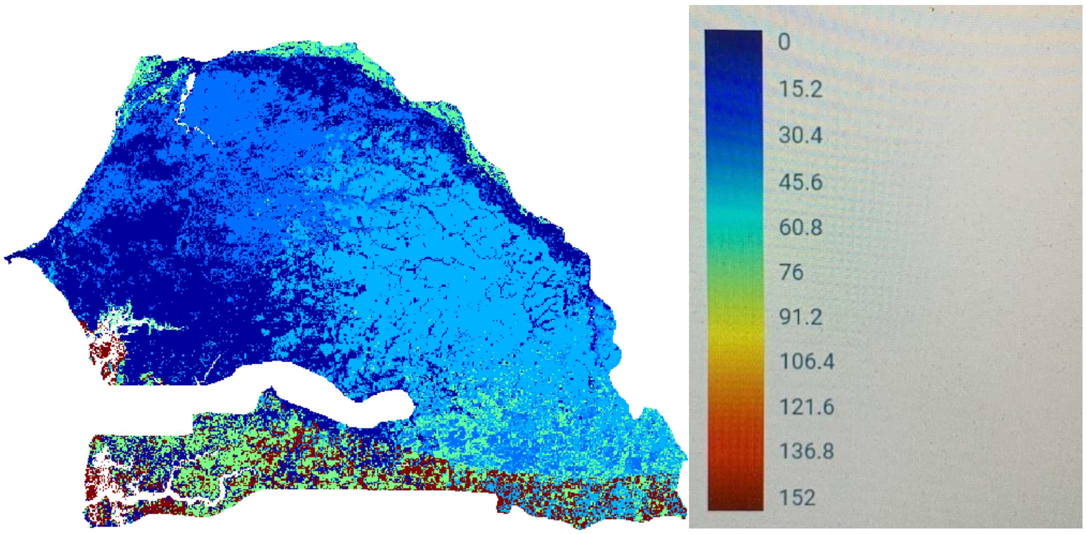
Hereto, Aries uses a Tier 1 IPCC approach: Aboveground & belowground vegetation carbon storage is quantified using a multilayer lookup table, based on the approach from Ruesch and Gibbs (2008). The key global data sets it uses are: land cover, eco-floristic region (FAO classification), continent, presence

[12] https://seea.un.org/content/aries-for-seea

[13] As land cover is such an important layer for virtually any ecosystem model, it is advisable to choose 1992 as earliest year due to the availability of a proper map with global coverage from that date onwards (the ESA-CCI at 300 meters resolution).

of frontier forests (proxy for forest degradation), recent occurrence of fires, and soil carbon storage. Key outputs of the model are estimated carbon stored in aboveground & belowground biomass, plus the upper 2 m of soil. The resulting estimates of carbon storage are presented by ecosystem types used in the ecosystem extent account, based on level 3 of the IUCN Global Ecosystem Typology, recommended by the SEEA EA.

Figure 2: Carbon stored in vegetation (aboveground and belowground biomass) (tons per hectare)



Source: output of ARIES for SEEA (Senegal, 2015)e

The carbon stock account can be used to estimate both the sequestration and the retention component. The sequestration component can be estimated by looking at those ecosystem types that have a NECB > 0. Carbon retention can be estimated by using opening stocks of carbon. The basic valuation of retention used in ARIES for SEEA is to use a value of 33.70 USD / tCO_2 as social cost of carbon (SCC) for 2015 (which is 124 USD tC) based on Nordhaus (2017). Social cost of carbon essentially represent the net present value of future costs calculated for long time horizons. The ARIES model annualizes these costs (following Turpie et al. 2021) based on a 3.66 percent discount rate (Kotchen et al. 2019) and a 100 year time horizon. The SCC is assumed to increase at 3% per year, so the retention service value will change not just with quantity stored but also with changes in price.

In the case of Senegal, we would obtain a value of carbon retention of 11,1 billion USD which is more than 60% of its GDP. Applying for instance a market price for carbon credits of 25 tCO_2, we would find an average annual value of sequestration of 310 million USD, which would be equivalent to 2% of GDP.

