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Carbon Removal Accounting for a Sustainable Future: Distributing CO_2 Flows in Multiservice Systems

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Abstract: Carbon dioxide removal (CDR) systems are an integral part of sustainable pathways limiting global warming to less than 2.0 °C. When the sole purpose of CDR is capturing and storing atmospheric CO_2, carbon registries offer detailed procedures to calculate the carbon removal credits. However, the registries do not address how to distribute CO_2 flows when CDR provides additional services. Standardized, transparent rules for distributing CO_2 flows among CDR services are required for the formation of efficient private and public carbon markets. The lack of such rules could result in double counting if those reductions are allocated to more than one service, decreasing the trustworthiness of carbon removal credits or deterring the delivery of an additional low-carbon service, thus limiting the economic viability and deployment of CDR. We examine allocation rules in carbon registries and carbon accounting guidelines, including their life cycle assessment (LCA) principles. We evaluate physical (mass-based) and non-physical (economic) allocation methods using a generic CDR system and find both to be unworkable. We then develop a mass balance (MB) approach which can reliably allocate captured and stored carbon (CSC) between carbon removal credits and other services based on the value CO_2 removal in those markets. This practical approach to allocation can be used in a transparent way to provide flexibility that would allow CDR services to capture the value of the multiple services they provide and, through this, promote the deployment of these sustainable alternatives.

Keywords: allocation; carbon accounting; carbon dioxide removal; life cycle assessment; mass balance

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1. Introduction

A 2023 World Meteorological Organization report stated that there is a 66% chance that the average annual temperature will breach 1.5 °C of warming between 2023 and 2027 [1]. This rise in temperature increases climate-related risks for both humans and the environment [2]. Nearly all pathways developed by the Intergovernmental Panel on Climate Change (IPCC) limiting warming to 1.5 or 2 °C require the deployment of carbon dioxide removal (CDR) to compensate for residual GHG emissions [3]. To achieve a globally sustainable future, the IEA Net Zero Scenario calls for accelerated scale-up of direct air capture (DAC) with an average of 32 DAC plants of 1 Mt CO_2/year capacity to be built each year between 2022 and 2050 [4].

CDR is a key component of sustainable net zero strategies because it can lower net emissions in the near term, sustain negative emissions in the long term and counter-balance sectors that are difficult to decarbonize [5]. Afforestation and reforestation are conventional CDR systems, while novel approaches include biochar carbon removal (BCR), bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS) [6]. Despite the importance of CDR, a clear gap exists between the proposed levels of deployment—currently, almost exclusively of the conventional kind—and what is required to meet the Paris temperature goal [7].

Achieving CDR deployment goals will require comprehensive policy support and public investment [8]. Understanding the cost of carbon removal is key to designing and implementing CDR policy because abatement cost data are essential to assessing the efficiency of investments, technologies and policies. According to economic theory, under ideal conditions, an economically efficient reduction in atmospheric carbon will result when the cost of carbon, whether achieved through reduced CO_2 emissions or CDR with permanent storage, is equal to the social cost of carbon [9]. Although such marginal reductions may be insufficient when the goal is carbon neutrality, setting sustainability-related policies to guide abatement investment that leads to more radical changes in carbon management also requires accurate and transparent CDR cost data [10]. Public policy incentives for CDR investment could be created by using the revenue from a fossil fuel tax to fund government procurement of CDR, or market-based approaches such as targeted carbon taxes combined with tradeable CDR credits that could be used to offset tax liability [8]. Achieving a cost-effective amount of CDR and ensuring that net emission targets are met requires knowledge of the incremental costs of carbon mitigation and removal across sectors.

Complementary to sustainability-related public policies that seek to increase investment in CDR, voluntary climate commitments have led to increasing demand for CDR in voluntary offset markets [11]. The sale of carbon offsets is one way CDR companies can profit from the carbon they capture and store—referred to herein as captured and stored carbon, CSC (CSC refers to a physical flow of carbon that is captured and then stored, while the more common abbreviation of CCS—carbon capture and storage—refers to the process of capturing and storing said carbon. Although CSC can be considered a product of any CCS, in the context of this paper, CSC refers only to atmospheric carbon that is captured and stored through CDR. This is because the allocation problem addressed here is between carbon removal credits and other services generated by the CDR, and removals can only be achieved by capturing and removing atmospheric CO_2). Projects registered in a carbon registry can be credited for emission reductions, i.e., for emitting less than a reference/baseline scenario—or for emission removals—when projects remove CO_2 from the atmosphere and store it elsewhere. Once a credit or offset is issued, it can be sold through a voluntary offset market or a carbon credit market, allowing the purchaser to claim those reductions or removals as theirs. In contrast to offset markets that are purely voluntary, carbon credit markets are enforced through policies, such as a cap-and-trade program which requires a company to purchase carbon credits to emit above a certain level.

