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Socio-economic life cycle assessment of future aircraft systems

Alexander Barke[a,*], Christian Thies[a], Sofia Pinheiro Melo[b], Felipe Cerdas[b], Christoph Herrmann[b], Thomas S. Spengler[a]

[a] Institute of Automotive Management and Industrial Production, Technische Universität Braunschweig, Braunschweig 38106, Germany
[b] Institute of Machine Tools and Production Technology, Technische Universität Braunschweig, Braunschweig 38106, Germany

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ABSTRACT

The development of novel aircraft based on electric propulsion is a key strategy to achieve emission reductions in the aviation sector despite the continuously growing demand for air travel. Most sustainability assessments of aircraft focus on environmental indicators and neglect important socio-economic aspects. We address this gap by developing a conceptual framework for the socio-economic sustainability assessment of aircraft with novel propulsion systems. The framework considers the specific requirements for socio-economic sustainability in the aviation sector and builds on established methods such as life cycle costing and social life cycle assessment to complement the environmental perspective in sustainability assessments.

1. Introduction

The aviation industry is facing significant challenges to achieve its self-imposed goals towards the reduction of environmental impacts and to comply with global environmental policies that seek to limit the temperature increase to 1.5 degrees Celsius above pre-industrial level, as laid out in the Paris Agreement (United Nations Framework Convention on Climate Change, 2015). Due to the high fuel demand of aircraft and the associated emissions, the aviation sector was responsible for 850 million tons of CO_2 emissions in 2017, which represented 2.6% of the total global amount (Staples et al., 2018). Recent studies of Airbus and Boeing predict that the demand for flights (passenger and cargo) continues to grow by up to 4.5% per year until 2038 (Boeing, 2019; Airbus, 2019). Based on current aircraft configurations with a propulsion system powered by kerosene, this would lead to a doubling or tripling of aviation-induced CO_2 emissions until 2050 (Gnadt et al., 2019).

A key strategy to avoid these in-flight emissions is the development of novel aircraft propulsion systems. Particular attention is given to electric and hybrid systems that replace the conventional jet engines powered by fossil fuels (Gnadt et al., 2019). In addition to that, alternative jet fuels produced from bio-feedstocks (Rye and Batten, 2011) and synthetic fuels made with renewable energy (electrofuels) (Goldmann et al., 2018) are discussed as potential candidates to replace the fossil kerosene.

A comprehensive evaluation of these technologies in comparison to aircraft with conventional propulsion concepts requires the assessment of diverse sustainability indicators and the consideration of different stakeholder groups. Most sustainability assessments that have been carried out so far focus on environmental aspects and only consider gradual improvements of conventionally powered aircraft systems, however (JOHANNING, 2015; Cox et al., 2018). Moreover, the assessments are often carried out from an aggregate perspective, ignoring the interests of specific stakeholder groups such as aircraft manufacturers, airlines, passengers, airport operators, residents in the vicinity of airports, and political decision-makers, who can directly or indirectly influence the development, the deployment, and the operation of novel aircraft propulsion systems. These stakeholder groups usually have diverging preferences and objectives, such as increasing profitability, minimizing costs, reducing emissions and noise pollution, or improving working conditions. The conflicting objectives often make it difficult to derive recommendations for the development of sustainable aircraft systems.

In this context, the existing literature neglects two important aspects. First, systematic approaches for the socio-economic evaluation of aircraft systems based on a comprehensive set of sustainability indicators and considering future technologies are missing. Second, the capabilities of existing approaches to analyze and to resolve the conflicting objectives of the various stakeholders are largely insufficient.

* Corresponding author.
E-mail address: a.barke@tu-braunschweig.de (A. Barke).

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Consequently, we address the following research question: How should a socio-economic sustainability assessment of future aircraft systems, that takes into account the specific characteristics of the aviation sector, be carried out? In particular, it is the objective of this paper to develop a conceptual framework for the socio-economic sustainability assessment of aircraft with novel propulsion systems. With its focus on economic and social sustainability and the consideration of the various actors in the aviation sector, the paper seeks to advance the literature on sustainability assessment of aircraft by addressing aspects that have received little attention so far. The conceptual framework provides guidance for the socio-economic assessment of future aircraft systems and builds the foundation for more comprehensive sustainability assessments as part of future research activities.

