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CUDe—Carbon Utilization Degree as an Indicator for Sustainable Biomass Use

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Abstract: Carbon (C) is a central element in organic compounds and is an indispensable resource for life. It is also an essential production factor in bio-based economies, where biomass serves many purposes, including energy generation and material production. Biomass conversion is a common case of transformation between different carbon-containing compounds. At each transformation step, C might be lost. To optimize the C use, the C flows from raw materials to end products must be understood. The estimation of how much of the initial C in the feedstock remains in consumable products and delivers services provides an indication of the C use efficiency. We define this concept as *Carbon Utilization Degree* (*CUDe*) and apply it to two biomass uses: biogas production and hemp insulation. *CUDe* increases when conversion processes are optimized, i.e., residues are harnessed and/or losses are minimized. We propose *CUDe* as a complementary approach for policy design to assess C as an asset for bio-based production. This may lead to a paradigm shift to see C as a resource that requires sustainable exploitation. It could complement the existing methods that focus solely on the climate impact of carbon.

Keywords: bio-economy; bioenergy; biogas; biomass; carbon efficiency; climate change; natural fibers; policy decision support; productivity; transformation

1. Introduction

Carbon (C) is an essential part of life on earth; approximately 50% of dry plant biomass is carbon (Table 1). All organisms rely on C in their metabolism, for example, to generate body tissue and energy carriers [1].

Table 1. Carbon content of different organisms (% of dry matter).

Organism	Mean Carbon Content (% of Dry Matter)	Range	Reference
Overall mean of energy crops	46.5		[2]
Maize (*Zea mays* L.) (whole plant)	48.6	47–50.2	[2]
Poplar (*Populus* spec.) (in wood)	47.5		[2]
Willow (*Salix* spec.) (in wood)	47.1		[2]
Wheat (*Triticum* L.) (whole plant)	45.2		[2]
Rye (*Secale cereale* L.) (whole plant)	48.0		[2]
Grasses	43.9	41.4–46.4	[2]
Hemp (*Cannabis* L.)	45.12		[3]
Bacteria	≈50		[4]
Microalgae (green/brown)	54.4/24.7	49–58/24–25	[5]

In the same way, human society relies on carbon, particularly in the form of chemical compounds:

- as carbohydrates and fats in food and feed,
- as hydrocarbons in energy carriers and
- as bulk chemicals for the chemical industry.

Humans are dependent on C as a production factor, whether derived from biogenic or fossil sources. However, this perception is not widely held: C is mostly addressed in the context of climate change in its bonded form in greenhouse gases (GHG; carbon dioxide: CO_2, methane: CH_4) or as a pollutant (e.g., in volatile organic compounds). Hence, it is more common to see C as a threat instead of an indispensable resource. The interest in its climate change impact is reasonable because the C buffer capability of the atmosphere and other natural sinks is limited [6].

The perception of C in CO_2 as a production factor has progressively gained scientific interest, which can be observed from conference topics [7], from the increasing number of studies on so-called 'dream reactions' [8], by which CO_2 is (re-)transformed into organic compounds as chemical bulk material [9], as well as from a journal with special focus on this topic since 2013 [10]. This is demonstrated by a three-digit increase in low-carbon studies since 2011 [11], representing also societies' interest in a transition from a fossil-based economy to a bio-economy ('low-carbon'). As stated above, one main reason for this transformation is to avoid climate change by using recently fixed rather than fossilized carbon compounds. However, sustainability assessments of biomass production and usage in the context of a transition to a bio-economy should include more than just their climate impact, and reliable indicators are needed [12,13]. Impact-oriented assessments have to address several methodological caveats, which are discussed in depth in scientific literature on climate impact. Among them are the appropriate choice of reference systems [14], the assessment of indirect effects [15], the allocation in multi-product systems [16], the CO_2 neutrality assumption for biomass [17], and changes in metrics (e.g., global warming potentials change with the new release of IPCC reports [18]). Such restrictions are also relevant for other impact assessments.

Following a paradigm shift from mainly impact-oriented perception (for example, climate change) to a productivity-oriented one, we suggest a consideration of C in biomass as a limited resource. Although C is abundant in its gaseous form as CO_2 in the atmosphere, its transformation into biomass C is a demanding process, needing, for instance, energy, land, water, and nutrients. Furthermore, C is a resource that cannot be substituted by other elements, and the strong sustainability concept needs to be applied [19]. We can assess its appropriate use with the methodological concept of '*productivity*', which is common in economics. Productivity is an indicator for the use of limited resources and is expressed as an output/input ratio, e.g., Hill [20]. Several published approaches use the productivity concept to assess C, for instance, technology- [21], sector- [22] or country-specific [23,24] (for more approaches, please refer to Table A1). However, their common focus is the cost-efficient reduction of CO_2 emissions to avoid climate change [21]. Recently, the limitation of resources has led to approaches that seek to decouple economic growth and resource use by switching from linear to more circular economic models. Circularity indicators were presented to measure their success [25]. However, they focus on non-renewable resources and have only limited applicability for renewable materials, such as biomass.

In this manuscript, we adopted the productivity concept for a new indicator, *Carbon Utilization Degree* (*CUDe*), and apply it to two case studies. *CUDe* aims to assess efficient C use in production chains. Our objectives are:

- to extend the perception of C (and accordingly CO_2) from having a negative impact to being an indispensable, limited resource and
- to provide a supplementary indicator for policy decision support to express efficient C use in production chains.