A DACCS facility could thus claim the difference between the amount of CSC and the total GHG emissions generated by the capture process—the net captured carbon—as carbon offsets or credits. (For convenience we will refer to carbon removal services that can be sold as offsets or credits simply as "carbon credits" because for our purposes the nature of the carbon market is irrelevant). Some CDR technologies, however, generate services or co-products along with CSC. For example, BECCS produces energy, mineralization processes may produce supplementary cementitious material (SCM), and biochar can be used as a soil amendment. (For convenience, we refer to these as "multiservice" processes, the outputs of which are all "services"). Under certain market conditions, it will be desirable to market these services as "low carbon" to obtain a price premium. To avoid double counting of the captured carbon, the net removal must be tracked and distributed among the multiple services produced.

Carbon registries that track carbon mitigation projects and issue credits are evaluated and accredited by the International Carbon Reduction and Offsetting Accreditation (ICROA) Program. The use of a method of distributing GHG flows between services is not a criterion used to evaluate the registries [12]. Avoidance of double counting is nevertheless a principle of both the Voluntary Carbon Markets Integrity Initiative (VCMI) and The Integrity Council for the Voluntary Carbon Market (IC) [13,14], but neither has set requirements in terms of how to allocate emissions in multiservice systems. Similarly, none of the four most widely used registries, as identified in the Voluntary Registry Offset Database [15]—The American Carbon Registry [16], Climate Action Reserve [17], the Gold Standard [18] and The Verified Carbon Standard [19]—indicate how emissions and CSC should be divided among services if multiple services are provided by a CDR. This absence can also be found in smaller registries, such as Plan Vivo [20] and Puro [21]—see Section 2.3 for further details.

With the exception of the Gold Standard, the aforementioned registries quantify the GHG emissions of a project based on a series of carbon accounting guidelines, namely "The GHG Protocol" [22,23], and ISO 14064 [24,25]. These guidelines/standards were developed to calculate the GHG emissions of projects, corporations or organizations and are based on life cycle assessment (LCA). LCA is an environmental management tool that quantifies the potential environmental impacts—including but not limited to global warming—of products, processes or services throughout their life cycle [26]. The standard LCA methodology uses a procedure known as "allocation" to apportion impacts between the different services of a multiservice system. According to the ISO standards on LCA, however, allocation should be avoided whenever possible [27,28]. Avoiding allocation as recommended in these standards presupposes that the objective of the LCA is to quantify the impacts of only one of the services provided by the system. If, however, the goal is to market multiple services, e.g., both the carbon offsets and low-carbon services of a CDR process, or to formulate efficient public policies that incentivize the provision of CDR and associated low-carbon services, then allocation of GHG flows among the multiple services is required [29].

In this paper, we address the challenges involved in distributing GHG emissions and CSC when CDR provides multiple services by proposing an allocation based on a mass balance (MB) chain of custody (CoC) model [30]. We begin in Section 2 by critically reviewing what LCA standards, carbon accounting guidelines and carbon registries advise on allocation. In Section 3, we introduce a generic CDR system that produces multiple services: carbon credits and an additional, potentially "low carbon", service. Using this model CDR system, we test in Section 4 the allocation procedures suggested by the ISO standards and carbon accounting guidelines. In Section 5, we develop the aforementioned MB allocation procedure and address its merits. In Section 6, we discuss the implications of implementing the proposed mass balance allocation procedure. Finally, in Section 7 we summarize our arguments for a straightforward, clear and flexible allocation method that is required for carbon markets to support the commercialization of, and the necessary investment in, multiservice CDR.