There is however large variation across countries: in case of the US we would find a much lower retention value (as % of GDP) of 4% and sequestration value of 0.05%. In case of the Netherlands, we find a retention value of about 2% of GDP. It is clear these results are dependent on the scope of carbon stocks included in the model.

5. Policy linkages

This section provides a preliminary analysis of how the various ecosystem accounts generate information that can inform several climate change policies such as NDCs, REDD+, and carbon markets.

5.1 NDC / Monitoring of GHG emissions

The focus of the UNFCCC (which has not changed by the Kyoto Protocol or the Paris Agreement) is on measuring "anthropogenic emissions by sources and removals by sinks in accordance with methodologies and common metrics assessed by the Intergovernmental Panel on Climate Change [of all greenhouse gases not controlled by the Montreal Protocol]." (Paris Agreement).
The Katowice rulebook (adopted by CoP 24) states that "All Parties shall use the same calculation methodologies based on the 2006 IPCC guidelines" and calls for a new transparency system

The SEEA CF air emission accounts, as discussed in Section 2, make adjustments for the residence principle (e.g. for international transport and tourism) as well as for short-cycle CO2 emissions which are included in the air emission accounts but excluded in emission inventories (biomass emissions are a memo item not included in national totals (Eurostat 2015 handbook). Apart from those adjustments, they essentially include all IPCC sectors[14], but not LULUCF as "emissions from natural processes such as unintended forest and grassland fires and human metabolic processes which are not the direct result of economic production are excluded" (SEEA CF Para 3.243). Likewise, removals through LULUCF acting as sink are also not included in air emission accounts (SEEA CF Para 3.242[15]). However, as we have seen LULUCF emissions/removals can in principle be derived from carbon stock accounts, by selecting relevant row entries (additions and reductions).

As it is not always straightforward how to distinguish anthropogenic from natural emissions in the LULUCF sector, the IPCC guidelines allow for the use of the managed land proxy (MLP) (IPCC 2009).[16] Essentially, emission inventories need to first assess which lands are (un)managed, and then proxy the anthropogenic emissions by all emissions from managed lands. The SEEA EA carbon account is in principle comprehensive as all ecosystem assets within an accounting area are in scope (regardless of them being managed or unmanaged). So, the MLP is equal to the use of NECB from managed lands. This would imply that in the compilation of the carbon account by ecosystem type an additional (un)managed layer needs to be included to allow making this split.

As for the actual estimation of emissions from the LULUCF sector, the carbon accounts are in principle aligned with IPCC principles on accounting for emissions in the LULUCF sector, as both are based on a systematic approach (e.g. completeness; consistency; avoiding double counting[17]). The approach

[14] The IPCC Guidelines distinguish between 5 sectors: Energy; Industrial Processes and Product Use (IPPU); Agriculture, Forestry and Other Land Use (LULUCF); Waste; Other.

[15] "Air emission accounts also do not record the extent of the capture or embodiment of gases by the environment, for example carbon captured in forests and soil."

[16] "The main rationale for this approach is that the preponderance of anthropogenic effects occurs on managed lands. .. while local and short-term variability in emissions and removals due to natural causes can be substantial (e.g. emissions from fire), the natural 'background' of greenhouse gas emissions and removals by sinks tends to average out over time and space. This leaves greenhouse gas emissions from and removals from managed lands as the dominant result of human activity." (2006 IPCC Guidelines).

[17] "Parties shall account for their nationally determined contributions. In accounting for anthropogenic emissions and removals corresponding to their nationally determined contributions, Parties shall promote environmental

towards compiling ecosystem extent – by overlaying multiple data layers – is essentially the same as a stratification approach - dividing a heterogeneous landscape into distinct sub-sections (or strata) based on some common grouping factor - recommended by IPCC Guidelines (see GOFC-GOLD 2016) to estimate carbon stocks.[18] Together, the layers used in compiling an extent account can be used to compile what is called a Look-Up Table facilitating connections with databases with carbon emission factors of storage coefficients. That this is practically feasible was demonstrated by the country example in the previous section.

5.2 REDD(+)

REDD stands for reduced emissions from deforestation and degradation. The GOFC-GOLD (Global Observation of Forest and Land Cover Dynamics) sourcebook clarifies that REDD covers reduced deforestation and degradation, while REDD+ adds also forest enhancement, conservation and sustainable management in addition to deforestation and degradation. Warsaw 2013 adopted REDD+, but did not specify how carbon markets would be initiated.