The remainder of this article is organized as follows. The introduction is followed by a literature analysis on existing assessment approaches for aircraft systems in Section 2. In Section 3, the conceptual framework for the assessment is developed with a special focus on the particularities of socio-economic assessment in aviation. The paper concludes with a discussion of the results and an outlook on future research in Section 4.

2. Literature analysis

To obtain an overview of previous research activities and to analyze the research gaps in the field of life cycle-oriented sustainability assessment of aircraft with novel propulsion concepts and especially the lack of socio-economic assessment approaches, a literature analysis has been performed. The search was carried out using Elsevier's Scopus database (www.scopus.com) with the keywords 'Life Cycle Assessment/Life Cycle Costing/Social Life Cycle Assessment' in the context of 'Aviation/Aircraft/Airplane'.

Promising assessment approaches of future aircraft systems regarding the different sustainability dimensions are pointed out and discussed below.

2.1. Assessment of environmental sustainability

First, promising approaches to environmental sustainability assessment are presented with particular attention to Life Cycle Assessment (LCA). The typical procedure of LCA is defined in the ISO 14040/14044 standards (Deutsches Institut für Normung e.V. 2020b; Deutsches Institut für Normung e.V. 2020a). An LCA study starts with the definition of goal and scope. Next, inventory data describing the exchanges between the unit processes and the environment is collected, before the data is assigned to environmental impact categories in the subsequent impact assessment. The procedure is accompanied by a continuous interpretation process (Thies et al., 2019).

Focusing on the aviation sector, Lopes conducts an LCA study for an Airbus A320-200 (Lopes, 2010). The study provides a comprehensive inventory of the manufacturing of the aircraft. Similar research is addressed by Lewis, who develops an LCA approach for passenger aircraft based on different flight scenarios (Lewis, 2013). That study concludes that emissions from aircraft production, kerosene production, and the infrastructure surrounding flight operations are not negligible and responsible for 16-21% of total greenhouse gas emissions over the entire life cycle.) Jemioło and Timmis et al. investigate the changes in the environmental impact of air transport due to the introduction of new materials in aircraft construction. Jemioło analyzes the general effects of aircraft weight reduction (Jemiolo, 2020), whereas Timmis et al. specifically address the use of composite materials (Timmis et al., 2015). They point out that the use of composite materials can reduce CO_2 emissions by 14-15% compared to the current material composition of aircraft.

2.2. Assessment of economic sustainability

While the environmental dimension has already been addressed by many authors, the economic dimension has been neglected so far. In recent years, however, more and more authors have begun to assess the sustainability of aircraft propulsion concepts based on the analysis of economic indicators like costs or prices.

A holistic method for the economic assessment along the entire life cycle is the Life Cycle Costing (Hunkeler et al., 2008). LCC is an instrument of strategic cost management and is similar to the Total Cost of Ownership approach. In both approaches, the entire life cycle of a product is examined and all costs incurred are recorded. In LCC, transaction costs are neglected, which leads to a more straightforward application (Geissdörfer et al., 2009). The general framework concerning the definition of the product system and the functional unit is derived from the ISO 14040/14044 standards (Deutsches Institut für Normung e.V. 2020b; Deutsches Institut für Normung e.V. 2020a).

A promising study that analyzes the economic dimension is performed by Seemann et al., who conduct an LCC of the maintenance and repair measures of conventional jet engines (Seemann et al., 2011). Their work points out that the operating costs, which are mainly driven by the propulsion system and fuel consumption, are the most significant cost factor in the life cycle. Thokala et al. develop a decision support tool based on an LCC approach to analyze the interactions between production, operation, and decommissioning (Thokala et al., 2010). The aim is to identify trade-offs between the processes. Sun also addresses these trade-offs by developing approaches for multi-criteria decision support (Sun, 2014). Hölzel et al. and Zhao et al. analyze the significance of the LCC on the basis of various databases to define requirements for the collected data (Hölzel et al., 2014; Zhao et al., 2015).

2.3. Assessment of social sustainability

A holistic method for the social assessment of products is Social Life Cycle Assessment (S-LCA) (UNEP/SETAC 2009; Thies et al., 2019; Karlewski, 2016). The S-LCA methodology enables the analysis of potential positive and negative social impacts along the entire life cycle of products, based on social indicators, which are socially significant themes or attributes. All activities that are related to the extraction and processing of raw materials, manufacturing, distribution, use, maintenance and repair, recycling, and final disposal are recorded. The resulting social impacts are considered as the consequences on the stakeholders in the context of these activities (UNEP/SETAC 2009; Thies et al., 2019; UNEP/SETAC 2013).