2. Distribution of Greenhouse Gas Emissions and Captured and Stored Carbon

2.1. Life Cycle Assessment

According to ISO 14044, the two requirements of an allocation procedure are (1) it should be clearly documented, and (2) "the sum of the allocated inputs and outputs of a unit process shall be equal to the inputs and outputs of the unit process before allocation" [28]. The preferred method is a distribution based on the underlying physical relationships between emissions and services. Allocation should reflect the way in which emissions change when the quantities of services vary. Physical allocation is often based on mass, but other options include volume and energy. When no physical relationships exist, it is recommended that allocation reflect other relationships between services and impacts. A common non-physical allocation method is defined by the ISO Standards as "partitioning based on the economic value of the services leaving the system" [27,28], and is often referred to as economic allocation.

2.2. Carbon Accounting Standards

As mentioned in Section 1, "The GHG Protocol" [22,23] and ISO 14064 [24,25] quantify GHG emissions at the system level, e.g., the emissions generated by a whole company. Therefore, emissions do not require distribution among the services provided and, consequently, no allocation method is necessary. Nevertheless, there are related carbon accounting standards that address smaller scales such as the service level, for example the "GHG Protocol for Products" [31,32], ISO 14067 "Carbon footprint of products" and the UK's Publicly Available Specifications (PAS) 2050 [27]. All these standards follow a life cycle approach, and thus do not differ greatly from ISO 14044. The GHG Protocol for Products also requires avoiding allocation when possible, and recommends physical over economic allocation [31]. Similarly, ISO 14067 prioritizes avoiding allocation, and recommends physical over non-physical allocation [33]. PAS 2050, however, has a somewhat different set of priorities related to allocation. First, any existing supplementary requirement such as sector/or product-specific rules [27] should be followed. If there are none, there is currently one for horticultural products and another for seafood and other aquatic food products [34,35]; economic allocation should be used.

2.3. Carbon Registries

None of the carbon registries introduced in Section 1 offer clear guidance on how to address allocation in multiservice systems. However, in its Section 3.24.7, the Verified Carbon Registry [19] indicates that it should be public information whether a system has been issued carbon credits as a result of an action that changes the carbon footprint of a service, but not how those changes are to be accounted for. The Gold Standard Methodology on "Carbon Sequestration Through Accelerated Carbonation of Concrete Aggregate" introduces a similar requirement since "the project developer shall clearly communicate [. . .] its ownership rights and intention of claiming emissions sequestered in the project activity" [18,36]. Puro goes a step further, indicating in its Section 3.5.6.1 that "where a physical product or material stores the removed CO_2, the product/material shall not be associated with any claims of CO_2 Removal nor other Attributes represented by the [credit], unless the corresponding [credits] have been retired on behalf of this physical material/product" [21]. However, the registry does not further develop a procedure to distribute removal claims. Overall, registries present clear rules to avoid double counting by two entities, e.g., the project owner and the buyer of carbon credits. They leave unanswered the question of whether it is possible to claim carbon credits resulting from a given action, and also allocate some part of those carbon reductions/removals to whichever other services a system might provide. In other words, they do not clearly indicate whether the generation of reduction/removal credits is, in LCA terms, a service. Considering that the sale of carbon credits generates revenue, we argue that any reduction or removal of CO_2 creating revenue should be a considered a distinct service.

3. Description of a Model CDR System

To exemplify the issues of carbon accounting in multiservice CDR processes, we describe a non-specific CDR system capable of delivering two different marketable services:

1. Carbon credits. A portion of the amount of CSC can be sold as carbon credits. If this is the only service provided by CDR, that amount will be the net difference between CSC and the life cycle GHG emissions generated by the CDR, and the carbon credits will be removal credits. If there is an additional service, the fraction that can be sold will depend on the allocation procedure used. Note that the term "credits" is used as defined by the carbon registries: either carbon reduction or carbon removal credits.
2. An additional service. In practice, this might be a physical flow such as energy from BECCS, a material flow like limestone or a supplementary cementitious material produced through mineralization, or an immaterial service, such as recreation in a newly afforested area paid for through a visitor fee.

