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The Doughnut Biotool: A tool to assess life-cycle biodiversity impacts from building projects

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Abstract. Life-cycle assessment (LCA) is widely used in certifications, regulations, and voluntary declarations covering the climate impact of buildings over their entire value chain. However, biodiversity impacts and other environmental impact categories are often disregarded. Conversely, there is a trend towards more systematic assessments of the biodiversity impacts that occur on-site as part of development projects (e.g. land transformation on the project site). However, off-site biodiversity impacts occurring throughout the rest of the value chain (e.g. from forestry activities, mining, manufacturing, heat and electricity production) are rarely considered. To bridge this gap, this article introduces the Doughnut Biotool, an open-source calculation tool to assess biodiversity impacts throughout the entire life cycle of development projects. The tool was initially developed to help implement Doughnut Economics and absolute sustainability principles in development projects. It constitutes a first step towards a better consideration of biodiversity impacts related to material- and energy use in building and construction projects. This paper presents the design of the tool and the method and data it relies on. The tool is applied to two separate case study projects, and used as a basis to discuss hotspots of biodiversity impacts within the building's life cycle. Finally, the paper includes a discussion of the main challenges and opportunities for the future development and use of the tool, as well as for biodiversity impact assessments in the building sector as a whole.

Keywords: LCA, biodiversity, doughnut economics, planetary boundaries, absolute sustainability, ecosystem.

1. Introduction

The construction of buildings and infrastructure is a major cause of non-renewable natural resource use (such as river sand), and buildings are responsible for about 37% of global greenhouse gas emissions [1]. Therefore, it is crucial to implement strategies to mitigate environmental impacts and resource uses linked with building construction. While the building sector is not on track regarding decarbonization pathways [2], climate impact mitigation has gained a lot of attention, and a wide range of decarbonization initiatives have been undertaken in procurement, certification and policy – not least the recent introduction of mandatory limit values for the life cycle climate impact of new buildings in various EU countries [3]. However, other environmental impacts have remained largely ignored. Impacts on ecosystems and biodiversity are particularly important to consider, for several reasons. First, because the planetary boundary of biosphere integrity is considered a core boundary due to its fundamental importance for the stability of the Earth system. Second, because this planetary boundary is already in a high risk zone [4]. Third, because many countries have now committed to taking urgent action to preserve biodiversity, as part of the Kunming-Montreal Global Biodiversity Framework [5]. And fourth, because decarbonization policies might affect biodiversity in ways that remain poorly understood (e.g. by encouraging an increased use of bio-based materials).

Biodiversity impacts happening on or near the project site are increasingly being addressed in private initiatives and in policies such as the requirement for on-site "Biodiversity Net Gain" introduced in the U.K. in 2023 [6]. However, there is a considerable knowledge gap regarding off-site biodiversity impacts, caused by the use of materials and energy throughout a building's life cycle. There is a rising interest among practitioners for decision support tools addressing the biodiversity impacts of development projects in a life-cycle perspective [7]. Frameworks like Science-Based Targets for Nature (SBTN) and the Taskforce on Nature-related Financial Disclosures (TNFD) have proposed approaches for companies to set biodiversity-related targets and disclose related risks and impacts. In the EU, the Corporate Sustainability Reporting Directive (CSRD) includes biodiversity reporting requirements as part of the reporting standard ESRS E4. Its progressive implementation creates a demand for biodiversity impact assessment tools among large property owners and real-estate companies. However, developers and building designers lack tools to identify hotspots of biodiversity impacts in building projects and mitigate them through design and material choices. This paper presents the Doughnut Biotool, a simple open-source prototype, developed as part of a project on the implementation of Doughnut Economics principles in development projects [8]. The tool is applied on real development cases to discuss biodiversity impact hotspots and opportunities for further development of the tool.

