Does renewable mean good for climate? Biogenic carbon in climate impact assessments of biomass utilization

Jan Matuštík1 | Vladimír Kočí1,2

1Faculty of Environmental Technology, University of Chemistry and Technology Prague, Prague, Czech Republic
2Faculty of Architecture, Czech Technical University, Prague, Czech Republic

Correspondence
Jan Matuštík, Faculty of Environmental Technology, University of Chemistry and Technology Prague; Technická 5, 160 00 Prague, Czech Republic. Email: matustij@vscht.cz

Funding information
European Commission, Grant/Award Number: CZ.02.1.01/0.0/0.0/17_049/0008407

Abstract
Using biomass to substitute fossil resources is seen as one of the sustainable ways to tackle climate change. Yet not all biomass projects can be a priori declared beneficial. A climate impact assessment, such as life cycle assessment or carbon footprint, is crucial for a science-based policy recommendation. However, those assessments can often be incomplete, especially since many of those adopt an assumption that biogenic CO₂ emissions cause no harm to the climate and do not need to be accounted. Such a simplistic “neutrality assumption” can lead to inaccurate results and thus to undesired consequences. This article synthesizes and further develops the diverse argumentation against the “neutrality assumption,” especially regarding the complexity of biomass production, differences in the timing of emission, allocation procedure, and climate change characterization methodology. Thus, the article draws a broader picture of the complex issue of biomass projects and argues for more comprehensive assessments.

KEYWORDS
bioenergy, biogenic carbon, biomass, carbon footprint, climate change, life cycle assessment

1 | INTRODUCTION

Utilization of biomass to substitute fossil fuels is increasingly seen as one of the ways to mitigate the ongoing climate change (Camia et al., 2021). Although the sources of biomass can be very diverse, biomass is often regarded as a uniform category in the context of climate policy. Similarly in climate impact assessments, such as carbon footprints or life cycle assessment (LCA), the differences among various kinds of biomass producing ecosystems are largely ignored. This approach is, among others, manifested in the so-called “neutrality assumption,” the view that biogenic carbon emissions (i.e., the CO₂ flowing in and out of biomass stocks) do not contribute to climate change.

Although this issue has been debated as long as there were studies where biomass was included, Vogtländer et al. (2014) assert that a majority of scientists and practitioners included in debates about the issue agreed “the best approach in LCA is not to calculate biogenic CO₂”; and, indeed, it is the most common way of dealing with biogenic carbon (Wilosó et al., 2016). This “neutrality assumption” is based on the general notion that all the carbon present in biomass and emitted from it was taken up, in the first place, during photosynthesis. Hence, the CO₂ sequestered, and the CO₂ emitted ultimately cancel each other out, and the balance is zero. This argument seems obvious when only the directly used biomass is accounted, such as timber or grain.
Still, the neutrality assumption has been criticized from various positions because it overlooks many potentially crucial aspects. Firstly, biomass harvesting affects other carbon pools on a broader landscape level, beyond the used biomass itself. Furthermore, even a net-zero carbon balance does not necessarily mean there is no climate impact (Helin et al., 2013), especially considering that uptake and emission can occur in very distant times. The results of environmental assessments can also be strongly affected by the way the burdens are allocated between side-products or along a recycling cascade, and which climate impact assessment methodology is chosen to characterize the greenhouse gas (GHG) flows. Combined with the assumptions on other issues, such as change in albedo or N₂O and CH₄ emissions, the results of environmental assessments can be largely variable, with ambiguous policy recommendations. Although there already are several articles pointing to the dangers of adopting the neutrality assumption, the critique usually aims at a single defect. This article aims to synthesize and further develop the diverse argumentation against the narrow approach and draw a broader picture of the complex issue of a complete climate impact assessment of biomass using projects.

2 | BIOMASS PRODUCTION

Unlike in a factory, where the production mechanisms are duly set and controlled, biomass is produced in complex ecosystems dependent on many factors beyond man’s direct control. Healthy soil, sufficient water supply, or suitable weather conditions are but a few of the many conditions affecting yield and thus the efficiency of a project. But this also stands true reciprocally—the production operations affect those very conditions. This makes an exhaustive environmental assessment of biomass utilization much more complicated than of most other materials. Small wonder then that many scientists tend to simplify their models, or, ultimately, adopt the “neutrality assumption.” However, using the words of John D. Sterman (2002): “The most important assumptions of a model are not in the equations, but what’s not in them…” Since agricultural land covers nearly 37% of global land area, and forest land covers 31% of the world (FAO, 2020), the way it is treated makes a crucial difference.

2.1 | Carbon pools

The terrestrial carbon pool is the third largest, after the geologic and oceanic (Lal et al., 2021). It consists of two main components: the obvious one is biosphere, including live vegetation and detritus, estimated at 620 Pg (Lal, 2020); however, the often disregarded soil carbon pool, estimated at 2500 Pg, is three times larger than atmosphere (880 Pg) (Lal et al., 2021).

Vegetation and its rate of growth is what predominantly determines the overall carbon dynamics of biosphere, since that is where carbon uptake happens (Virto et al., 2012). Yet it is not only the primary productivity but also how much of the carbon stays on site and what is its nature. Indeed, the soil carbon storage can be a more important determinant of climate impacts than aboveground biomass (Yang & Tilman, 2020), and it largely depends on agricultural practice. Although mechanisms aiming at increasing short-term production, such as ploughing, use of mineral fertilizers, or the push to use all available biomass, would seemingly result in increased carbon sequestration, those measures also lead to soil carbon depletion, depending on the procedure and environmental conditions (Bhattacharyya et al., 2021). The effect on soil carbon is often ignored in assessments though, also because a prediction of long-term effects on soil is very difficult (Dash et al., 2019). For a comprehensive assessment, instead of focusing solely on immediate productivity, a thought should also be given to the way the crops are produced and its sustainability (FAO, 2019; Yang et al., 2018). Adoption of some unconventional techniques such as no-tillage, agroforestry, or use of cover crops could be of a great benefit, not only from the point of view of climate (Lal et al., 2021). However, “there is no single technology for sustainable management of C pool in world’s soils and biota” (Lal et al., 2012). Hence, here lies an opportunity for environmental impact assessments, but also a danger, if the assessments are incomplete or simply wrong.