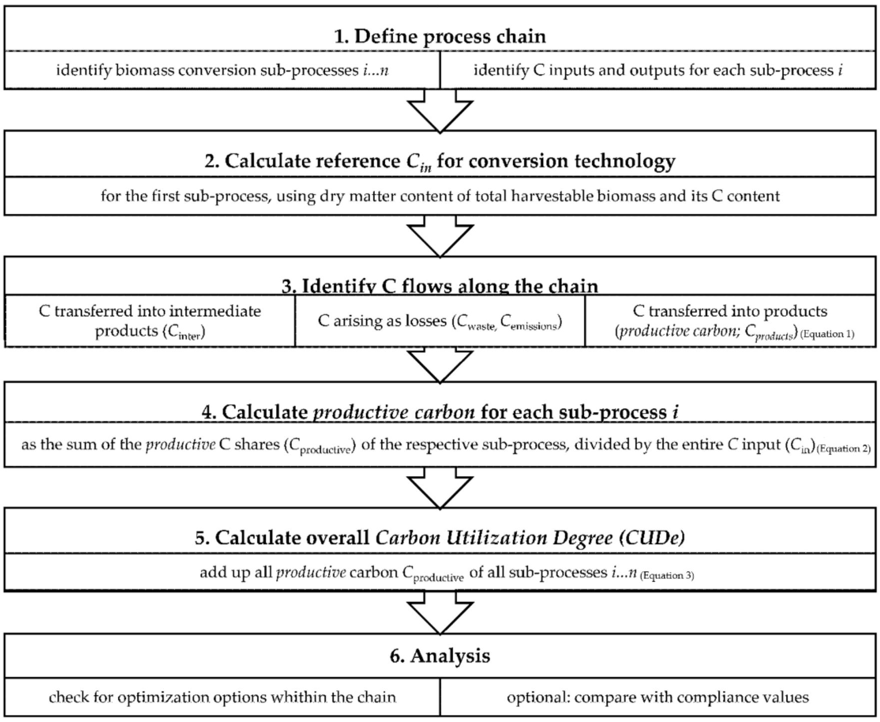
2. The Carbon Utilization Degree Approach

Productivity is generally defined as the ratio of output to input (r = output/input), sometimes expressed as a percentage (r_p = output/input × 100) [20]. Accordingly, productivity increases if more output is produced from the same input. This can occur if losses are reduced or if additional outputs are generated, for instance, by putting waste to use.

We adopt this concept and propose *CUDe* (We use the term '*CUDe*' to avoid confusion with other concepts: '*C productivity*', which was defined as the specific GDP/CO_2 in Kaya and Yokobori [23], or with '*C efficiency*', which was defined as the ratio of the target level of C emissions and the actual level of C emissions of an economy in Yang [22]. *Productiveness*, as another possible term, has a different meaning than productivity in an economic context ("[. . .] productiveness (or productive capacity) is a measure of the quality of being productive or having the capacity to produce" [26]).) as a supplementary indicator for policy decision support to assess biomass conversion technology. It expresses the *productive* carbon fraction of the biomass that is utilized in biomass conversion chains. *CUDe* is defined as the ratio of carbon which is finally *productive*, to the carbon that was originally available in the biomass. Carbon is considered *productive* in an anthropocentric view if it provides a useful output, i.e., it:

- is transformed into marketable products or provides useful services, e.g., insulation material, forage or energy generation (direct benefit), or
- performs important ecological functions, e.g., improves soil fertility (indirect benefit).

The approach to calculate the *Carbon Utilization Degree* for a biomass conversion pathway follows a process chain assessment and comprises five steps plus an analysis step (Scheme 1).



Scheme 1. Workflow to calculate the *Carbon Utilization Degree (CUDe)* of biomass conversion technologies plus an analysis step. For details, please refer to Equations (1)–(3).

First, all relevant transformation processes in the chain need to be identified and described. In the second step, the system's carbon input is defined as a reference value: the amount of fixed carbon C_{in} in the harvestable biomass that enters the process chain is calculated. Third, for each of the subsequent processes, the C balance is determined. C is considered in the following flows: transfer to the chain boundary as products (C_{products}), transfer to a following process as intermediates (C_{inter}), and C in wastes (C_{waste}) and emissions ($C_{\text{emissions}}$). Then, the *productive* carbon is calculated by adding up C_{products}, which equals the difference between C_{in} and the C in wastes, emissions and intermediate products (Equation (1)). The *productive* C related to the originally fixed C_{in} is expressed as a percentage share for each (sub-)process (Equation (2)). In the fifth step, the *Carbon Utilization Degree* of the chain is calculated by adding up the *productive* carbon shares of all sub-processes (Equation (3)). In the final step, sub-processes with wastes and emissions or the complete chain can be analyzed further to identify the optimization potential and, optionally, to check whether compliance values are reached. The latter could be set by policy in the future, for example, that a minimum *CUDe* of 66% has to be reached for a specific technology to receive tax reductions or to apply for incentives.