Deforestation

Changes in ecosystem extent can be used to assess deforestation (or afforestation) in the ecosystem accounting area, at a detailed level of classes (the SEEA EA calls changes from one ecosystem type to another ecosystem conversions). These classes can also be aggregated towards the 6 IPCC classes for reporting purposes.

A difference may arise as the SEEA EA (based on the IUCN GET) provides a universal definition of forests, while the IPCC allows countries to apply their own forest definition, within certain specified parameters[19], as long as it is applied consistently. A more fundamental difference exists in case "a change in the forest cover [is] not followed by a change in use, such as for timber harvest with regeneration expected, the land remains in the forest classification." (GOFC-GOLD 2016). In other words, REDD+ (aligned with FAO forest definitions) takes land use/tenure into account in defining forests, which may result in differences with SEEA EA with its focus on ecosystem extent which is more closely aligned with land cover/vegetation class.

In most countries different agencies apply different definitions of ecosystems such as forests (or wetlands). The advantage of using accounts to generate information regarding deforestation is that the

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integrity, transparency, accuracy, completeness, comparability and consistency, and ensure the avoidance of double counting, in accordance with guidance adopted by the Conference of the Parties serving as the meeting of the Parties to this Agreement."

[18] GOFC-GOLD (2016, section 2.3.4.1) states: "Different carbon stocks exist in different forest types and ecoregions depending on physical factors (e.g., precipitation regime, temperature, soil type, topography), biological factors (tree species composition, stand age, stand density) and anthropogenic factors (disturbance history, logging intensity). For example, secondary forests have lower carbon stocks than mature forests and logged forests have lower carbon stocks than unlogged forests. Associating a given area of deforestation with a specific carbon stock that is relevant to the location that is deforested or degraded will result in more accurate and precise estimates of carbon losses."

[19] Minimum forest area: 0.05 to 1 ha. Potential to reach a minimum height at maturity in situ of 2-5 m
These parameters are: "1. Minimum forest area: 0.05 to 1 ha 2. Potential to reach a minimum height at maturity in situ of 2-5 3. Minimum tree crown cover (or equivalent stocking level): 10 to 30 %. With this definition a forest can contain anything from 10% to 100% tree cover; it is only when cover falls below the minimum crown cover as designated by a given country that land is classified as non-forest." (GOFC-GOLD 2016).

accounts have been compiled through an integration process confronting different data sources and through a consultative process settling on a commonly agreed measurement approach.

Degradation

Regarding forest degradation – the IPCC Guidelines define degradation as “a direct, human-induced, long-term loss (persisting for X years or more) of at least Y% of forest carbon stocks [and forest values] since time T and not qualifying as deforestation”. The GOFC-GOLD Sourcebook states that “In practice it is likely to be difficult to agree the values for X, Y and T and doing so has the disadvantage of introducing a possible incentive to degrade to just above the threshold values. Therefore, it is also possible that no specific definition is needed, and that any ”degradation of forest” will be reported simply as a net decrease of carbon stock.”

The SEEA EA defines ecosystem degradation as “the decrease in the value of an ecosystem asset over an accounting period that is associated with a decline in the condition of an ecosystem asset during that accounting period.” The condition of ecosystems is assessed based on a range of variables covering A1 Physical state; A2 Chemical state; B1 Compositional state; B2 Structural state; B3 Functional state; C1 Landscape / seascape. The condition variables cover a range of carbon related variables such as soil organic carbon content; dry matter productivity and forest area density.

Most important is that the SEEA EA makes a similar distinction as the IPCC guidelines between changes in extent (conversions in SEEA, afforestation/deforestation in IPCC) and changes in condition (degradation or enhancement). The carbon retention component defined in Section 3 would allow to obtain a valuation that could be used in market mechanisms for REDD+ (as still being discussed under Article 6 of the Paris Agreement)[20]. Applying the SEEA EA definition of degradation would have the advantage that it allows embedding this measurement in a broader perspective on ecosystem integrity that also takes wider issues such as biodiversity loss into account.