Even bigger potential for climate change mitigation is seen in forests. Trees, not only in forests, take up carbon, and thus constitute a significant, though variable, carbon pool (Brandt et al., 2020). However, mostly the trees in forests and plantations make the core of biomass utilization projects. Accordingly, trees (wood) are usually the only part of forests that is included in an assessment. In this case, harvesting trees indeed seems carbon neutral from a long term or a landscape perspective—if the total area of a forested land does not change, the trees that are cut-down are replaced by new ones in later time or in another place (Vogtländer et al., 2014). This assumption obviously leads to measures supporting fast growth and fast turnover rate, that is, intensively managed forests and plantations.

Another forest carbon pool is the forest floor, where some amount of carbon is stored in litter, debris, etc. Overall, this carbon pool is small, in comparison with the others (Houghton, 2012), yet none the less important for C dynamics. Decomposition of slash and deadwood is not only a major source of CO₂ emission from a forest, especially in the years after harvest, but also an important
source of nutrients and a supply of carbon for the largest carbon pool, the soil. Generally, about half of the soil carbon is present in the topsoil layer, to the depth of approximately 30 cm, which directly communicates with atmosphere and the decaying organic matter (Balesdent et al., 2018). Another half is stored in the subsoil layers, below 30 cm. The dynamics of carbon in subsoil is about seven times slower than that of topsoil; here the intermediate age of mid-profile horizons (20–70 cm) is between 100–1000 years, and the age of carbon in the deeper layers is millennia (Balesdent et al., 2018).

The size of soil carbon pool and its dynamics strongly depend on the type of ecosystem, its management, availability of nutrients, or climatic factors, especially temperature and precipitation. Therefore, the effect of forestry practice on soil C in largely variable (Mayer et al., 2020). Yet intensive whole-tree harvesting, soil preparation, use of heavy machinery, drainage, and other techniques promoting higher biomass extraction in most cases lead to significant soil C losses (Achat et al., 2015; Mayer et al., 2020). Overall, the measures promoting productivity of the forest can have a positive impact on carbon sequestration, but local conditions should be considered, and disturbances should be minimized (Jandl et al., 2007).

2.2 | Reference systems

With the Earth having a limited land area, using a piece of land for one purpose always comes at an expense of another opportunity. The act of converting one type of ecosystem (e.g., a forest) for another purpose (e.g., a cropland) is called land use change, and when it actually happens in the course of a project, it usually is included in the boundaries of the assessment. This is not the case though, when the actual conversion happened years or decades ago. Nevertheless, all impacts that occur as a result of an activity should be included in an assessment, while those that would have happened anyway should not be inventoried; which translates to the need to define a reference “no-use” or “alternative-use” scenario (Helin et al., 2013). The way a reference scenario is defined can greatly affect the judgment about the proposed project—a more harmful alternative would support executing the project, while a more advantageous alternative would discredit it. The ultimate reference scenarios are the natural ecosystems that were there before the transformation by people or that would eventually evolve were the human activity to cease: primary forests, savannahs, wetlands, and other ecosystems, depending on the local conditions.

Yet natural ecosystems are often disregarded in the assessments, partly because they are not a result of human activity, and thus people cannot claim credit for their benefits, but also because they were assumed to contribute little to climate change mitigation. Based on the long-standing tenet of ecology, the Odum’s framework (Odum, 1971), it was assumed that, following an initial growth stage, natural forests eventually reach a carbon equilibrium (Bellassen & Luyssaert, 2014). This would mean that mature forests play no active role in carbon sequestration. Yet, based on empirical data, it was found that this theory does not always correspond to reality, at least in temperate and boreal forests, which continue to accumulate carbon for centuries (Luysaert et al., 2008). On the other hand, any serious disturbance to some of the natural carbon-rich ecosystems, like for example tropical peat forests, can result in a significant increase of C emission (Prananto et al., 2020) and a substantial loss of the “old-carbon” that has been piling-up for centuries and millennia (Moore et al., 2013). Conversely, even well-meant projects like afforestation can lead to overall loss of carbon storage when a natural grassland is replaced (Lal et al., 2021).

There are several hypotheses on why old-growth forests keep on accumulating carbon, such as increased levels of CO₂ or increased N deposition (Bellassen & Luyssaert, 2014; Janssens et al., 2010). Still, it is clear that at least some ecosystems (e.g., peatlands) have always been active carbon sinks. On the other hand, after some climate thresholds are exceeded, climate change is expected to have notable negative consequences for natural ecosystems, feeding back the climate change: such as increased danger of forest fires (Stephens et al., 2013), increased tree mortality (McDowell & Allen, 2015), or increased insect pest outbreaks (Jactel et al., 2019).

However, the extent and dynamics of those effects are still uncertain and would also largely depend on the actual rate of climate change. Next to directly mitigating the climate change, another aspect in which natural ecosystems, especially forests, play a vital role is adaptation and regulation. In that matter, the other benefits of forests, for example their role in water cycling or surface temperature regulation, might be more important than carbon storage (Ellison et al., 2017), notwithstanding the greater biodiversity in natural ecosystems (Watson et al., 2018).