CUDe can be calculated according to Equations (1)–(3):

$$\begin{gathered} C_{\text{productive } i}\ [\text{kg C}] = C_{\text{products } i} = C_{\text{inter } i-1} - C_{\text{emissions } i} - C_{\text{waste } i} - C_{\text{inter } i} \\ \text{with } i = 1, \ldots, n;\ C_{\text{inter } 0} = C_{\text{in}};\ C_{\text{inter } n} = 0 \end{gathered} \tag{1}$$

$$C_{\text{productive } i}\ [\%] = \frac{C_{\text{productive } i}}{C_{\text{in}}} \cdot 100 \text{ with } i = 1, \ldots, n \tag{2}$$

$$CUDe\ [\%] = \sum_{i=1}^{n} C_{\text{productive } i}\ [\%] \tag{3}$$

C_{in} is the carbon content [kg C; $C_{\text{in}} > 0$] of the entire harvestable biomass (i.e., including the harvest residues) that enters the biomass transformation chain at sub-process $i = 1$. It explicitly includes the C in harvest residues that remains in the field, for instance, as stubble, to address other sustainability aspects. Although C in stubble is finally returned to the atmosphere via soil biota on varying time scales, we consider it *productive* because it contributes to sustainable agricultural management. However, this effect is limited and could be accounted for more precisely, for instance by inclusion of site-specific characteristics.

C_{in} can be calculated from own data generated by a chemical analysis, from published C contents of biomass that are available in the literature (some dry matter contents are listed in Table 1), or from data repositories, for instance, from ecoinvent [27]. Data on harvest residues can also be derived from repositories, for example, from FAO [28].

The total number of transformation processes in the conversion chain is denoted by n, whereas i denotes the respective sub-process, where C is further transformed to products and intermediates or is lost. $C_{\text{emissions } i}$ consists of the gaseous C losses [kg CO_2, kg CH_4] that are converted into kg C according to their molar conversion factors: $CF_{CO2} = 12/44$ [kg C/kg CO_2], and $CF_{CH4} = 12/16$ [kg C/kg CH_4] as well as fluid C losses. $C_{\text{waste } i}$ is the C in production waste. $C_{\text{productive } i}$ is the *productive* C of sub-process i, whereas *CUDe* represents the *productive* carbon of the complete transformation chain. $C_{\text{inter } i}$ [kg C] is the carbon that is transferred as an intermediate product from sub-process i to the following sub-process $i + 1$. We assume that every transformation chain yields some useful carbon. Hence, $CUDe \in (0, \infty]$, representing that C reuse is theoretically infinite. The upper frontier ∞ originates from the possibility of using biomass in a cascading way: biomass can—like many non-renewable resources—be used several times, first (or more often) as a material and finally as an energy carrier. With this understanding, we follow the definition of cascading use in Carus et al. [29]. n greater than two means that after the harvesting step, (part of) the biomass is used at least two times. In such cases, in contrast to common productivity or efficiency calculations, the numerator can take values higher than the denominator and the total *CUDe* can yield values greater than 100%.

In the following section, we apply the *CUDe* concept to simplified systems of current technologies that transform biomass into energy (bioelectricity from maize silage) or to a material (hemp fibers as insulation).

3. Example Application

3.1. Carbon Utilization Degree of a Biomass Transformation to Bioenergy—Anaerobically Digested Maize

Electricity generation from digested maize silage is a bioenergy pathway that is frequently associated with GHG mitigation potentials (e.g., 15%–44% of emissions compared to fossil electricity) [30]. However, it is necessary to be aware that some carbon is not productive along the biomass transformation chain (Figure 1).