That said, a key theoretical issue to overcome alignment of SEEA EA with LULUCF / REDD+ is that where the boundary between degradation and deforestation lies, may differ due to the different focus on land cover/extent versus land use. That said, a lot of countries will compile ecosystem extent accounts using their own national classification / typology, so depending on data sources used in practice these differences may be small. This needs however further piloting at the country level.

When it comes to measurement, the IPCC distinguishes between two measurement approaches (gains-loss and stock-difference) that in theory results in the same estimate when it comes to changes in carbon. The carbon retention approach necessitates information on stocks themselves (since the level of the stock is a proxy for the level of the service) and therefore applies a stock-difference approach, which arguably has not been the focus of IPCC measurement.

5.3 Carbon markets

World Bank (2021) provides an overview of various types of carbon markets and mechanisms in place. It distinguishes between carbon tax, where the government determines the price and lets market forces determine emissions reductions, and two forms of emission trading systems: cap-and-trade and baseline-and-credit. A distinction is also made between regulated markets and mechanisms that create

[20] Currently there are various standards for carbon markets such as ..

tradable credits based on voluntarily implemented emission reduction or removal activities. Finally, distinctions are made between explicit and implicit carbon prices, as well as shadow carbon price.

The 2008 SNA and subsequent discussions ruled that emission permits should be treated as taxes, due to the absence of an underlying asset such as the atmosphere. From an environmental economics standpoint this is an unsatisfactory solution, as it implies very different policy instruments (carbon tax or ETS / cap and trade) receive a similar accounting treatment.

The SEEA – by extending the SNA production boundary to recognize ecosystems as producers of ecosystem services – makes these services visible, both in physical as well as monetary units. As discussed in section 3, prices from existing markets can be used to value these ecosystem services.

Integration with the SNA sequence of accounts is obtained as discussed in SEEA EA Chapter 11 (Para 11.55 and 56). The ownership of ecosystem assets is partitioned based on the users of different types of ecosystem services. When an ecosystem asset generates ecosystem services that contributes to SNA benefits (such as a provisioning service), that part of the value of the asset will be considered to be owned by the sector that uses that service. For instance, a farmer who is the economic (and/or legal) owner of his land. The ES is recorded as additional output supplied and used by the farmer thereby leaving aggregated such as value added intact. In case of ecosystem assets generating non-SNA benefits (such as global climate regulation services), that part of value of the ecosystem asset is assigned to a newly created subsector of general government sector called "ecosystem trustee". (Para 11.56) Ecosystem services such as global climate regulation are recorded as output of the trustee sector, consumed by general government.

In principle, there is therefore no need to reallocate existing SNA transactions related to carbon markets, the ecosystem services recording is complementary.

A key new policy proposed (in the EU but also beyond) is a so-called CABM or carbon border adjustment mechanism. Carbon footprint calculations using MRIO tables could provide relevant information to estimate such adjustments, although further research would be required, especially whether the product detail commonly found in footprint calculations would be sufficiently granular.

6. Atmosphere as an asset

The SEEA EA considers the bottom part of the troposphere i.e. the layer of the atmosphere directly above the earth as part of the ecosystem asset, as one of the abiotic components within the spatial unit. The main rationale being that various ecological processes such as sequestration and nitrogen fixation depend on the interaction with the atmosphere (Para 3.13-3.14). At the same time it is mentioned that the volume of air is not considered an environmental asset (Para 3.15).

The extended balance sheet which integrates the SNA and SEEA asset classification (Table 11.2) includes an entree for "atmospheric systems" under which the radio spectrum would fall as an *of which* item. At the same time (Para 11.45 and 11.46) the SEEA EA says: "*The scope of ecosystem assets excludes the atmosphere .. an alternative scope for an extended balance sheet that incorporates a wider range of ecosystem assets such as marine areas beyond the exclusive economic zone and the atmosphere could be compiled. Such accounts could recognise the important functions of these ecosystems, for example the role of the ozone layer.. in regulating global climate.*"