2. Methods

2.1. Description of the Doughnut Biotool

An important design goal for the Doughnut Biotool has been to make it as easy to use and as transparent as possible for the user, without compromising on the validity of the calculation. This led to several choices in terms of methodology and implementation. From a methodological point of view, the tool allows the user to implement a simplified life cycle assessment (LCA), covering modules A1-A3 (material extraction and production), B4 (material replacement during operation), B6 (operational energy use) and C3-C4 (waste treatment and disposal) according to the EN15978 terminology. Moreover, the LCA results are combined with a calculation of the on-site biodiversity impacts associated with direct land use change on the project site. The input for the LCA calculations is a bill of materials used in the building and information on the building's operational energy use during a 50-year reference study period. The tool links the input data with unit process data from the ecoinvent database (v3.9.1) with the "cut-off cumulative" system model to create an inventory of all the emissions and resource uses that occur during the building's life-cycle. The impacts of the emissions and resource uses on biodiversity are characterized using the ReCiPe 2016 v1.03 life cycle impact assessment methodology [9]. This method expresses biodiversity impacts via the endpoint category "ecosystem quality", as a local loss of species integrated over time, in "species.years". The ecoinvent database and ReCiPe were selected primarily because of their broad use in LCA, their accessibility, their coverage of multiple drivers of biodiversity loss, and the large amount of data available. This addressed the issue of data scarcity, one of the main barriers to biodiversity assessments, and contributed to the goal of limiting complexity. Unfortunately, the ecoinvent license prohibits the communication of ecoinvent data. For this reason, the open-source tool is provided online with dummy data, along with instructions for users with an ecoinvent license to import the right data, and a Python script that can retrieve the necessary data from ecoinvent automatically if the database is downloaded in spreadsheet format.

Regarding the tool's implementation, the goal of ease of access led to the use of Microsoft Excel. Three versions of the tool were published. In the "simple" version, the user only enters the total amounts of various materials in the building (along with information on energy use and local land use). This reduces the complexity of data entry, but also limits the possibilities for hotspot analyses, since this version does not distinguish between different building elements (walls, roof, slabs, etc.).

Conversely, the "detailed" version of the tool requires the user to enter a detailed bill of materials, disaggregated into four levels: elements (e.g. "internal walls"), sub-elements (e.g. "non-load bearing internal walls"), components (user-defined, e.g. "bedroom partition wall") and products (e.g. "aerated concrete"). The nomenclature follows that of the Danish building LCA tool LCAbyg. The detailed version of the tool uses macros to perform hotspot analyses at these various levels, identifying which elements, sub-elements, material types, etc. contribute most to biodiversity impacts.

Finally, the "LCAbyg import" version of the Biotool is a useful alternative when the user has already performed an LCA for their case using the LCAbyg tool. The "LCAbyg import" version has a level of detail similar to the "detailed" version, and enables the same kind of hotspot analyses. However, instead of manually entering the bill of materials, the user can directly paste a results sheet exported from LCAbyg, which the tool can read, format and interpret. This considerably speeds up data entry, and allows the user to visualize side-by-side climate and biodiversity impacts.

Table 1. Main properties of each version of the Doughnut Biotool

		Simple	Detailed	LCAbyg Import
Data entry	Materials	Only total quantities for each product type.	Full bill of materials disaggregated in elements, sub-elements, components, and products (manual entry).	Full bill of materials disaggregated in elements, sub-elements, components, and products (imported from LCAbyg).
	Local land use	Land use types before and after development entered manually.		
	Operational energy use	Yearly electricity and heat use entered manually.		
	Environmental data	Must be imported from ecoinvent.		
Analysis and output	Impact on-site, from materials, and from energy.	✓	✓	✓
	Impact per material type.	✓	✓	✓
	Impact per element, sub-element or component		✓	✓
	Also visualizes climate impact			✓