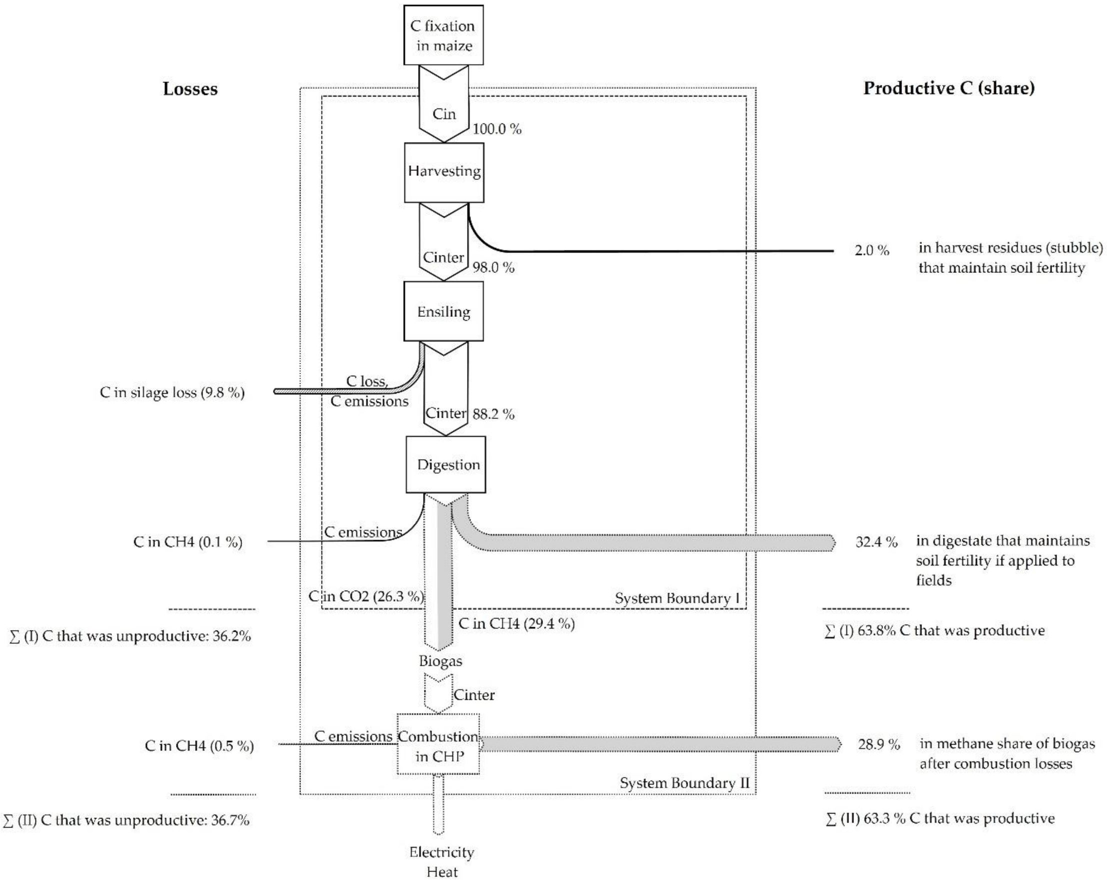


Figure 1. Carbon flows as a percentage of carbon fixed in harvestable biomass C_{in}, including stubble, and the resulting *productive* (**grey** arrows) and unproductive C (hatched arrows) during biogas generation from maize (Boundary I) and further use of this biogas in a combined heat and power (CHP) unit (Boundary II).

Maize plants fix atmospheric carbon in their biomass. Biomass in the roots, leaves, and the lower part of the stem (stubble) remains in the field after the 'harvest' step, and its C content is returned to the soil pool, maintaining soil productivity. Ratios of 1%–3% of C in stubble vs. C in directly harvestable biomass have been reported from a long-term field experiment of different fertilizer treatments in maize [31]. Although C in stubble is eventually returned to the atmosphere via soil biota activity on varying time scales, we consider it *productive* because it contributes to sustainable agricultural management. Accordingly, it is included in the *CUDe* calculation. A total of 98% of the harvested biomass is then transferred to the next step.

During the next step, 'ensiling', C can be lost in silage effluent as well as from microbial activity in the silage. Such losses have been reported with ranges from 1% to 3% [32] as well as from 15% to 25% [33]. We applied a value of 10% loss. The maize silage is then transferred as an intermediate product to the 'digestion' process, where some gaseous leakage may occur (C lost as methane; 0.01% *v*/*v* [34]). The digestion step delivers digestate as a co-product, which can be re-applied to agricultural fields as a fertilizer, returning to the soil C pool and maintaining soil productivity [35], and can thus be considered *productive*. Adding up the *productive* C for these steps of the biogas generation technology results in a *CUDe* of 63.8% (*CUDe* = 2% + 32.4% + 29.4%; Boundary I in Figure 1) if we assume that only the CH_4 share of the biogas is of interest and optionally *productive*. If the boundary is expanded by including 'energy generation', the biogas is considered as an intermediate product. In a combined heat and power plant (CHP), the CH_4 share of the biogas (approximately 53% *v*/*v* [36]) is burned to generate electricity and heat and therefore becomes *productive*. However, depending on the CHP engine type, 1.5%–3% of the methane may be emitted to the atmosphere [37]. The CO_2 share of the biogas (47% *v*/*v*; [36]) is not considered *productive*. Accordingly, the total *CUDe* of the electricity and heat generation from maize silage results in a *CUDe* of 63.4% (*CUDe* = 2% + 32.4% + 29.0%; Boundary II in Figure 1). More than one-third of the harvestable C did not become productive.