The treatment of the atmosphere is relegated to the SEEA research agenda. *"Further work is needed to articulate how the atmosphere and its functions may be appropriately characterised in accounting terms. This work should consider how the atmosphere might be partitioned into relevant spatial units; how the condition of the atmosphere might be assessed; whether there are ecosystem services provided by the atmosphere; and how transactions related to the atmosphere, for example transactions related to reducing greenhouse gas emissions, are most appropriately recorded. Research on this topic must link to related work in the context of the SEEA Central Framework and the SNA."*

It is the author's view that the atmosphere as a whole (or perhaps our climate system) should be considered an environmental asset, but arguably a different class of assets considering its public goods character, as well as the fact that it essentially sustains all life on earth. It is possible to measure this asset based on various services it provides (such as filtering of UV radiation by the ozone layer in the stratosphere, or burning of meteorites in the mesosphere, or through the strength of its jetstream), and its condition (think of air pollution). However, a potentially more practical framing for these assets which was explored in Issue paper 5.4 (Van de Ven et al. 2019) and mentioned in SEEA EA Chapter 13, is to introduce a concept of ecological debt / liabilities based on some of the ideas put forward initially by Andre Vanoli (2015).

Vanoli's proposal was to introduce a recording of "unpaid ecological costs", to account for all ecosystem degradation costs (essentially as overconsumption, leading to negative savings, and hence a liability). To avoid double counting, a variation of his proposal would be to differentiate between degradation costs to assets for which an economic owner can be identified (say a forest losing carbon) and which are described in the SEEA EA monetary asset account, and those degradation costs for which one cannot establish an economic owner. Examples of the latter concern the atmosphere and fisheries in the high seas[21]. Such degradation costs could be recorded as an "atmospheric debt" (a type of non-financial liability) on balance sheets of countries responsible for such emissions. Double counting would be avoided, as such assets would not be on any balance sheet to begin with. Such a recording would be complementary to the SEEA CF and EA as it allows to monetize non-LULUCF GHG emissions.[22] This liability would grow / decrease based on a country's (net) emissions from geocarbon pools.

The treatment of the atmosphere is currently being discussed as part of the update process of the 2008 SNA, specifically in the context of the treatment and recording of emission permits. If the SNA were to regard the atmosphere as an asset, the current treatment of taxes on production would need to be reconsidered.

7. Conclusions

The paper has analyzed how various ecosystem accounts can provide relevant information for carbon monitoring as well as various existing or emerging carbon policy instruments (although deeper analysis

[21] Although the High Seas are increasingly becoming managed through the establishment of Marine Protected Areas and a new treaty currently being developed under the U.N. Convention on the Law of the Sea

[22] Likewise, the current level of GHG concentrations could be expressed in terms of a global liability and apportioned to Parties based on their historic emissions (akin to the Brazilian proposal in climate negotiations)

is obviously required). There are also two instances where the SEEA EA may also prompt reconsideration (or further advancing) of existing measurement practices:

- Countries could consider all land included in the ecosystem accounting area as managed land.[23] So far, the IPCC has not been able to provide a clear definition of anthropogenic emissions that distinguishes between direct, indirect, and natural causes (IPCC 2009) – hence the use of the MLP. Indeed, one could argue that due to the impacts of climate change, the natural causes category has declined to such an extent that it may be easier to consider all land as managed. At the same time, we could still make a distinction between natural and anthropic ecosystems, based on the IUCN GET. This would imply that also emissions from natural sources (e.g. forest fires) would be included.[24] The effect of such a shift would be that the reported LULUCF emissions would be closer to what the atmosphere actually receives. Such an approach may help in directly linking NCP to targets under the Paris Agreement. Moreover, such a measurement approach may be more practical to implement.
- UNFCCC CoP25 decision "underlined the essential contribution of nature to addressing climate change and its impacts and the need to address biodiversity loss and climate change in an integrated manner". CoP 26 has a clear focus on nature and restoration of ecosystems and response in the form of Nature-Based solutions (https://ukcop26.org/nature/). The SEEA statistical framework, by weaving together both the environmental aspects of climate and nature and the economy in an integrated measurement framework, has the potential to support such a broader view of integrated climate policies, that considers climate regulation as one of many essential ecosystem services.

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[23] The author would like to credit Richard Houghton for this idea presented during the 2019 SEEA EA Forum of Experts.

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