Construction materials

Product name	Amoun	Unit	Preferred un	Material type
Aerated concrete	144313	kg	kg	Concrete
Aggregates	0	kg	kg	Aggregates
Aluminium	111846	kg	kg	Metal
Anhydrite (CaSO4)	0	kg	kg	Cement and gypsum
Asphalt	14301.2	kg	kg	Asphalt
Bricks, clay	759405	kg	kg	Clay
Bricks, sand-lime	0	kg	kg	Stone and masonry (other than clay)
Bricks, shale	0	kg	kg	Stone and masonry (other than clay)
Cast iron	0	kg	kg	Metal
Cellulose fibre insulation material	0	kg	kg	Insulation
Cement	68920.3	kg	kg	Cement and gypsum
Cement bound particle board	0	m3	m3	Cement and gypsum
Cement mortar	196212	kg	kg	Cement and gypsum

Description	Name	User defined amount	Unit	Service life	Replacements	Calculated amount	Unit	Data value [species.year/unit]	Project value [species.year]	Material type
Sum	Building			50					3.69E-02	
Element	Roofs								4.00E-03	
Subelement	Roofs								4.00E-03	
Construction	Roof	1	Piece						4.00E-03	
Products	Gypsum plasterboard	81800	kg/Piece	60	0	81800		3.67708E-09	3.01E-04	Cement and gypsum
Products	Sawnwood	209	m3/Piece	100	0	209		8.23719E-06	1.72E-03	Wood
Products	Stone wool insulation	177040	kg/Piece	50	0	177040		6.78254E-09	1.20E-03	Insulation
Products	Paint, coating, etc.	3657	kg/Piece	15	3	3657		3.39502E-08	4.97E-04	Paint, varnish, etc.
Products	Asphalt	49130	kg/Piece	20	2	49130		8.31142E-10	1.23E-04	Asphalt
Products	Polyethylene (PE)	3370	kg/Piece	30	1	3370		2.30319E-08	1.55E-04	Plastic
Element	Ground floor slabs								1.26E-02	
Subelement	Gound floor slabs								1.26E-02	
Construction	Wet room floor	546	m2						1.31E-04	
Products	Cement screed	120	kg/m2	80	0	65520		1.02865E-09	6.74E-05	Cement and gypsum
Products	Ceramic tiles	20	kg/m2	100	0	10920		3.96035E-09	4.32E-05	Clay
Products	Cement mortar	3.1	kg/m2	100	0	1692.6		1.24942E-09	2.11E-06	Cement and gypsum
Products	Polystyrene foam insulation (EPS)	1.2	kg/m2	80	0	655.2		2.73324E-08	1.79E-05	Insulation
Construction	Floor construction	1	Piece						1.05E-02	
Products	Cement bound particle board	46.3	m3/Piece	100	0	46.3		3.90953E-06	1.81E-04	Cement and gypsum
Products	Stone wool insulation	57080	kg/Piece	80	0	57080		6.78254E-09	3.87E-04	Insulation
Products	Sawnwood	1366	m3/Piece	100	0	1366		7.02841E-06	9.60E-03	Wood
Products	Cement bound particle board	77.884	m3/Piece	80	0	77.884		3.90953E-06	3.04E-04	Cement and gypsum

Figure 1. Screenshots of the data entry sheets from the simple (top) and detailed (bottom) versions of the Doughnut Biotool

2.2. *Case studies*

The tool was tested on two cases, a housing development project and an office building (hereafter referred as Housing and Office respectively for the sake of anonymity). Both cases were selected because of their use of wood materials, which offers an opportunity to visualize the biodiversity impact of such materials alongside mineral materials. In addition, the two cases differ widely in their density, with Housing being a spread-out, low-rise development and Office a single high-rise tower. This difference offers an opportunity to illustrate cases with particularly high and low ratios of on-site impacts. Both cases were implemented in the "LCAbyg Import" version of the Biotool. Since LCAbyg files were readily available for both cases, the "LCAbyg Import" tool offered a high level of detail for a relatively simple data entry.

The bill of materials for the two buildings comprises the foundation, floor, exterior walls, interior walls, roofs, staircases, balconies, windows, doors and glass walls/facades. Included installations are electrical and mechanical systems including solar panels. The technical installations were based on default values due to a lack of specific data.