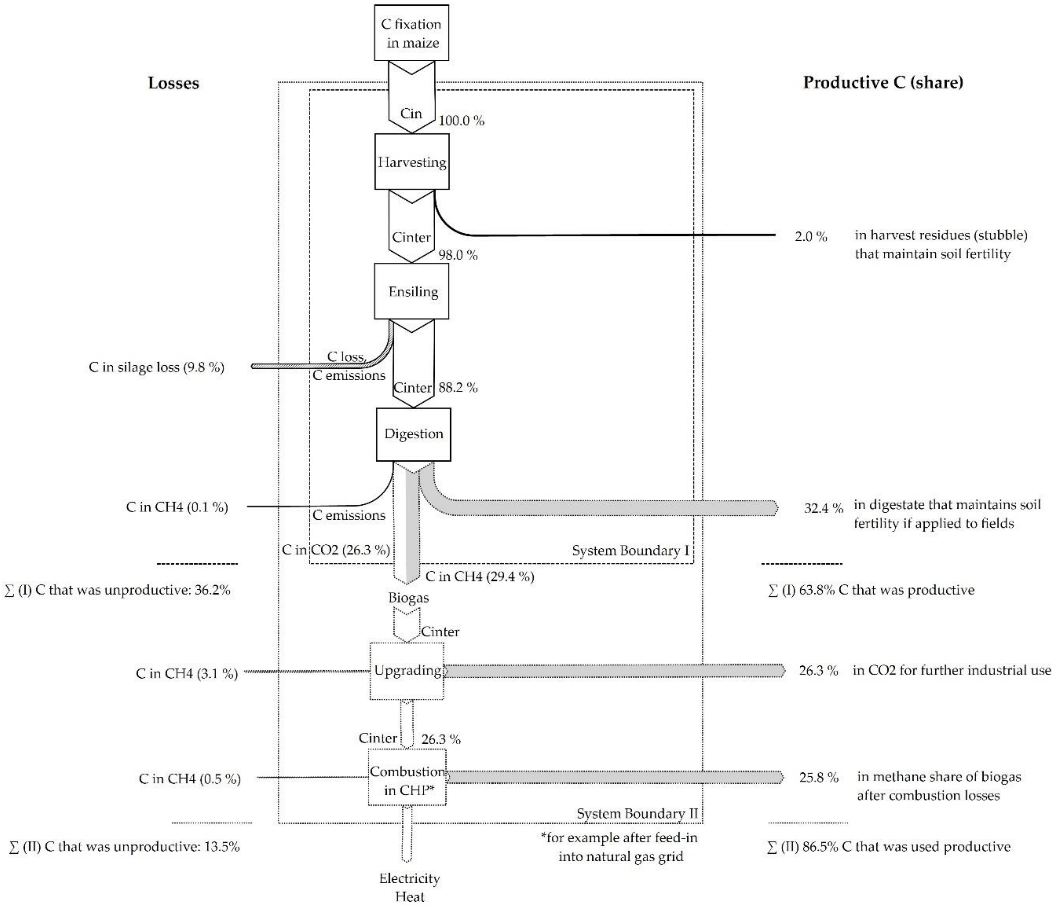


Figure 2. Carbon flows as a percentage of carbon fixed in harvestable biomass C_{in}, including stubble, and the resulting *productive* (**grey** arrows) and unproductive *C* (hatched arrows) during biogas generation from maize (Boundary I) and further upgrading to bio-methane by conversion in a combined heat and power (CHP) unit, as well as separation of CO_2 for further industrial use (Boundary II).

Approximately 25% of harvestable C_{in} is used by the microorganisms in the digester to metabolize the biomass to biogas, which, as a consequence, consists of a mixture of combustible methane and CO_2. If this CO_2 is separated from the biogas in an additional step to produce bio-methane (upgrading), the *CUDe* does not automatically increase. It could even decrease because of additional losses from 0.1%–8% during the upgrading, depending on the treatment process [38]. However, it could increase if the cleaned CO_2 share is used as a resource in further technological processes [8,39,40]. As the following example shows, upgrading biogas to bio-methane and utilization of the separated CO_2 could increase the overall *CUDe* up to 86.5% (Figure 2). We assumed a feed-in into the natural gas grid and final use in a CHP plant.

3.2. Carbon Utilization Degree of a Biomass Material Usage—Hemp Fibers as Insulation Material

The overall *Carbon Utilization Degree* may increase for some technology chains with a cascading type of biomass use (Figure 3): Hemp is used as a material for building insulation (Boundary I; *CUDe* = 20% + 2% + 10% + 63% = 95%), and after detaching, it is once again used as an insulation material.