Research in the field of social analysis of propulsion concepts is rather limited and usually only mentioned in the context of other sustainability dimensions. For example, Franz et al. examine the economic and environmental impacts resulting from more sustainable aircraft design and briefly discuss the associated social effects (Franz et al., 2013). Wang et al. investigate the sustainability of biofuels for aviation and focus on the social impacts in the supply chain (Wang et al., 2017).

2.4. Novel propulsion systems

Previous research in the field of sustainability assessment has almost exclusively addressed conventional propulsion concepts. However, some authors and institutions analyze the potentials of novel aircraft systems.) Johanning offers an outlook on renewable propulsion concepts (JOHANNING, 2015). He analyzes the energy requirements of electrified aircraft but neglects the required storage systems such as batteries. The situation is similar in the work of Kasliwal et al. and Schäfer et al.. Kasliwal et al. investigate the potential of vertical take-off and landing aircraft (VTOLs) for CO_2

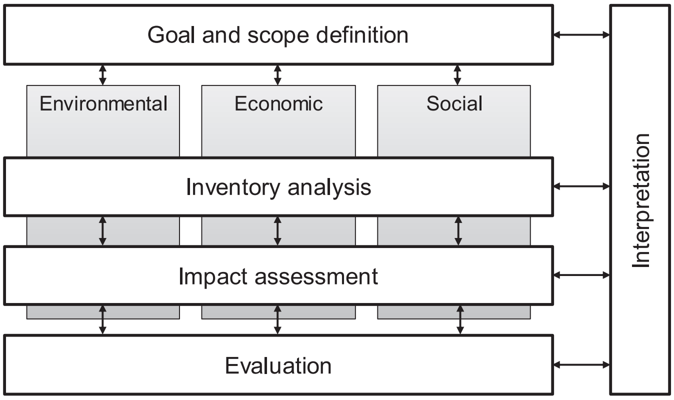

Fig. 1. Framework for life cycle sustainability assessment (Thies et al., 2019).

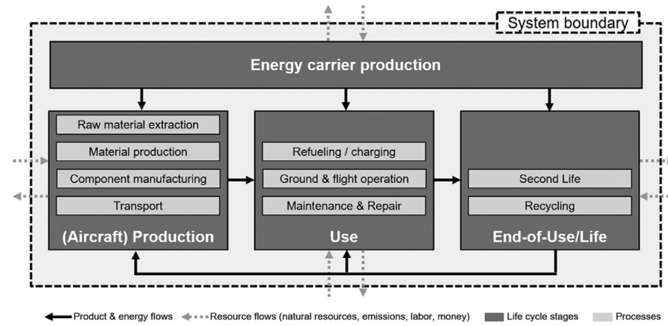

Fig. 2. Overall system and system boundaries.

reduction compared to cars in urban areas (Kasliwal et al., 2019). Schäfer et al. discuss the importance of the electricity mix and the economic aspects regarding the cost structure during operation for electrified aviation (Schäfer et al., 2016). In both articles, the potentials are pointed out, but no systematic analysis and assessment take place. To the best of our knowledge, only Ploetner et al. perform a comprehensive LCA of the universally electric-powered aircraft Ce-Liner (Ploetner et al., 2016). They investigate the potential of the aircraft with regard to zero-emission targets as well as the necessary electricity mix for the charging.

Research regarding the further development of the aviation sector is also carried out by the Fraunhofer Institute, Airbus, and various other companies, research institutions, and universities as part of the EU's Horizon 2020 program 'Clean Sky'. The aim of this program is to analyze and develop approaches and strategies for reducing CO_2 and noise in air traffic (Clean Sky Joint Undertaking 2019).

This brief literature overview reveals that existing approaches for life-cycle oriented sustainability assessment of aircraft primarily focus on environmental aspects and increasingly consider economic aspects. However, the consideration of social aspects and novel propulsion systems is rather limited so far. At the same time, the sustainability assessment has been carried out from an aggregate perspective and does not take into account the large number of actors in the aviation sector.