Housing is a residential building complex comprising 126 units along with a shared common house. These housing units are built using wood as the primary structural material, integrated within box module systems. The development is part of a local plan encompassing a 60-hectare area, with focus on sustainability, community, and engagement of neighbours, tenants, and stakeholders. The surrounding

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environment is developed with a focus on connecting residents with nature, achieved through the implementation of open urban drainage systems and the integration of buildings into the landscape.

Office is a single high-rise building with the primary purpose of serving as office spaces but with opportunities for public activities in the lower floors. It is a hybrid structure building combining timber framing and sheeting with an elevator and staircase core in concrete. The office development attempts to bridge indoor and outdoor spaces for the occupants, as well as connect and interact with the surrounding urban area, including providing green spaces on site. The building uses wood for some of the walls, floor slabs, columns, and beams, but still includes a higher weight of concrete and steel, used in the foundations as well as some slabs and core walls, in particular for staircases and elevator shafts.

For the sake of carrying out a conservative calculation, local land use was assumed to include only unexploited forests before the development, and urban land after the development. It should also be noted that the assessment of global warming potential used a different mix for operational energy supply than the biodiversity impact assessment. The global warming potential assessment is carried out according to the Danish mandatory LCA declaration for new buildings, which includes a scenario for the future evolution of the energy supply. Conversely, the Biotool uses an average present European mix (ENTSO-E) for the electricity supply.

3. Results

Figure 2 illustrates the life-cycle assessment results for the two case studies. For comparison purposes, the figure shows the shares of each building's mass, global warming potential and biodiversity impact attributed to various material types. The tool only calculates impacts on biodiversity – global warming potential was calculated using the Danish building LCA tool LCAbyg.

The results indicate that on-site biodiversity impacts in both cases are significantly lower than off-site impacts, even with conservative assumptions regarding local land use before construction. In the Office case, a high-rise building with a small site area, on-site impacts represent only 1.2% of life-cycle biodiversity impacts, while they represent 34% of impacts in the more spread-out Housing case.

Operational energy use represents a larger hotspot for biodiversity impacts than for global warming potential, corresponding to 64% of biodiversity impacts in the Office case and 39% in the Housing case. The difference between the two cases is primarily due to a much lower operational electricity use in the Housing case.

Material types constituting the main hotspots for biodiversity impacts are different from global warming potential hotspots. Biogenic materials are responsible for the largest share of embodied biodiversity impact in both cases (36% for Office, 51% for Housing), while they represent a much smaller share of global warming potential (7% for Office, 9% for Housing). Conversely, concrete, metals and insulation materials represent a much lower share of biodiversity impacts, compared to their contribution to global warming potential.

These results should be interpreted cautiously, as both case study buildings were atypical in their widespread use of timber, and because the assessment of global warming potential uses a different energy supply mix than the biodiversity impact assessment.