Figure 1 shows the key environmental and economic flows of the system. There is a physical flow of CSC measured in units of tCO_2/year. The additional service (S) can be physical or not, so its flow will be measured generically in units/year. The price of CSC sold as carbon credits is P_C (USD/t CO_2 eq.), while the price of the additional service is P_S (USD/unit). The costs of deploying and operating the CDR are annualized to C_{CDR} (USD/year). The amount of CSC is equivalent to the global warming potential (GWP) of the carbon taken from the atmosphere, I_{CSC} (tCO_2 eq./year). The carbon emissions that result from deploying and operating the CDR are lumped together and annualized as I_{CDR} (tCO_2 eq./year). In LCA terms, the two services provided can fulfill widely different functions, and therefore have unique functional units (FUs). The only commonality between the two services is that they are both produced by the same process and are sold into a market. A service must be sold, and therefore have a price, in order to apply economic allocation. For the latter, as discussed in Section 5, there should also be a market for a low-carbon version of the additional service. That is, there should be a market for the service and a willingness to pay a premium for that service if it is low-carbon.

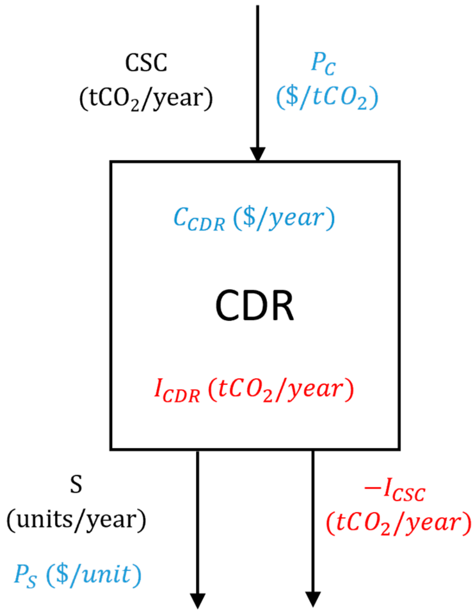

Figure 1. Key environmental (red) and economic (blue) aspects of the CDR system. CSC represents the physical flow of atmospheric carbon captured and stored by the CDR in a year, while S represents the number of units of a service—not necessarily physical—generated by the CDR in a year. I_{CDR} represents the impacts generated by the CDR during its yearly operation—including annualized impacts of its capital investments—while I_{CSC} represents the yearly impact of the captured and stored carbon—negative because it is a removal of carbon already present in the atmosphere. P_C is the unit price of CSC, more likely in the form of a carbon removal credit; P_S is the unit price of the service generated by the CDR; and C_{CDR} represents the annualized cost—operational and capital—of running the CDR.

4. Testing of Allocation Procedures on the Model CDR System

The non-specific CDR system described above is used in the sections that follow to evaluate the use of the allocation methods recommended by the different carbon accounting guidelines in the order of preference suggested by the ISO Standards and the GHG protocol [27,28,31].

4.1. Physical (Mass-Based) Allocation

Mass-based allocation requires all services generated by a system—CDR in this case–to have mass. This would exclude energy from BECCS, a visitor fee to newly afforested areas, or a "low carbon ski experience". Mass-based allocation cannot be applied even in the case of a material service that can be sold on a per-ton basis, e.g., wood, or carbonated minerals, because these services are physical outputs of the system, while the generation of credits is based on a physical input and the result of adding inputs to outputs to define the total services produced makes no physical sense.

4.2. Economic (Price-Based) Allocation

With economic allocation, the impacts of carbon credits and the additional service vary with their prices. If P_C is the price of carbon credits, and P_S the price of the additional service provided by the CDR system, the revenue from those two services is $\alpha\ (I_{CSC} - I_{CDR})\cdot P_C + S\cdot P_S$, where α is the fraction of net CSC sold as carbon credits. This revenue function results in the allocation presented in Table 1. It is, however, self-referential, and therefore not mathematically sound as the economic value of the carbon sold on the market, $\alpha(I_{CSC} - I_{CDR})\cdot P_C$, depends on the amount of carbon credit that can be sold, $\alpha(I_{CSC} - I_{CDR})$, which is precisely what we are trying to allocate.

Table 1. Impacts allocated by economic value.