3 | TIMING OF EMISSION

Let us assume for a moment that utilization of biomass from sustainably managed croplands, plantations, or forests is indeed carbon neutral in the long term, meaning that CO₂ emission from biomass oxidation ultimately equals the amount taken up. Would it mean the climate impacts of such projects are zero, naught? Not necessarily.
There is another factor at play—the timing of the actual uptake and emission.

The time difference between the moment the carbon is taken in by the plant and the moment it is eventually released can be from around a year for annual crops, decades for perennial plantations, to over a century for forests. Although the yearly difference for annual crops is probably of marginal importance for climate, decades of presence/absence of a CO₂ molecule in the atmosphere can make a difference. Yet the common approach to calculating climate change impacts completely ignores this difference. Using the Global Warming Potential (GWP) method, all emissions are typically added to a single aggregate flow (Levasseur et al., 2010); hence, CO₂ uptake and emission cancel each other out, and no harm is assumed. To differentiate the timing, specific recommendations were presented in some standards, and several alternative impact assessment methodologies were proposed, which can have a notable effect on the results. What is also noteworthy regarding timing of emission is the selected time horizon during which is the impact calculated. For GHGs the time horizon is typically 100 years (Brandão et al., 2013). Yet, since there is no “natural” scientifically robust time horizon for GHGs, the selection of the 100 years (or other) is based mostly on consensus of values and preferences, which are evolving.

### 3.1 Perspectives

Moreover, whether cutting down and burning a forest is instantly considered beneficial or not can be determined by a simple choice of perspective. Combustion of biomass invariably leads to an immediate emission of carbon dioxide to the atmosphere, but what does it mean for the Earth’s climate? Do we reap the fruits of previous endeavors, or do we, thus, create a debt that needs to be paid for? In other words: is it a CO₂ previously sequestered by the trees or does the emission create a deficit in the global carbon budget that needs to be compensated by regrowth? The first perspective concurs with secondary forests, where a large part of the harvested trees were planted by people for the purpose of wood production. Hence, the sequestration is considered part of the system. Similarly, such perspective comes instinctively for plantations, especially those established on abandoned cropland with the view of carbon sequestration. However, this would imply that upon combustion there is no climate harm, since the carbon only returns back to the atmosphere; contrarily, climate benefits should be attributed for the temporal storage. Seen in this way, it is apparent that this is not what has been happening. When a forester, decades or centuries ago, planted the trees, it was only in place of those previously cut down, going way back to the first forester cutting down a naturally grown forest. Thus, every seedling replanted in a forest means only paying back the “original debt.” This may be obscured when regarding the forests that have been managed for centuries, but it is quite obvious when primary boreal or tropical forests are harvested. The second perspective is based mainly on the view of carbon budgets: to maintain a balance in the global cycles, those who disturb a carbon budget have a responsibility to see it replenished.

The debates which perspective is more appropriate cannot be decided on purely empirical grounds. There is no real difference in the physical world. Cycles of disturbance and regrowth were happening in forests even before the presence of people; it is the old chicken-and-egg dilemma. Yet adopting either of the perspectives can make a lot of difference in the outcomes of assessments and subsequent policy recommendations. The “before” perspective supports exploitation of the available biomass resources. In this view, the biomass is carbon neutral even if no regrowth occurred and desert remained. The “after” perspective takes a more precautionary approach, making it decades until the emission is finally compensated (Head et al., 2019). The unpredictability of the future needs to be considered with this approach as well, when there is, for example, a risk that with ongoing climate change the forest will never fully recover. With the second approach, the benefits of biomass utilization are far less obvious.

### 3.2 Temporary storage—Carbon in products

A major delay of CO₂ emission happens when the carbon is stored in long-lived biomass products, such as furniture or construction materials, which effectively keep the carbon in anthroposphere before eventually being oxidized (Guest et al., 2013). On the one hand, it can be argued that the delay in radiative forcing of several decades is negligible from a long-term perspective (Pawelzik et al., 2013). On the other hand, it can be seen as buying some time until a better long-term solution occurs. Considering how close the planetary tipping-points are (IPCC, 2021), such arguments should not be dismissed; although without the second step (research and societal transformation) the problem would just return later and stronger (Kirschbaum, 2006). Ignoring the emission delay can be problematic not only from the “physical” perspective, but also from a formal-methodological perspective. For example, treating a delayed CO₂ emission that occurs in, say, 50 years with the same 100-year characterization factor means that while
for the immediate emission the accounting time horizon is 100 years, for the delayed one it would be 150 years, that is, the time horizon is inconsistent (Levasseur et al., 2013). Yet the emission delay and C storage in products are rarely considered in LCA or carbon footprint standards (Ahlgren et al., 2015; Pawelzik et al., 2013). Thus, no benefit to longer cascade systems and material recycling in comparison with immediate combustion is usually given.

4 | ALLOCATION

When all the harvested biomass is directly used for bioenergy, the question where to attribute the burdens is quite simple. Allocation gets more complicated when a part of the biomass is used to create products, the products are reused and recycled, while the rest is used for bioenergy. With the drive for a circular economy and sustainability, this situation is likely to become more and more common. A typical way to avoid allocation is system expansion or substitution (Van Der Voet et al., 2010). Yet system expansion is not always applicable and does not alone solve all allocation issues, so another way needs to be found. Generally, one of the main criteria for allocation is whether the flow is considered a product or a waste (Guinée et al., 2009). In this way, all the environmental inputs and outputs are attributed to the product and none to the waste. However, this is just a matter of perspective and the perceived function of the system. What is a waste for some, can be a resource for others. How, then, should be the environmental impacts (and benefits) divided between the multiple co-products and down the recycling cascade?