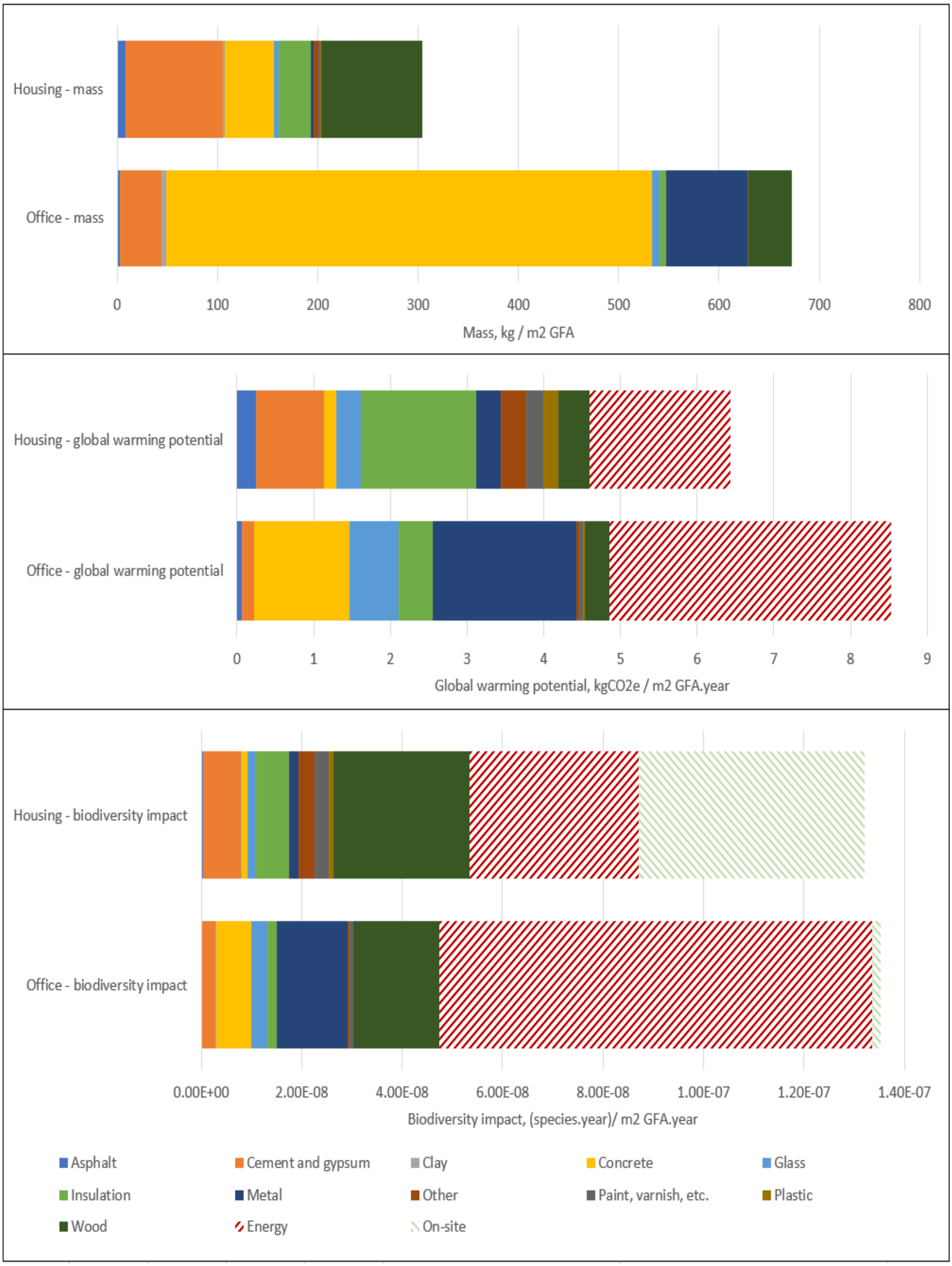

Figure 2. Share of each material type in the buildings' mass, global warming potential and impact on biodiversity, as well as impacts from operational energy use and local land use.

4. Concluding discussion

4.1. Relevance of the tool for biodiversity assessments

The Biotool constitutes a first step towards considering biodiversity impacts over the full life cycle of buildings. Quantifying on- and off-site biodiversity impacts is a way of putting ecosystem preservation on the agenda and supporting discussions around the best ways to assess and mitigate these impacts across the value chain. The tool was met with interest from practitioners, not least because of the increasing importance of reporting frameworks such as the EU Taxonomy, CSRD and Science Based Targets for Nature. It is becoming important for large property owners and developers to be able to report on the biodiversity impacts of their activities, but there is a mismatch between the requirements of these reporting frameworks and the tools and data available for project-level assessments.