	Carbon Credit	**Additional Service**
Allocation factor (unitless)	$\alpha = 1 - \frac{S\cdot P_S}{(I_{CDR} - I_{CSC})\cdot P_C}$	$\beta = \frac{S\cdot P_S}{(I_{CDR} - I_{CSC})\cdot P_C}$
Allocated impacts (t CO_2 eq./year)	$(I_{CDR} - I_{CSC})\cdot\left(1 - \frac{S\cdot P_S}{(I_{CDR} - I_{CSC})\cdot P_C}\right)$	$\frac{S\cdot P_S}{P_C}$

5. Development of a Mass Balance Allocation Procedure

5.1. Mass Balance and General Restrictions

As mentioned in Section 2.1, a logical requirement of an allocation method is that the sum of the allocated emissions of the system is equal to the total emissions of the system prior to allocation [28]. This requirement is analogous to a mass balance requirement found in the mass balance CoC model [30]. The mass balance CoC approach distributes certified and not-certified input materials among the output products. This "certified" claim can be allocated to any physical product leaving the system as long as the amounts are appropriately balanced [37]. MB is already used in accounting for environmental performance in the supply chain, such as the distribution of recycled content in plastics [38].

An allocation method based on MB would allow free distribution of the impacts of the system between its products, provided that the sum of the impacts of all products is equal to the impacts of the whole system. Because, effectively, any distribution of impacts that meets the mass balance criteria would comply with MB allocation, it is necessary to impose some restrictions to ensure that the net balance of carbon removal is positive and trackable:

1. To prevent the possibility of creating artificially high-impact products and their ultra-low-impact counterparts, no single service shall be allocated more impacts than the total of the positive (generated) impacts.
2. The results of mass balance allocation shall be clearly communicated. For example, MB allows a system offering two services to leave service A burden-free and allocate all the burden to service B. If service A is advertised as "Carbon Neutral", then service B would need to be sold with a label saying, "Now with vastly more carbon". Thus, the use of MB allocation can only be recommended in those situations where the impacts of all services provided are clearly stated. Systems in which all products have an Environmental Product Declaration (EPD) could use MB allocation as there would be the possibility of appropriate market consequences for both the low-carbon and a high-carbon service. This requirement is adapted from ISO 22095, in whose Section 5.2 it specifies that for MB CoC "*it shall be transparently shown how the claimed content is calculated [and] be clear that this content does not necessarily correspond directly to the physical content in the product*" [30].

5.2. Additional Restrictions in Imperfect Markets and General Application

Following MB's general restriction, and the two we have imposed ourselves, still does not guarantee that the CDR results in net carbon removal. It would be possible to assign all environmental burdens (I_{CDR}) to the additional service while allowing the carbon credit service to potentially claim all of CSC's impact (I_{CSC}) and not merely the net difference between the carbon captured and stored and the GWP generated by the CDR system ($I_{CSC} - I_{CDR}$). Under this allocation, the existence of an additional service does not restrict the amount of carbon that can be sold as carbon credits. Rather, besides serving as an additional source of revenue, the additional service acts as a repository for all carbon emissions, allowing the maximum amount of carbon to be sold as credits.

To ensure CDR provides a net carbon benefit, the amount of CSC claimable as credits should depend on the impact of the CDR relative to a reference system (RS) capable of delivering the same additional service produced by the CDR, which carbon registries refer to as the *baseline scenario* for the additional service. Thus, two possible situations arise:

1. $I_{CDR} \leq I_{RS}$. CDR is net carbon-negative, and it would be a relative benefit compared to the RS even if no carbon capture took place.
2. $I_{CDR} > I_{RS}$. CDR is a net environmental benefit, but it is only a relative benefit when compared to the RS thanks to its carbon-capture capabilities.

In Figure 2, we present an example of how two CDRs (A and B) capturing and storing the same amount of carbon, but with different emissions ($I_{CDRA} < I_{RS} < I_{CDRB}$), could allocate their emissions following MB principles depending on their ability to sell credits and to be compensated for selling a service with reduced climate impact. The "Removal Credits" panel represents the situation where a CDR can sell removal credits as well as an additional service. In this situation, CDR A would allocate all its CSC to removal credits and the remaining emissions would be associated with the additional service, which still has a lower GWP than the RS. In this same situation, CDR B, which has higher emissions, must first balance its emissions with some of its removal to reach the level of the RS before the remaining CSC can be sold as removal credits.

If, in addition to the service, it is possible to sell both reduction and removal credits, CDR B would find itself in the same situation as above, since its emissions before balancing are higher than those of RS. The lower-emitting CDR A can sell all its CSC as removal credits and also sell the difference between its remaining emissions and those of the RS as reduction credits. The remaining emissions are allocated to the additional service as before.