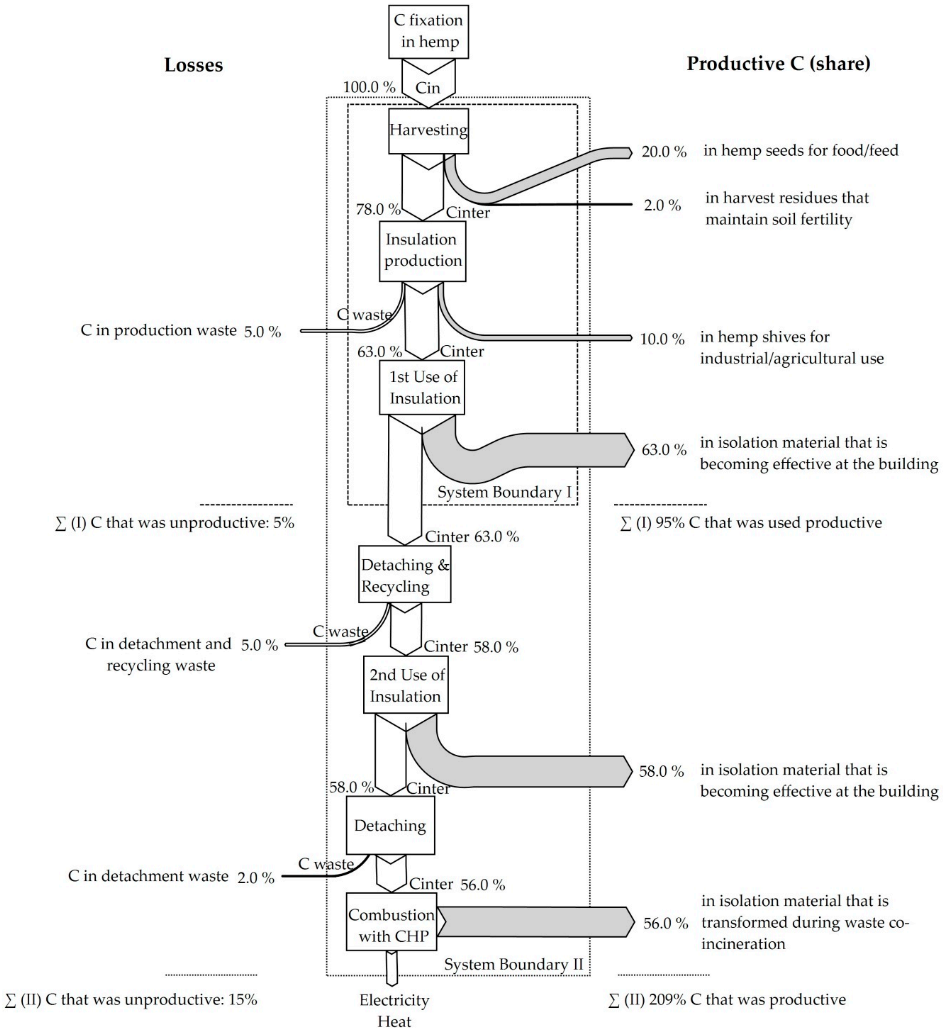


Figure 3. Carbon flows as a percentage of carbon fixed in harvestable biomass C_{in} and the resulting *productive* (**grey** arrows) and unproductive C (hatched arrows) of a cascading use of natural fibers as building insulation, followed by thermal recycling in a CHP unit.

Finally, the material is detached and incinerated with energy recovery (Boundary II). In this scenario, *CUDe* might reach 209% (*CUDe* = 20% + 2% + 10% + 63% + 58% + 56%) for the transformation chain. Such a *CUDe* value greater than 100% represents cascading C use which is explained at the end of Section 2.

4. Discussion of the Approach

4.1. Impact-Oriented Approaches vs. Resource-Use-Oriented Approaches for Policy Decision Support

Numerous assessment approaches have been published within the last twenty-five years that address carbon and that inherently use a productivity concept. Some of their specifications are listed in Table A1 and are compared to our *Carbon Utilization Degree* approach. Mainly, they address the sustainability goal of 'avoiding climate change' and thus are, by definition, impact-oriented assessments: Emissions of CO_2 and other GHGs are to be reduced because of their negative effects if they are released into the atmosphere. However, their names and/or methodological approaches suggest that they are productivity-oriented.

To achieve the sustainability goal of 'avoiding climate change', policy makers can choose between different regulatory methods: emission pricing (carbon taxes or 'cap and trade') or technology mandates and performance standards [41]. Some policy instruments are currently in place for carbon pricing, for example, the European Union Emission Trading System (EU ETS) [42]. So far, mainly energy-intensive sectors, such as power generation and manufacturing industries, participate in the scheme. During the transition to a bio-economy, bioenergy may be included in the carbon trading market, calling for a reliable assessment of its CO_2 emissions. A pricing approach transforms C as CO_2 into a limited resource. For both pricing and standards, we need profound knowledge of the biogenic carbon emissions associated with the biomass conversion processes. It would not be appropriate to assume carbon neutrality of biomass (setting its emission factor to zero) or to calculate CO_2 emissions from the biomass C content. This has been discussed comprehensively in the scientific literature on biofuels [15,43,44]. Additionally, emissions from biomass conversion can vary depending on the type of biomass used, the process conditions and the conversion technology or emission reduction measures implemented [45]. Admittedly, this is also true for fossil-based energy carriers.

If we consider the difficulties to reliably assess biogenic process emissions and that additional criteria need to be taken into account to ensure that the transition to bio-economies is performed in a sustainable way (i.e., not only addressing climate impact), then we should focus on the other policy options, technology mandates and performance standards. This is even truer because recent projections suggest that European targets—set at 40% emission reductions compared to 1990 [46]—will probably not be met by the current policies (e.g., by the EU ETS, which is a pricing instrument [47]). If, in society in general, a transition could be initialized to improve efficient C use, i.e., a paradigm shift to 'C is a resource' from 'C is a threat', then more actors could enter the field to achieve the goal [48]. Such a paradigm shift by implementing efficiency standards for (biomass) conversion technologies could be a promising way to develop a sustainable transition pathway. Additionally, the strategy could go hand-in-hand with other public goals to increase efficient resource use [49] and energy efficiency [50].

Reliable criteria and appropriate indicators are necessary for such standards. To fill this gap, we proposed the *CUDe* approach. Optimization options could be identified at the process level, which subsequently could have an impact on the design of entire transformation chains. For bioenergy, the *CUDe* could offer a regulatory instrument, for instance, if a *CUDe* level exceeds a specific threshold, then incentives are paid, or fees fall due if a level is not reached.

Even if *CUDe* as an indicator might not influence policy making directly, it could have the potential to open debates and perspectives, which recently was identified as one important characteristic of indicators [51]. On the other hand, Runhaar [52] recently stated that the performance of integration tools is modest ("tools that aim to steer particular actors in such a way that they are stimulated (or forced) to incorporate environmental objectives in their policies or practices") and expectations should be realistic. Nevertheless, we think that *CUDe* could complement the existing assessment approaches' toolbox as an additional indicator in a way that a 'dashboard' is provided, where different indicators are presented (as suggested by Jakob and Edenhofer [53]). Furthermore, a combination of integrated assessment models with those of other disciplines was recently identified as necessary to support policy formation and action toward low-carbon transitions [54]. As with the concept of 'umbrella' species that was proposed in conservation biology in the 1980s [55], *CUDe* could help to address more than one sustainability goal—avoiding climate change—because it inherently considers the enhancement or at least maintenance of soil productivity.