There are multiple principles to partition inputs and outputs in multifunctional processes: by mass, volume, economic value, etc. (Pelletier et al., 2015). Although maximal consistency with respect to the purpose and nature of the study should be aimed for, the bottom-line is, there is not a one “correct” approach to allocation. Any way the flows are divided in is inherently embedded with value-judgments concerning causality, responsibility, or fairness, which can ultimately presuppose the outcome of the assessment. This gets even more tricky with biomass, because, in contrast to typical industrial processes, there are also potential environmental benefits of carbon sequestration to be divided. For example, the rationale behind economic allocation is that the flow bringing more revenue is the main driver of the process and therefore should be attributed the main portion of environmental impact. However, if carbon credits come in play the original logic is reversed—the overall climate impact of the main product is effectively diminished as it is attributed most of the credits. Each specific situation can bring about different issues with different allocation methods.

The reversal of the original logic of an allocation method can be even more prominent when it is applied to recycling. Here, the way environmental impacts are allocated (Schrijvers et al., 2016) is usually directly driven by the opinion about which behavior should be encouraged. However, with biogenic carbon credits, the method that would normally incentivize reuse and recycling can now support short cycles and primary material extraction (Finkbeiner et al., 2013). Therefore, the rationale behind which method of allocation is selected should always be thoroughly justified and carefully interpreted.

5 | CLIMATE IMPACT ASSESSMENT METHODOLOGIES

After a successful quantification of all relevant GHG flows from the system, there is one last step, climate impact assessment. However, there is not just one dimension of climate change, but, as it was argued, there are at least three different kinds of negative consequences: those directly related to surface temperature, the rate of change, and the cumulative temperature increase (Kirschbaum, 2006). How adverse is each of those effects depends, next to the size of the GHG emission, largely on its timing. Consequently, there are several different methodologies that capture different perspectives of the issue, and hence can provide contrasting results.

The by far most common indicator is the GWP (Myhre et al., 2013). GWP predicts cumulative energy added to the climate system by the GHG over the set time horizon, in relation to CO₂. However, this is not directly equal to temperature change or another climatic variable. Despite its limitations, GWP has become the default metric in Kyoto Protocol and most of the standards and guidelines. Another well-known metric, also presented by the IPCC, is the Global Temperature change Potential (GTP), which allows to translate the radiative forcing of a GHG to a physical climate variable—temperature (Myhre et al., 2013). The intrinsic character of this metric also raises a fundamental question: what does temperature at a particular date in the future tell of the character and impact of climate change (Brandão et al., 2019)?

To capture the temporal dimension missing in the GWP and GTP, other metrics were developed, such as the Moura-Costa method, which assumes credit for temporal carbon storage based on the time integral of the CO₂ residence time and decay-curve (Moura Costa & Wilson, 2000). An analogous approach based on the decay curve is taken in the Lashof method (Fearnside et al., 2000). Here, the decay curve is shifted by the delay time. The part that
lays beyond the set time horizon is then cut off, and the integral under the remaining part is calculated (Brandão et al., 2019). These methods were further refined, for example, with longer time horizons (Müller-Wenk & Brandão, 2010).

The dynamic LCA method (Levasseur et al., 2010) allows to calculate instantaneous and cumulative climate impacts by providing dynamic characterization factors, depicting the global warming impact at a particular year (Levasseur et al., 2013). It allows to display the trend in radiative forcing over the assessment time horizon, not only the cumulative value at the end. The method of biogenic GWP (GWPbio) calculates the radiative forcing caused by biomass combustion until the moment the carbon is sequestered by plant regrowth (Cherubini et al., 2016). Another alternative method is the climate-change impact potential developed by Kirschbaum (2014) to represent the three aspects of climate change.

Brandão et al. (2019) compared these and several other climate change impact methodologies on three model case studies. While for annual crops, where the time-difference between emission and sequestration is low, the differences between the methodologies are rather low, the results of forest bioenergy systems vastly diverged with different methodologies, taking opposite directions. Next to the timing of emission, the original land use was important as well (Brandão et al., 2019). With the effect of the choice of impact assessment methodology in view, the importance of using consensus methodologies for results to be comparable is further stressed. However, assessing only a single aspect of the issue could lead to overlooking another problem. Thus, it was recommended to use at least two complementary methods capturing both short-term and long-term effects (Jolliet et al., 2018).

6 POLICY IMPLICATIONS AND CONCLUSION

Biomass is regarded as renewable resource. Although it is dubitable whether the rich and complex ecosystems of, for example, tropical forests could recover on a human time scale to its original state, from the narrow perspective of single plants, biomass can indeed be renewed fairly quickly. In this narrow perspective, using biomass to substitute fossil resources for energy and products appears as an opportune alternative. Hence, exploitation of the available bioresources and intensive management to increase biomass growth has been advocated (Guest et al., 2013). According to Favero et al. (2020) and their economic model, supporting biomass exploitation and utilization would ultimately lead to increased carbon stocks, next to the benefits of avoided fossil emissions. However, as it was shown in the previous sections, there are many variables, assumptions, and decisions to be taken during an assessment of a biomass project that affect the outcome. The model of Favero et al. (2020) is an archetypical example, as they conclude that increased demand for forest products would result in price growth, motivating afforestation and efficient management of those forests. Yet they do not, among others, consider the fact that while cutting-down a forest brings an immediate revenue, the profit from afforestation, replanting, and management comes (if ever) after many decades. A much more likely outcome of increased demand seems to be increased biomass harvesting with no regard for other values of those ecosystems and massive deforestation in old-growth boreal and tropical forests. Although such predictions of behavior of the global economy are disputable and essentially impossible to empirically test and prove, there are also crucial assumptions regarding the nature of the affected ecosystems and their carbon balance. Mainly it is the assumption that unmanaged forests and plantations hold the same amount of carbon, and that natural and artificial ecosystems are essentially equivalent, disregarding the effects on soil carbon and other factors. If those were considered, the results would most likely be opposite.