When, in addition to removal credits, there is a market for low-carbon versions of the additional service, MB would allow a portion of the CSC to be allocated to the additional service to earn this "low-carbon" premium. That is, the CDR operator could voluntarily reduce a certain amount of the emissions of the additional service by balancing them with an equivalent quantity of CSC. We illustrate this at the bottom of Figure 2 in two different ways. CDR A would reduce the amount of CSC it makes available for removal credits in order to reduce the remining emissions allocated to the additional service. The reason for this would be that being able to sell the additional service with a lower carbon footprint is more economically beneficial than the sale of that amount of CSC as removal credits. In this example, CDR B acts the opposite way. It balances some of its removal with a fraction of the emissions allocated to the additional service, while leaving its impact above that of the RS. The underlying reason to apply such allocation would be that there is some incentive to reduce the emissions of the additional service below a certain point, but not to the same level as the reference system.

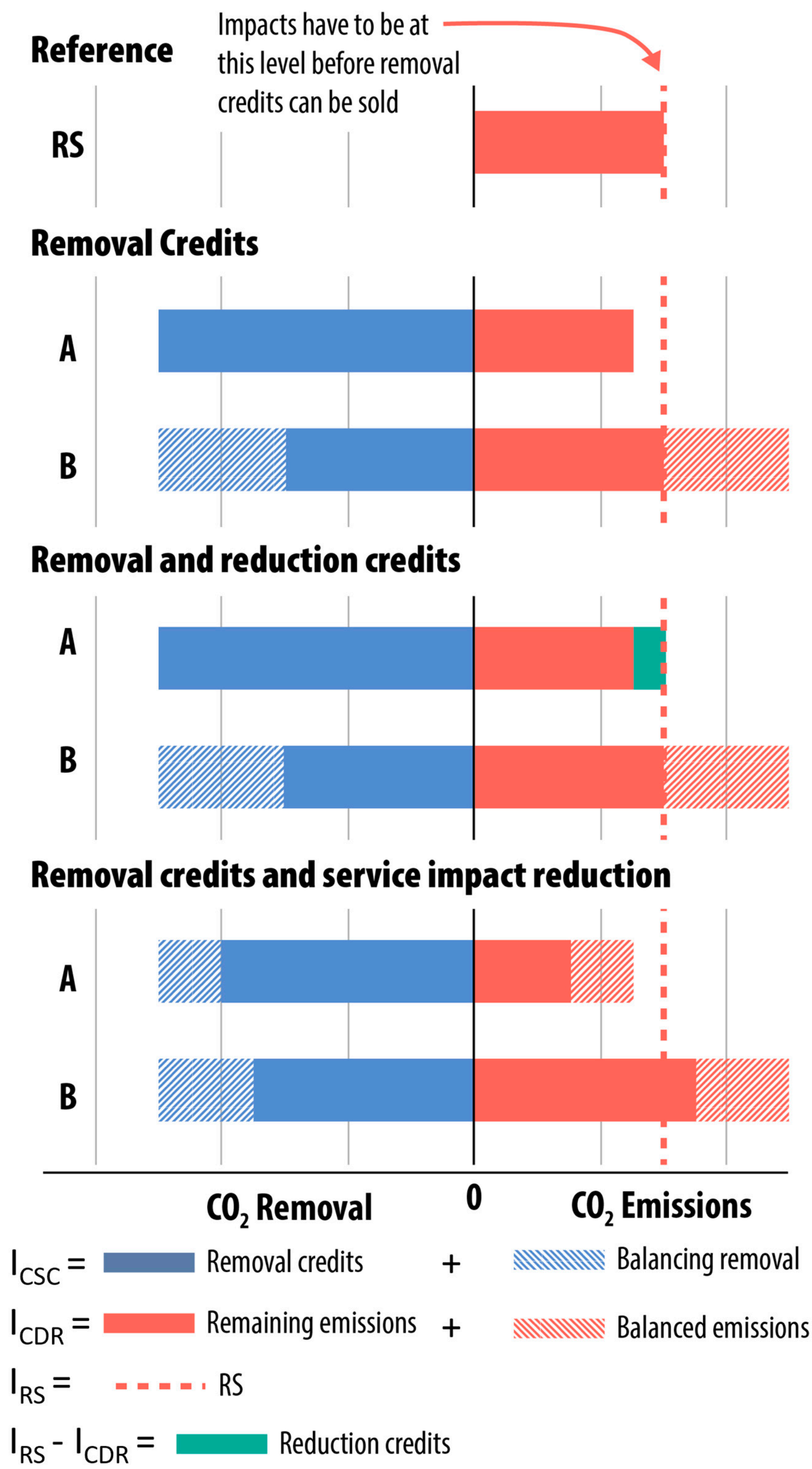

Figure 2. Removal and reduction credits available under MB allocation, as a function of the relative impact of the CDR (I_{CDR}), and a reference system (I_{RS}), for two different CDR systems ((**A**) $I_{CDR} \leq I_{RS}$, (**B**) $I_{CDR} > I_{RS}$ and I_{CDR}-$I_{CSC} < 0$) in three different situations: (1) the CDR can only sell removal credits, (2) the CDR is able to sell both removal and reduction credits, and (3) the CDR is able to sell removal credits, and there is value in reducing the impact of the additional service. The red dotted line (RS) corresponds to the impact of the reference system (I_{RS}), while the sum of both red bars—solid and patterned—corresponds to the impact of the CDR system (I_{CDR}). Similarly, the sum of both the solid and patterned blue bar corresponds to the impact of the captured and stored carbon (I_{CSC}).

It this case, the allocation we selected for CDR B breaks the rule that the emissions of a CDR should be equal to those of an RS before it can start selling removal credits. We show this to illustrate that enforceable references—such as the one we selected based on RS—are necessary only in the absence of a well-developed market for low-carbon services. Without them, CDR B would, logically, choose to sell all its CSC as removal credits together with a high-carbon additional service. When low-carbon services are sufficiently valued, enforceable limits for the impact of the additional service will not be necessary. The market for the additional service—as opposed to the actions of a regulatory body such as a carbon registry—would define what constitutes low carbon. In the example, when there are both removal credits and a low-carbon market for the additional service, CDR A sees from market signals that there is value in having an additional service with an impact below that of the RS. The example we selected for CDR B, however, illustrates a situation where there is no financial incentive to reach the emission levels of RS. However, in response to a different set of market incentives, CDR B could choose to reduce the impact of its additional service to match those of RS.