4.2. Boundaries, Time Frames, and Carbon Sequestration

An important aspect of the *CUDe* approach is the definition that the C baseline is set at the carbon content of the theoretically harvestable biomass in the field. This addresses the aspect that input levels in agriculture are site-dependent (climate, soils, etc.). It is not our focus to advise where (and how) to produce biomass(-C) but to advise how we should use it. Methodologies are already available that are more suitable to choose biomass production ways, for example Life Cycle Assessment (LCA, [56,57]).

The *CUDe* system boundary includes all possible co-products in the analysis that a crop might yield. It also accounts for the fact that in the future, new technology options or market situations might be available to make the C in the harvest residues economically useful. Furthermore, this boundary enables, to some extent, the inclusion of ecological effects in the assessment, for example, the impacts on the humus balance and soil productivity. A prominent example is the use of straw, which could either be left in the field to, among other effects, replenish soil organic carbon pools or be used in stables for bedding or as an energy carrier for combustion [58]. In either use, the C content of the straw would be considered *productive*.

Another example of the ecological effects is the ecosystem service 'provision of important habitats'. In forestry, stubble use has been propagated in GHG mitigation studies [59]. This could trigger a loss of important habitats. Our baseline choice might reduce this pressure because the C in stubble is already considered *productive* and *CUDe* would not increase further.

The end-point of a *CUDe* analysis is not fixed, and it can be extended depending on the cycles of biomass use if the technology under study starts to use the carbon from biomass in a cascading way (as in Section 3.2). *CUDe* values greater than 100% indicate cascading usage. The same effect has been reported from a cascade factor in the wood industry [60]. One could argue that additional energy—which is mostly C-based today—is necessary for C recycling. As already highlighted, biomass transformation systems should be assessed with a variety of metrics including energy-related ones, such as cumulated energy demand [61]. Hence, the concept could in the future be expanded by a combined presentation with such an energy-related metric, for example in a 2-dimensional metric to illustrate different biomass technology pathways and visualize target corridors.

Another relevant boundary is the time frame. Fixed time frames are defined in other approaches, for example, in the *Carbon Stability Factor* (CSF) for biochar [62] (100 years, Table A1). For GHG assessments, different time horizons are used depending on the scope of the study and the longevity of the involved greenhouse gases. The published global warming potentials (GWP) with horizons of 20, 100 or 500 years reflect this [63]. These GWP characterization factors have been changing over time due to progress in the scientific understanding of atmospheric processes. The *CUDe* approach does not have a fixed time horizon by definition and, accordingly, does not rely on such external factors and is robust against changes in external metrics. Calculations of *CUDe* can be performed for different time horizons, but they must be properly communicated.

Biomass carbon can be stored in different pools with different time frames. In the context of climate change mitigation, the sequestration effect is an important aspect. However, the *CUDe* approach does not explicitly focus on this topic. This can be observed by how the C in soils is addressed. *CUDe* considers the C, which is returned to the soil, as *productive* (e.g., it could improve soil fertility), even though it is eventually re-emitted to the atmosphere by soil biota activity. This represents the perception that *CUDe* is an approach for efficient C use in general, not just with a focus on climate change mitigation. In the latter case, it would be necessary to account for additional benefits for C that is stored long-term.

Multi-product systems, such as most biomass conversion systems, can be assessed by numerous approaches. The methodologies account for possible product and co-product diversity. For instance, LCA, as an impact-oriented assessment, uses, among others, 'system enlargement'. However, system enlargement can lead to increasing uncertainty in the analysis' outcome due to the diversity of possible biomass uses and potential reference products. *CUDe* considers all biomass co-products in its calculation directly; hence, it avoids the difficulty of defining reference products and reduces the time for the analyses because no additional data need to be gathered.

The *CUDe* approach could help to compare biomass transformation systems where biomass is used for energetic and/or material purposes. Although different biomasses have similar C contents per dry matter (Table 1), they can lead to differing *CUDe* values as one biomass can be more suitable for a certain purpose than another. Thus, the approach considers different biomasses as well as the design of biomass conversion chains as a whole.

5. Conclusions and Outlook

Existing approaches to assessing C, which are used to analyze biomass conversion chains, have some critical issues to address. These include external effects, such as changes in the underlying assumptions. Robust indicators for decision support for biomass use are needed. We proposed *Carbon Utilization Degree CUDe* as an indicator that represents the efficient use of carbon as a production factor in biomass conversion processes for energetic and material use. This indicator could reflect a paradigm shift that CO_2 is not a threat but a finite resource that requires suitable management. *CUDe*, as a supplementary indicator for existing methods, could aid in the design of policies for biomass transformation pathways by defining threshold values for efficient carbon use in conversion processes. The approach needs additional testing to prove its applicability even to more complex pathways than those provided in this manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