Contrary to general notion, renewable does not necessarily mean “good for climate.” A crucial determinant of the overall carbon balance is what kind of ecosystem is affected or substituted. While afforestation of degraded agricultural land usually leads to increased carbon stocks, old-growth forests are often better left undisturbed (Hudiburg et al., 2011). A similarly important factor is the harvest intensity. Although low-intensity forest harvesting can be sustainable and lead to long-term carbon accumulation, intensive whole-tree harvesting significantly depletes the carbon stocks (Hammar et al., 2019), especially when heavy machinery is used. On the other hand, lowering the harvest intensity for a more sustainable practice means less biomass is available to substitute fossil resources. The recommended policy would also depend on the selected climate variables and whether short- or long-term effects are considered (Kirschbaum, 2017). Another important factor is that using biomass to produce energy does not physically reduce emission from the chimneys. The neutrality assumption in policy, can result in the situation when power plants burn wood as a substitution for coal and claim to have achieved major carbon footprint reduction (Norton et al., 2019). While “on paper” such power plants are close to being carbon neutral and are eligible to receive public subsidies, in reality they effectively contribute to higher atmospheric CO2 concentration. It is clear, then, that using biomass for energy production is not a priori beneficial or neutral for climate, but it depends on many factors (Haberl et al., 2012).

Although this article was mainly about biogenic carbon assessment, it should be stressed that climate effects of
MANAGING LAND FOR BIOMASS PRODUCTION ARE NOT JUST ABOUT CARBON BALANCE. THE CLIMATE AND TEMPERATURE ARE ALSO AFFECTED BY FACTORS LIKE SURFACE ROUGHNESS, ALBEDO, N₂O EMISSION FROM MINERAL FERTILIZER USE ETC. CHANGES IN THESE OFTEN COME AS TRADE-OFFS THAT CAN NEUTRALIZE THE CLIMATE BENEFITS (S. LUYSSAERT ET AL., 2018). FURTHERMORE, WELL-FUNCTIONING LANDSCAPE PROVIDES OTHER INVALUABLE CONTRIBUTIONS NEXT TO CARBON SEQUESTRATION. THE ROLE NATURAL ECOSYSTEMS, ESPECIALLY Forests, PLAY IN WATER CYCLING AND SURFACE TEMPERATURE REGULATION CAN BE OF AN EVEN GREATER IMPORTANCE TO ENDURE THE INCOMING CLIMATE CRISIS (ELLISON ET AL., 2017). YET THE ABILITY OF LANDSCAPE TO PROVIDE THESE SERVICES IS USUALLY SIGNIFICANTLY DIMINISHED WHEN NATURAL ECOSYSTEMS ARE MODIFIED TO MAXIMIZE YIELD (PLANTATIONS, CROPLANDS), NOTWITHSTANDING THE FACT THAT DIVERSE NATURAL ECOSYSTEMS ARE USUALLY MORE RESILIENT AND SUPPORT HIGHER BIODIVERSITY.

ACKNOWLEDGMENTS
This work was supported by the institutional support of University of Chemistry and Technology Prague. The study has been written in connection with the project Innovative and additive manufacturing technology—New technological solutions for 3D printing of metals and composite materials (Reg. No. CZ.02.1.01/0.0/0.0/17_049/0008407) financed by the structural funds of EU.

CONFLICT OF INTEREST
The authors declare that they have no conflict of interest.

ORCID
Jan Matusík @ https://orcid.org/0000-0001-9161-4160
Vladimir Kočí @ https://orcid.org/0000-0001-9428-8655