3. Conceptual framework

To address the research gap of socio-economic sustainability assessment of future aircraft systems identified in Section 2, a conceptual framework for the assessment is developed. The framework supports the research in this field by providing guidance for the socio-economic sustainability assessment of aircraft with novel propulsion concepts.

The general procedure is derived from the ISO 14040/14044 standards (see Fig. 1) and inspired by the Life Cycle Sustainability Assessment (LCSA). It is adapted for the application in the aviation sector and considers its unique characteristics. As there are already guidelines for the environmental assessment defined in the ISO standards, our framework focuses on social and economic sustainability assessment. The individual steps within the procedure as well as the main assumptions are discussed and presented below.

3.1. Goal and scope definition

The goal of the study is to analyze social and economic aspects of aircraft with novel propulsion concepts as part of a life-cycle oriented sustainability assessment. Therefore, the product system under consideration is the propulsion system of an aircraft. As mentioned in Section 1, the key technologies to reduce in-flight emissions are electric propulsion concepts based on batteries (Gnadt et al., 2019; Ploetner et al., 2016) or fuel cell systems (Kadyk et al., 2018) in combination with an electric propeller as well as renewable fuels like biofuels (Rye and Batten, 2011; Schäfer et al., 2016) or electrofuels (Goldmann et al., 2018). They are assessed with regard to socio-economic criteria and compared to fossil kerosene-based jet engines.

Next, the overall system has to be defined. In this process, it is essential to ensure the comparability of the technologies to be assessed by defining an appropriate functional unit. Typical functional units that are used for the assessment of aircraft or jet engines are passenger kilometers traveled by a 70 kg passenger with 30 kg luggage and an aircraft load factor between 60% and 90% (Cox et al., 2018; Lewis, 2013; Umweltbundesamt 2019). Here, the functional unit is defined as 100 kilometers traveled by a 70 kg passenger with 30 kg luggage and an aircraft load factor of 80% on a generic flight profile. All social and economic reference flows of the various propulsion concepts are allocated to this functional unit.

The overall system includes the entire life-cycle, especially the stages of extraction and processing of raw materials, manufacturing, use, and End-of-Life (EoL) (see Fig. 2). Within these system boundaries, the foreground and background systems have to be defined. The foreground system includes all processes that can be directly attributed to the product system and are specific to it (Hauschild et al., 2018). In the raw material extraction and production, the foreground system includes the processes of raw material extraction, material production, and component manufacturing as well as transports. The use stage is divided into three groups of processes. These are refueling/charging, operation, and maintenance/repair/overhaul (MRO). The modeling of refueling and charging processes requires the inclusion of energy carrier provision and production because they are primarily responsible for the impacts during operation. Here, the process chains of fuel production, hydrogen production, and electricity generation are included in the sustainability assessment. During operation, both the actual flight operation and the movements of the aircraft at the airport, the so-called ground operations, are included. Within MRO, all processes are included that are necessary to ensure the operational capability of the propulsion system. Depending on the system, recycling and the recovery of raw materials, disposal, or second-use are recorded in the EoL.

Next to the foreground system, the background system has to be defined. The background system includes all processes that are not specific to the product system (Hauschild et al., 2018). Along the life cycle of aircraft propulsion concepts, this includes, for example, the electricity supply used for the production. Cut-off rules are used to determine which processes are included in the background system. A process can be omitted if it contributes less than a given percentage to the mass or energy consumption.

3.2. Inventory analysis

The second step of the procedure is the inventory analysis. Here, the material-, energy- and monetary flows of all processes within the system boundaries are recorded. For this purpose, data from the industry and the literature are used to describe the individual processes and are extended by data from databases (Hauschild et al., 2018).

The data is compiled from different sources. Economic data, for example, can be obtained from company reports of manufacturers or airlines (Boeing, 2019; Airbus, 2019). A further possibility is provided by research institutions or other scientists who have already worked in this field and make their results available (Clean Sky Joint Undertaking 2019).

Collecting data regarding social aspects is more complicated. In this context, studies or previous research of other scientists regarding social themes can be used as references (Wang et al., 2017). This data is supplemented by the use of specific databases, such as the Social Hotspot Database (SHDB), a comprehensive database for social life cycle assessment (Thies et al., 2019). With the SHDB, country- and industry-specific information of processes can be collected. Similarly, SOCA is an add-on to the ecoinvent database that provides more than 50 social indicators as well as data about prices and costs of the processes.