C	Carbon
CF	Characterization factor
CH_4	Methane
CHP	Combined Heat and Power
$C_{emissions}$	Carbon in gaseous losses, e.g., in CO_2 or CH_4
C_{in}	Carbon content in biomass dry matter that enters the biomass conversion chain
C_{inter}	Carbon in intermediate products
CO_2	Carbon dioxide
$C_{productive}$	Carbon that becomes productive in a wide anthropocentric view
$C_{products}$	Carbon in final products and co-products
CSF	Carbon Stability Factor
CUDe	Carbon Utilization Degree [%]
C_{waste}	Carbon in waste, e.g., in production waste
EU ETS	European Union Emissions Trading System
GDP	Gross Domestic Product
GHG	Greenhouse Gas(es)
GWP	Global Warming Potential(s)
L.	Carl von Linné (botanical author citation)
LCA	Life Cycle Assessment
MACC	Marginal Abatement Cost Curves
NPP	Net Primary Production
NEP	Net Ecosystem Production

Appendix A

Table A1. Overview of some productivity approaches dealing with carbon. *CUDe—Carbon Utilization Degree*, CSF—Carbon Stability Factor, GDP—Gross Domestic Product, GHG—Greenhouse Gases, MACC—Marginal Abatement Cost Curves, NPP/NEP—Net Primary Productivity/Net Ecosystem Productivity, S&P/IFCI—Standard & Poor's International Finance Corporation Indexes.

Name	**NPP/NEP**	**Carbon Productivity**	**Carbon Intensity**	**C Balance**	**MACC**	**S&P/IFCI Carbon Efficient Index**	**CSF**	**Carbon Efficiency**	***CUDe***
Denominator	Unit of area and unit of time	Unit of emitted CO_2[a] per period per country	Unit of sales		Unit of mitigated CO_{2e}		Unit of C in fresh biochar	Total C present in reactants	Carbon fixed in harvestable biomass
Numerator	Unit of generated energy (or biomass)	Unit of the specific value of GDP in the same period	C emissions		Unit of cost of a technology		Unit of biochar C after 100 years	Amount of C in product × 100	*Productive* C
Unit	$g \cdot C \cdot m^{-2} \cdot year^{-1}$	Currency kg^{-1} $CO_{2\ emitted}$	kg C emitted/ unit of sales $	%	Currency t^{-1} $CO_{2e\ mitigated}$		Dimensionless or %	%	%
Baseline	Usually one year	Arbitrary period length, often one year			Marginal cost and projected emissions of reference technology		100 years	Not stated	Adjustable
Description	Rate at which energy is converted into biomass	Used in economics; reciprocal of carbon emission intensity per unit of GDP [b]; "Reflects economic benefits yielding from per unit of CO_2 emission" [c]			"A MAC curve is a graph that indicates the marginal cost (the cost of the last unit) of emission abatement for varying amounts of emission reduction." [d]		Remaining C in carbonized biomass (biochar) after labile and instable fractions are released		Ratio of productive C to initial C_{in} in the biomass
Target audience	Science	Policy			Policy		Science	Pharmaceutical industry	Policy
Methodology	1. Measure biomass production (for example: destructive measurements /NPP; flux measurements /NEP; models) 2. Convert biomass dry matter according to C contents	1. Define period 2. Look up GDP and fossil resource use for that period 3. Calculate CO_2 emissions from resource use via emission factors			1. Define baselines (emissions in target year; technology) 2. Identify and describe possible abatement technologies and their costs for the target year 3. Plot abatement potentials on *x*-axis and costs per ton on *y*-axis		1. Measure C content in fresh biochar 2. Identify labile (after a few weeks) and instable (e.g., via accelerated ageing methods) C shares in original biochar		Please refer to Scheme 1

Table A1. *Cont.*

Name	**NPP/NEP**	**Carbon Productivity**	**Carbon Intensity**	**C Balance**	**MACC**	**S&P/IFCI Carbon Efficient Index**	**CSF**	**Carbon Efficiency**	***CUDe***
Benefits	In combination with modelling approaches, shortcomings (see below) can be overcome.	Comparison of different nations possible Different development stages visible			Comparison of different nations possible Illustrative tool to present mitigation options		Intuitive to understand Reflects C sequestration Percentages in different products in multi-product systems can be summed up.	Simplified formula takes into account the stoichiometry of reactants and products of interest to the pharmaceutical industry where the development of carbon skeletons is key to their work.	Paradigm change to carbon being an asset of the bio-economy instead of a threat Reflects the C use efficiency of the conversion process
Shortcomings	Representativeness for analyzed biomes and attributed area critical Accounting for land use change	Only fossil CO_2 (no other GHG included, for example, nitrous oxide, CH4) Inherent connection to economic cycle and growth paradigm			Static representation of costs for single years; no allocation of costs to ancillary benefits of GHG mitigation; lack of transparency; poor treatment of uncertainty, inter-temporal dynamics, interactions between sectors (see details in d)		No additional necessary C for conversion processes considered CSF uncertain due to the wide range of assumed residence times of C remaining in the biochar after application to soils (293–9259 years [e])		No complete GHG assessment (only CO_2 and CH_4 included) *CUDe* is not directly related to output quantity No energy-related C input considered
References	[64]	[6] [c], [23] [b], [65] [a]. [a] uses CO_2 equivalents as a basis.	Only sparse information given in [66]	[67]	[68], [69] [d]	[70]	[62] [e], [71,72]	Acc. to [73] developed at GlaxoSmithKline (GSK); no original source available	This manuscript

Unless otherwise indicated by superscripts, information was taken from cited References in the last row.

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