REFERENCES
Achat, D. L., Fortin, M., Landmann, G., Ringeval, B., & Augusto, L. (2015). Forest soil carbon is threatened by intensive biomass harvesting. Scientific Reports, 5. https://doi.org/10.1038/srep15991
Ahlgren, S., Björklund, A., Ekman, A., Karlsson, H., Berlin, J., Böjö, P., Eckvall, T., Finnveden, G., Janssen, M., & Strid, I. (2015). Review of methodological choices in LCA of biorefinery systems—Key issues and recommendations. Biofuels, Bioproducts and Biorefining, 9(5), 606–619. https://doi.org/10.1002/bbb.1563
Balesdent, J., Basile-Doelsch, I., Chateau, J., Cornu, S., Derrien, D., Fekiacova, Z., & Hatté, C. (2018). Atmosphere–soil carbon transfer as a function of soil depth. Nature, 559(7715), 599–602. https://doi.org/10.1038/s41586-018-0328-3
Bellasser, V., & Luysaert, S. (2014). Carbon sequestration: Managing forests in uncertain times. Nature, 506(7487), 153–155. https://doi.org/10.1038/506153a
Bhattacharyya, S. S., Leite, F. F. G. D., Adeyemi, M. A., Sarker, A. J., Cambarerti, G. S., Favero, C., Tieri, M. P., Castillo-Zacarías, C., Melchor-Martínez, E. M., Iqbal, H. M. N., & Parra-Saldivar, R. (2021). A paradigm shift to CO₂ sequestration to manage global warming—with the emphasis on developing countries. Science of the Total Environment, 790. https://doi.org/10.1016/j.scitotenv.2021.148169
Brandão, M., Kirschbaum, M. U. F., Cowie, A. L., & Hjuler, S. V. (2019). Quantifying the climate change effects of bioenergy systems: Comparison of 15 impact assessment methods. GCB Bioenergy, 11(5), 727–743. https://doi.org/10.1111/gcbb.12593
Brandão, M., Levasseur, A., Kirschbaum, M. U. F., Weidema, B. P., Cowie, A. L., Jorgensen, S. V., Hauschild, M. Z., Pennington, D. W., & Chomkhamksi, K. (2013). Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. The International Journal of Life Cycle Assessment, 18(1), 230–240. https://doi.org/10.1007/s11367-012-0451-6
Brandt, M., Tucker, C. J., Kariyaa, A., Rasmussen, K., Abel, C., Small, I., Chave, J., Rasmussen, L. V., Hiernaux, P., Diouf, A. A., Kergoat, L., Mertz, O., Igel, C., Gieseke, F., Schöning, J., Li, S., Melocik, K., Meyer, J., Sinno, S., ... Fensholt, R. (2020). An unexpectedly large count of trees in the West African Sahara and Sahel. Nature, 587(7832), 78–82. https://doi.org/10.1038/s41586-020-2824-5
Camia, A., Giuntoli, J., Jonsson, R., Robert, N., Cazzaniga, N. E., Jasinevičius, G., Avitabile, V., Grassi, G., Barredo, J. I., & Mubeareka, S. (2021). The use of woody biomass for energy production in the EU. Publications Office of the European Union.
Cherubini, F., Huijbregts, M., Kindermann, G., Van Zelm, R., Van Der Velde, M., Stadler, K., & Stromman, A. H. (2016). Global spatially explicit CO₂ emission metrics for forest bioenergy. Scientific Reports, 6. https://doi.org/10.1038/srep10216
Dash, P. K., Bhattacharyya, P., Roy, K. S., Neogi, S., & Nayak, A. K. (2019). Environmental constraints’ sensitivity of soil organic carbon decomposition to temperature, management practices and climate change. Ecological Indicators, 107. https://doi.org/10.1016/j.ecolind.2019.105644
Ellison, D., Morris, C. E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., Noordwijk, M. V., Creed, I. F.,Pokorny, J., Gaveau, D., Spracklen, D. V., Tobella, A. B., Ilstedt, U., Teuling, A. J., Gebrehiwot, S. G., Sands, D. C., Muys, B., Verbist, B., ... Sullivan, C. A. (2017). Trees, forests and water: Cool insights for a hot world. Global Environmental Change, 43, 51–61. https://doi.org/10.1016/j.gloenvcha.2017.01.002
FAO, F. a. A. O. o. t. U. N. (2019). Recarbonization of global soils, A tool to support the implementation of the Korinivia joint work on agriculture. www.fao.org FAO, Food and Agriculture Organization of the United Nations. http://www.fao.org/3/ca6522en/CA6522EN.pdf
FAO, F. a. A. O. o. t. U. N. (2020). Land use indicators. http://www. fao.org/landstat/en/#!/data/EL
Faverol, A., Daigneault, A., & Sohngen, B. (2020). Forests: Carbon sequestration, biomass energy, or both? Science Advances, 6(13). https://doi.org/10.1126/sciadv.aay7692
Fearnside, P. M., Lashof, D. A., & Moura-Costa, P. (2000). Accounting for time in mitigating global warming through land-use change and forestry. Mitigation and Adaptation Strategies for Global Change, 5(3), 239–270. https://doi.org/10.1023/A:1009625122628
Finkbeiner, M., Neugebauer, S., & Berger, M. (2013). Carbon footprint of recycled biogenic products: The challenge of modelling...
CO₂ removal credits. *International Journal of Sustainable Engineering*, 6(1), 66–73. https://doi.org/10.1080/19397038.2012.663414

Guest, G., Bright, R. M., Cherubini, F., & Strømman, A. H. (2013). Consistent quantification of climate impacts due to bio-genic carbon storage across a range of bio-product systems. *Environmental Impact Assessment Review*, 43, 21–30. https://doi.org/10.1016/j.eiar.2013.05.002

Guinée, J. B., Heijungs, R., & Van Der Voet, E. (2009). A greenhouse gas indicator for bioenergy: Some theoretical issues with practical implications. *International Journal of Life Cycle Assessment*, 14(4), 328–339. https://doi.org/10.1007/s11367-009-0080-x

Haberl, H., Sprinz, D., Bonazountas, M., Cocco, P., Desaubies, Y., Henze, M., Hertel, O., Johnson, R. K., Kastrap, U., Laconte, P., Lange, E., Novak, P., Paaova, J., Reenberg, A., van den Hove, S., Vermeire, T., Wadham, P., & Searchinger, T. (2012). Correcting a fundamental error in greenhouse gas accounting related to bioenergy. *Energy Policy*, 45, 18–23. https://doi.org/10.1016/j.enpol.2012.02.051

Hammar, T., Stendahl, J., Sundberg, C., Holmström, H., & Hansson, P. A. (2019). Climate impact and energy efficiency of woody bioenergy systems from a landscape perspective. *Biomass and Bioenergy*, 120, 189–199. https://doi.org/10.1016/j.biombioe.2018.11.026

Head, M., Bernier, P., Levasseur, A., Beauregard, R., & Margni, M. (2019). Forestry carbon budget models to improve biogenic carbon accounting in life cycle assessment. *Journal of Cleaner Production*, 213, 289–299. https://doi.org/10.1016/j.jclepro.2018.12.122

Helin, T., Sokka, L., Soimakallio, S., Pingoud, K., & Pajula, T. (2013). Approaches for inclusion of forest carbon cycle in life cycle assessment—A review. *GBCB Bioenergy*, 5(5), 475–486. https://doi.org/10.1111/gcbb.12016

Houghton, R. A. (2012). Historic changes in terrestrial carbon storage. In R. Lal, K. Lorenz, R. F. Hüttel, B. U. Schneider, & J. von Braun (Eds.), *Recarbonization of the biosphere: Ecosystems and the global carbon cycle* (pp. 59–82). Springer. https://link.springer.com/chapter/10.1007/978-94-007-4159-1_4

Hudiburg, T. W., Law, B. E., Wirth, C., & Luysaert, S. (2011). Regional carbon dioxide implications of forest bioenergy production. *Nature Climate Change*, 1(8), 419–423. https://doi.org/10.1038/nclimate1264

IPCC. (2021). *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the Intergovernmental Panel on Climate Change* (V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yeleckí, R. Yu & B. Zhou, Eds.). Cambridge University Press.