Finally, missing data needs to be estimated. For example, cost models, such as the model by Roskam and Eastlake, can help to estimate specific costs of components in the life cycle of an aircraft propulsion concept (Gudmundsson, 2014). As the available data determines the quality of the evaluation, inventory analysis must be carried out as precisely and extensively as possible

3.3. Impact assessment

In order to analyze the socio-economic impacts resulting from the inventory analysis and to identify potential hotspots in the life cycle, the S-LCA and LCC methods are used for the impact assessment. The application of the assessment with the unique requirements in aviation is described in the following.

3.3.1. Social assessment

In the first step, the relevant stakeholders in the aviation sector have to be identified and the relevant indicators for each stakeholder have to be determined. Since the socio-economic assessment has been neglected for aircraft propulsion concepts, references from other sectors can be used as a benchmark. For example, Karlewski has performed a social analysis in the automotive industry and has identified a multitude of indicators and stakeholders (Karlewski, 2016). The most important stakeholders and indicators can be used for the assessment of aircraft in a similar way. The relevant stakeholders directly or indirectly affected by air traffic, especially by the propulsion concepts of aircraft, are aircraft manufacturers, airlines, passengers, airport operators, political decision-makers, and the local community/population near production sites or airports.

According to Karlewski, political decision-makers are particularly interested in high-level topics, such as human rights, working conditions, and health and safety. Relevant indicators address the whole society and not just some parts of it (Karlewski, 2016).

Aircraft manufacturers and airlines are probably the most influential stakeholders in the aviation sector. Next to their intrinsic economic objectives, socially relevant topics such as their behavior towards other market actors and customer satisfaction are gaining relevance (Karlewski, 2016).

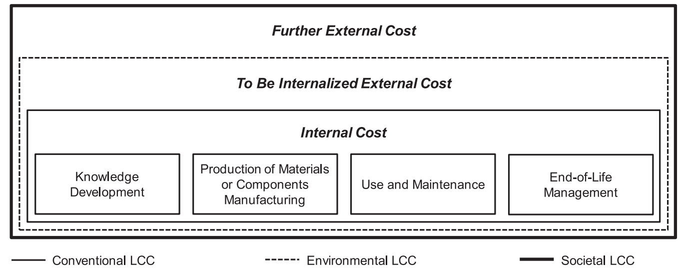

Fig. 3. Concepts of LCC adapted from Hunkeler et al. (Hunkeler et al., 2008).

Indirectly affected by the aircraft propulsion system are passengers and airport operators. From a social perspective, passengers are interested in personal issues like high comfort or low noise emissions. Their own well-being is prioritized. Airport operators are focused on their relationship to customers and other market actors. The most important indicators for this stakeholder group are the customer satisfaction and market bahavior between airport operators and airlines (Karlewski, 2016).

Finally, the local communities, i.e., the population living in the vicinity of airports, mining areas, or production sites, need to be considered (Karlewski, 2016). Relevant themes for this stakeholder group include noise pollution, local safety issues, and economic prosperity. This stakeholder group is diverse, so the relevant indicators are also diverse. For example, the population in the vicinity of airports might be more interested in reducing noise pollution while the communities near production sites might be more interested in increasing local prosperity. Overall, there are strong interdependencies due to the existence of only a few big market actors within the aviation sector.

3.3.2. Economic assessment

The economic assessment is based on different indicators, such as prices or costs of a product. The assessment on the basis of LCC is based on the costs of a product. The SETAC-Europe Working Group on Life Cycle Costing defined three types of LCC: conventional LCC, environmental LCC, and societal LCC (Hunkeler et al., 2008). Their scope is illustrated in Fig. 3 and described below.

In conventional LCC, all costs associated with the product life cycle that are directly covered by the producer or user are assessed. The approach is focused on real and internal costs (Hunkeler et al., 2008).

In environmental LCC, as suggested by Rebitzer and Hunkeler (Rebitzer and Hunkeler, 2003), all costs within the life cycle of a product that are covered by one or more actors are assessed. In addition to the conventional LCC, all life cycle stages, as well as to-be-internalized costs in the decision-relevant future, are included in the environmental LCC. If subsidies and taxes are expected in the future, they can be included in environmental LCC as well (Hunkeler et al., 2008).