6. Discussion

When applied to CDR systems, MB allocation is simple, and—unlike mass and economic allocation—it is not self-referential. The rules we proposed in Section 5.1 are a minimum set that keep allocation within reasonable boundaries and ensure it is used to promote low-impact alternatives in a transparent way. The requirement we set in Section 5.2 that the impact of the additional service must be less than the RS is only needed when markets alone are not sufficient to enforce the delivery of those low-impact alternatives.

Having an allocation procedure that promotes revenue can encourage the deployment of much needed CDR. As is the case with economic (price-based) allocation, fluctuations in the market will change how impacts are distributed. However, MB allocation is less sensitive to price changes. The reason for that is that the key question is which market, carbon removal credits, or low-carbon services is willing to pay more for the CSC, not how much more. Naturally, the premium for low-carbon services can be structured in multiple ways, e.g., a continuous function, brackets of increasing value as impacts reduce or merely one threshold—but a detailed development of these situations is beyond the scope of this paper. As presented above, MB allocation can be readily applied in the LCA of CDR. With it, an LCA practitioner can divide emissions and CSC between the two services rationally and ensure they fulfill the first requirement of the ISO standards: the sum of allocated impacts must be equal to the impacts generated by the system. Although MB allocation overcomes the limitations of standard allocation methods, its practical implementation has implications that must be considered.

6.1. Allocation and Environmental Product Declarations

As stated in Section 5.1, a benefit of using MB allocation in combination with EPDs is that the latter prevents any potential obfuscation of the impacts caused by the CDR system while generating carbon credits. Although EPDs help make MB allocation more transparent, their combined implementation is not without complications. EPDs rely on attributional LCAs based on the past physical flows in a system, and they are valid for several years after their publication. Under MB allocation, the flows of carbon to products in the CDR system would not be constant through the validity period of an EPD. Although the detailed integration of EPDs and carbon markets through MB and PMS allocation falls outside the scope of this paper, a few solutions can be outlined:

Ideally, EPDs would become living documents, not only for the sake of reflecting market changes, but also to reflect technological changes. Eventually, it should be possible to compute the prices of carbon in both markets, as well as the market sizes, in real time, and, based on them, allocate the CSC between the services for the next (short) vintage.