Jactel, H., Koricheva, J., & Castagneyrol, B. (2019). Responses of forest insect pests to climate change: Not so simple. *Current Opinion in Insect Science*, 35, 103–108. https://doi.org/10.1016/j.cois.2019.07.010

Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D. W., Minkkinnen, K., & Byrne, K. A. (2007). How strongly can forest management influence soil carbon sequestration? *Geoderma*, 137(3–4), 253–268. https://doi.org/10.1016/j.geoderma.2006.09.003

Janssens, I. A., Dieleman, W., Luysaert, S., Subke, J.-A., Reichstein, M., Ceulemans, R., Ciais, P., Dolman, A. J., Grace, J., Matteucci, G., Papale, D., Piao, S. L., Schulze, E.-D., Tang, J., & Law, B. E. (2010). Reduction of forest soil respiration in response to nitrogen deposition. *Nature Geoscience*, 3(5), 315–322. https://doi.org/10.1038/ngeo844

Jolliet, O., Antón, A., Boulay, A.-M., Cherubini, F., Fantke, P., Levasseur, A., McKone, T. E., Michelsen, O., Milla i Canals, L., Motoshita, M., Pfister, S., Verones, F., Vigon, B., & Frischknecht, R. (2018). Global guidance on environmental life cycle impact assessment indicators: Impacts of climate change, fine particulate matter formation, water consumption and land use. *International Journal of Life Cycle Assessment*, 23(11), 2189–2207. https://doi.org/10.1007/s11367-018-1443-y

Kirschbaum, M. U. F. (2006). Temporary carbon sequestration cannot prevent climate change. *Mitigation and Adaptation Strategies for Global Change*, 11(5–6), 1151–1164. https://doi.org/10.1007/s11027-006-9027-8

Kirschbaum, M. U. F. (2014). Climate-change impact potentials as an alternative to global warming potentials. *Environmental Research Letters*, 9(3). https://doi.org/10.1088/1742-6596/9/3/034014

Kirschbaum, M. U. F. (2017). Assessing the merits of bioenergy by estimating marginal climate-change impacts. *The International Journal of Life Cycle Assessment*, 22(6), 841–852. https://doi.org/10.1038/s4136-016-1196-4

Lal, R. (2020). Managing soils for negative feedback to climate change and positive impact on food and nutritional security. *Soil Science and Plant Nutrition*, 66(1), 1–9. https://doi.org/10.1080/00380768.2020.1718548

Lal, R., Lorenz, K., Hüttel, R. F., Schneider, B. U., & Von Braun, J. (2012). Terrestrial biosphere as a source and sink of atmospheric carbon dioxide. In R. Lal, K. Lorenz, R. F. Hüttel, B. U. Schneider, & J. von Braun (Eds.), *Recarbonization of the biosphere: Ecosystems and the global carbon cycle* (pp. 1–16). Springer. https://link.springer.com/chapter/10.1007/978-94-007-4159-1_1

Lal, R., Monger, C., Nave, L., & Smith, P. (2021). The role of soil in regulation of climate. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 376(1834). https://doi.org/10.1098/rstb.2021.0084

Levasseur, A., Lesage, P., Margni, M., Deschénes, L., & Samson, R. (2010). Considering time in LCA: Dynamic LCA and its application to global warming impact assessments. *Environmental Science and Technology*, 44(8), 3169–3174. https://doi.org/10.1021/es9030003

Levasseur, A., Lesage, P., Margni, M., & Samson, R. (2013). Biogenic carbon and temporary storage addressed with dynamic life cycle assessment. *Journal of Industrial Ecology*, 17(1), 117–128. https://doi.org/10.1111/j.1530-9290.2012.00503.x

Luysaert, S., Marie, G., Valade, A., Chen, Y.-Y., Njakou Djomo, S., Ryder, J., Otto, J., Naudts, K., Lanse, A. S., Ghattas, J., & McGrath, M. J. (2018). Trade-offs in using European forests to meet climate objectives. *Nature*, 562(7726), 259–262. https://doi.org/10.1038/s41586-018-0577-1

Luysaert, S., Schulze, E.-D., Börner, A., Knöhl, A., Hessenmöller, D., Law, B. E., Ciais, P., & Grace, J. (2008). Old-growth forests as global carbon sinks. *Nature*, 455(7210), 213–215. https://doi.org/10.1038/nature07276

Mayer, M., Prescott, C. E., Abaker, W. E. A., Augusto, L., Cécillon, L., Ferreira, G. W. D., Vesterdal, L., James, J., Jandl, R., Katzensteiner, K., Laclau, J.-P., Laganère, J., Nouvellon, Y., Paré, D., Stantuff, J. A., Vangelova, E. I., & Vesterdal, L. (2020).
Moore, S., Evans, C. D., Page, S. E., Garnett, M. H., Jones, T. G., McDowell, N. G., & Allen, C. D. (2015). Darcy’s law predicts widespread forest mortality under climate warming. *Nature Climate Change*, 5(7), 669–672. https://doi.org/10.1038/nclimate2641

McDowell, N. G., & Allen, C. D. (2015). Darcy’s law predicts widespread forest mortality under climate warming. *Nature Climate Change*, 5(7), 669–672. https://doi.org/10.1038/nclimate2641