In societal LCC, all costs associated with the product life cycle that are covered by anyone in the society, whether today or in the long-term future, will be assessed. The societal LCC extends the environmental LCC by additional assessment of further external costs, usually in monetary terms (based on willingness-to-pay methods) (Hunkeler et al., 2008).

The economic assessment approach can be selected based on the addressed stakeholder (Karlewski, 2016). For political decision-maker, the societal LCC should be used as it is the most comprehensive assessment approach, and all external societal costs are taken into account. If, for example, new taxes on emissions could arise, this would have an impact on society's behavior and must be taken into account.

For the other stakeholders, the assessment approach depends on the aspired level of detail of the analysis. If potential future taxes or other external costs are relevant for specific decisions within the life cycle of the propulsion system, the environmental or societal LCC should be selected. However, if the stakeholder is only interested in the economic performance of the propulsion system during individual stages of the conventional LCC is sufficient. For example, if the manufacturer wants to analyze the production, he only takes costs into account, which are directly related to it, such as costs of material or labor (Hunkeler et al., 2008).

3.4. Evaluation and interpretation

In the last step of the procedure, an evaluation is carried out. This evaluation is required to compare the different novel and conventional aircraft systems, based on the analyzed sustainability indicators. Most often, the stakeholders' decision regarding the most suitable system is difficult because of conflicting objectives. For example, it is not possible to simultaneously minimize CO_2 emissions and noise pollution, reduce production costs and child labor, and maximize wages for workers. Accordingly, preferences must be set in order to prioritize individual goals. This is a so-called "Multi-Criteria Problem", which is defined by the fact that there are several conflicting objectives with incommensurable units (Zopounidis and Pardalos, 2010). To resolve this conflict of objectives and to enable the comparability of the different propulsion systems, a multi-criteria decision-making (MCDM) model should be used. MCDM models enable the assessment of future aircraft systems by using preferences for the different objectives of the stakeholders (Thies et al., 2019; Zopounidis and Pardalos, 2010; Thies et al., 2018). Approaches like the "Preference ranking organization method for enrichment evaluation" or the "Analytic Hierarchy Process" can be used to structure and to solve this decision-making problem. MCDM models do not always require full compensation (Zopounidis and Pardalos, 2010).

In contrast to simple weighting methods, MCDM models prevent a (complete) compensation between objectives/indicators. This means that bad values of indicators cannot be fully compensated by good values of other indicators (Zopounidis and Pardalos, 2010). Accordingly, this supports a comprehensive understanding of sustainability. In this way, decision support can be made possible despite the fact that objectives are often irreconcilable.

All steps of the procedure are accompanied by interpretation, which may be carried out in an iterative process. By doing so, new insights or data limitations can be used for a continuous redefinition of the study focus, goal, and methods. Particularly concerning data availability of social aspects in the aviation sector, the study can thus be adapted quickly, and the system can be redefined if necessary (Thies et al., 2019).

4. Conclusions and outlook

The presented framework can be seen as guidelines to support the socio-economic sustainability assessment of aircraft with novel propulsion concepts by providing assistance for the individual steps of an assessment procedure according to the ISO 14040/14044 standards.

The general structure of the framework is based on the LCSA, which has been adapted to the specific characteristics of the aviation sector. Important actors of the aviation sector are identified and relevant indicators for the social and economic sustainability assessment are determined. Furthermore, ways to deal with conflicting objectives of the different actors in order to derive recommendations for action from the sustainability assessment are demonstrated.

Future research should address the refinement of the socio-economic assessment methodology and its integration with an environmental assessment methodology into a holistic sustainability assessment framework for aircraft with novel propulsion systems. The method development and validation are carried within the cluster of excellence 'Sustainable and Energy Efficient Aviation' (SE^2A) at Technische Universität Braunschweig in Germany.

CRediT authorship contribution statement

Alexander Barke: Conceptualization, Methodology, Validation, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Christian Thies:** Conceptualization, Methodology, Validation, Writing - review & editing, Project administration. **Sofia Pinheiro Melo:** Conceptualization, Methodology. **Felipe Cerdas:** Conceptualization, Project administration. **Christoph Herrmann:** Supervision, Funding acquisition. **Thomas S. Spengler:** Conceptualization, Resources, Supervision, Funding acquisition.

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This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.