A less dynamic alternative would be to update prices and demand on a regular basis, and use those values to report the range of potential impacts allocated to the additional product. This would be a refinement of the requirement mentioned in Section 2.3 concerning the selling of carbon credits associated with the production of a product. In this case, instead of merely indicating that "Carbon credits have been generated while creating this product", an EPD could be more specific and add "and therefore its GWP can oscillate between X and Y kg CO_2 eq./FU, based on the credits traded between [Date 1] and [Date 2]", offering a narrower set of values for the GWP of the additional service. In this case, caution is required when comparing an EPD with one GWP value with that for a product for which carbon credits have been sold—and thus with an uncertain GWP. The conservative option would be to assume all CSC has been sold as carbon credits. In that case, the GWP of the product is the highest it can be, which might put CDR services at an unnecessary disadvantage. To counterbalance this, a CDR operator could set the price at which carbon is allocated to the service above the price of carbon removal credits to consistently allocate all or most of the CSC to the additional service.

6.2. Allocation and Carbon Registries Revisited

Registries should have clearly stated rules for allocating emissions—and, therefore, CSC and related credits. From our point of view, ICROA should use the existence of a well-developed allocation procedure as a criterion to evaluate the endorsement of carbon registries. Registries aiming at a high degree of compatibility with one another should have a common allocation procedure. If MB allocation is used, it would be necessary that for a certain CDR, the RS should be the same across registries.

To successfully implement MB allocation, registries would likely have to shorten their vintage periods—"*periods for which a particular set of GHG emission [. . .] removals [. . .] are verified*" [39]—to capture changes in the prices offered for CSC in the carbon market and prices of carbon in the additional service. This requirement is consistent with the MB CoC method, which states that "*the balancing period*"—the period needed to "*verify that the outputs relate appropriately to the inputs—should be as short as possible*" [30]. The way to overcome this hurdle does not have to be the same for all registries, but having a common set of solutions will facilitate compatibility between them.

MS allocation allows the CDR operator to maximize the revenue coming from their CSC efforts, and might facilitate the deployment of CDR. More importantly, it prevents double counting of CSC efforts by the multiple services provided by the CDR, safeguarding CDR as a net-benefit solution when it comes to mitigating climate change. It does not, however, alter the need for verification to avoid double counting between the CDR and buyers of the removal credits. MB allocation promotes transparency, but it is only one of several measures required for reliable, transparent carbon markets.

7. Conclusions

CDR methods are a necessary component of sustainable public policy in the context of global warming. Their cost today, among other limitations, currently hampers their deployment at the levels they are needed. Carbon removal credits, traded through voluntary carbon markets, represent a financing opportunity for CDR. For those methods providing other services in addition to carbon removal, it is necessary to distribute captured carbon among all services. However, physical and economic allocation currently promoted by LCA and related frameworks are self-referential. That makes them unsuitable for application to multiservice CDR, which further limits the conditions under which CDR can be economically feasible.

Using MB principles, it is possible to allocate impacts, including captured and stored carbon, between services while following LCA's ISO 14040 and 14044. Since CDR methods are expected to receive economic compensation for their capture and storage efforts, restrictions must be applied to prevent malpractice:

(1) No single service can have more impacts allocated to it than the total impact generated by the system;

(2) The impact of all services should be disclosed, and not only the service deemed environmentally sustainable or low-carbon.

MB allocation could be used to maximize the revenue a CDR method receives for its efforts capturing and removing carbon, e.g., maximizing the number of removal credits it can receive. In markets that do not value a low-carbon service, however, it would require an additional restriction:

(3) The CDR cannot emit more GHG than a reference system producing the same service but which does not capture carbon.

In markets where a low-carbon service is valued, MB allocation could be used to reduce the impact of that service at the expense of being able to offer fewer carbon removal credits.

We therefore suggest that MB should be used as a guiding principle to distribute impacts between services in CDR methods. We encourage ICROA to include allocation as a criterion to evaluate carbon registries, IC and VCMI to include clear allocation rules as part of their principles and to all three institutions to consider MB as a feasible option. We also encourage carbon registries to implement MB allocation in their methodologies. MB allocation's transparency prevents double counting of captured and stored carbon, whether this takes the form of carbon removal credits or as embodied negative carbon, and could stimulate the deployment of CDR methods, increasing profitability while ensuring a fair comparison with non-CDR solutions.

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