Moore, S., Evans, C. D., Page, S. E., Garnett, M. H., Jones, T. G., Freeman, C., Hooijer, A., Wiltshire, A. J., Linim, S. H., & Gauci, V. (2013). Deep instability of deforested tropical peatlands revealed by fluvial organic carbon fluxes. *Nature*, 493(7434), 660–663. https://doi.org/10.1038/nature11818

Moura Costa, P., & Wilson, C. (2000). An equivalence factor between *Müller-Wenk*, R., & Brandão, M. (2010). Climatic impact of land use in LCA-carbon transfers between vegetation/soil and air. *International Journal of Life Cycle Assessment*, 15(2), 172–182. https://doi.org/10.1007/s11367-009-0144-y

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., & Zhan, H. (2013). Anthropicogenic and natural radiative forcing. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgle (Ed.), *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Norton, M., Baldi, A., Buda, V., Carli, B., Cudlin, P., Jones, M. B., Korhola, A., Michalski, R., Novo, F., Oszláni, J., Santos, F. D., Schink, B., Shepherd, J., Vet, L., Walloe, L., & Wijkman, A. (2019). Serious mismatches continue between science and policy in forest bioenergy. *GCB Bioenergy*, 11(11), 1256–1263. https://doi.org/10.1111/gcbb.12643

Oдум, E. (1971). P. 1969. The strategy of ecosystem development. *Science*, 164(3877), 262–270.

Pawelzik, P., Carus, M., Hotchkiss, J., Narayan, R., Selke, S., Wellisch, M., Weiss, M., Wicke, B., & Patel, M. K. (2013). Critical aspects in the life cycle assessment (LCA) of bio-based materials—Reviewing methodologies and deriving recommendations. *Resources, Conservation and Recycling*, 73, 211–228. https://doi.org/10.1016/j.resconrec.2013.02.006

Pelletier, N., Ardente, F., Brandão, M., De Camillis, C., & Pennington, D. (2015). Rationales for and limitations of preferred solutions for multi-functionality problems in LCA: Is increased consistency possible? *International Journal of Life Cycle Assessment*, 20(1), 74–86. https://doi.org/10.1007/s11367-014-0812-4

Prananto, J. A., Minasny, B., Comeau, L. P., Rudiyanto, R., & Grace, P. (2020). Drainage increases CO₂ and N₂O emissions from tropical peat soils. *Global Change Biology*, 26(8), 4583–4600. https://doi.org/10.1111/gcb.15147

Schrijvers, D. L., Loubet, P., & Sonnemann, G. (2016). Developing a systematic framework for consistent allocation in LCA. *International Journal of Life Cycle Assessment*, 21(7), 976–993. https://doi.org/10.1007/s11367-016-1063-3

Stephens, S. L., Agee, J. K., Fulé, P. Z., North, M. P., Romme, W. H., Swetnam, T. W., & Turner, M. G. (2013). Managing forests and fire in changing climates. *Science*, 342(6154), 41–42. https://doi.org/10.1126/science.1240294

Sterman, J. D. (2002). All models are wrong: Reflections on becoming a systems scientist. *System Dynamics Review*, 18(4), 501–531. https://doi.org/10.1002/sdr.261

Van Der Voet, E., Lifset, R. J., & Luo, L. (2010). Life-cycle assessment of biofuels, convergence and divergence. *Biofuels*, 1(3), 435–449. https://doi.org/10.4155/bfs.10.19

Virto, I., Barré, P., Burlot, A., & Chenu, C. (2012). Carbon input differences as the main factor explaining the variability in soil organic C storage in no-tilled compared to inversion tilled agrosystems. *Biogeochemistry*, 108(1), 17–26. https://doi.org/10.1007/s10533-011-9600-4

Vogtländer, J. G., Van Der Velden, N. M., & Van Der Lugt, P. (2014). Carbon sequestration in LCA, a proposal for a new approach based on the global carbon cycle; Cases on wood and on bamboo. *International Journal of Life Cycle Assessment*, 19(1), 13–23. https://doi.org/10.1007/s11367-013-0629-6

Watson, J. E. M., Evans, T., Venter, O., Williams, B., Tulloch, A., Stewart, C., Thompson, I., Ray, J. C., Murray, K., Salazar, A., McAlpine, C., Potapov, P., Walston, J., Robinson, J. G., Painter, M., Wilkie, D., Filardi, C., Laurance, W. F., Houghton, R. A., ... Lindenmayer, D. (2018). The exceptional value of intact forest ecosystems. *Nature Ecology and Evolution*, 2(4), 599–610. https://doi.org/10.1038/s41559-018-0490-x

Wiloso, E. I., Heijungs, R., Huppes, G., & Fang, K. (2016). Effect of biogenic carbon inventory on the life cycle assessment of bioenergy: Challenges to the neutrality assumption. *Journal of Cleaner Production*, 125, 78–85. https://doi.org/10.1016/j.jclepro.2016.03.096

Yang, Y., & Tilman, D. (2020). Soil and root carbon storage is key to climate benefits of bioenergy crops. *Biofuel Research Journal*, 7(2), 1143–1148. https://doi.org/10.18331/BRJ2020.7.2.2

Yang, Y., Tilman, D., Lehman, C., & Trost, J. J. (2018). Sustainable intensification of high-diversity biomass production for optimal biofuel benefits. *Nature Sustainability*, 1(11), 686–692. https://doi.org/10.1038/s41893-018-0166-1

**How to cite this article:** Matuštík, J., & Kočí, V. (2022). Does renewable mean good for climate? Biogenic carbon in climate impact assessments of biomass utilization. *GCB Bioenergy*, 14, 438–446. https://doi.org/10.1111/gcbb.12925