The case studies showed similarities in the kinds of hotspots identified. Overall, on-site impacts were smaller than off-site impacts, even under the very conservative assumption that the local land use went from 100% unexploited forest to 100% urban land. This is consistent with previous case studies, showing for instance that embodied off-site impacts from green roofs far outweigh their on-site impacts and benefits [10]. This hypothesis was the initial rationale for developing the tool, along with the observation that off-site impacts receive comparatively little attention, and the results justify the tool's relevance. Still, on-site impacts were significant in the Housing case, representing a third of life-cycle biodiversity impacts. This indicates that preserving local ecosystems is still an important strategy to mitigate biodiversity impacts, particularly in spread-out developments. This result was highly sensitive to assumptions about local land use before the project. Assuming that the development area consisted of exploited forests or shrublands (instead of unexploited forests) lowers the share of on-site biodiversity impacts in the Housing case to 13% or 15% respectively. On the other hand, it should be noted that on-site impacts only consider the stressor of direct land use change and occupation. Impacts related e.g. to the users' behavior, noise- and light pollution, or chemical leaching (during construction and operation) have not been taken into account due to the lack of inventory data or characterization factors for these stressors [11].

Furthermore, the biodiversity impact assessment draws attention to different hotspots compared to assessments of global warming potential. In particular, operational energy use represents a large hotspot for biodiversity impact. This should be interpreted carefully, as the tool relies on a present European electricity mix while the LCA for global warming potential uses a Danish mix with future scenarios. A closer look at the ecoinvent database indicates that local loss of species per kWh for the present Danish electricity mix is about 20% lower than with a European mix. The main drivers of biodiversity loss appear to be climate change caused by cogeneration in fossil-powered plants, followed by land use caused by cogeneration in plants using wood chips. Therefore, implementing the right energy mix in the tool (possibly alongside future scenarios) is particularly important to get accurate results. In particular, future scenarios with a high share of biomass in the energy mix might still lead to relatively high biodiversity impacts from land use, even though they might lead to a lower climate impact. Still, the biodiversity impact of operational energy use is large. This is consistent with a previous Danish LCA study, which found operational energy use to be the main driver of forest transformation in a building's life cycle ([12], although it should be noted that this study used a consequential LCA approach, different from the Biotool's attributional LCA approach).

Wood corresponds to a comparatively larger share of biodiversity impacts, compared to their climate impact, and most mineral products (concrete, steel, mineral wool, etc.) correspond to a comparatively lower share of impacts. However, there are large variations between different products among the same material category – for instance, gypsum plasterboards are responsible for a higher share of impacts in the biodiversity assessment than in the climate impact assessment (due in part to a relatively high acidification impact occurring during the plasterboards' disposal). It is likely that considerable differences could be found between two similar products from different manufacturers, due to differences in manufacturing processes but also differences in the sourcing of raw materials. For instance, the actual biodiversity impact of wood products will likely depend considerably on forestry practices. This should be reflected in the method and data used for the assessment. However, due to the reliance on generic data and an impact assessment method where land use impacts are not spatialized, the tool is currently unable to properly consider these differences.

Due to the reasons above, the tool's primary utility at this point is for screening, e.g. to identify likely hotspots of biodiversity impacts prior to a more thorough assessment focused on these products (including e.g. a full mapping of their supply chain and the localization of major biodiversity impacts). Thus, property developers can use the tool to identify impact hotspots where they must pay particular attention when selecting their suppliers, to mitigate impacts on climate and biodiversity.

4.2. Front-end considerations: Tool design and ease of use

The Biotool has already been tested by several industry practitioners in practical cases. While this first version was met with interest, there are also challenges to a more widespread adoption of the tool. The main challenge is access to background environmental data from ecoinvent. Some practitioners, especially from smaller organizations who rarely work with LCA, have mentioned the need to purchase a license as a considerable barrier. Unfortunately, this can only be progressively overcome by the development of more open generic data on biodiversity impacts (or the inclusion of such impacts in EPDs), as there is currently no alternative to LCA databases with a paid license when it comes to biodiversity impacts.

The three versions of the Biotool offer different trade-offs between complexity and depth of analysis. The "detailed" and "LCAbyg import" versions offer a much more granular analysis to identify hotspots among products, building elements, etc. However, the "detailed" version of the tool requires a considerable amount of manual data entry, which is daunting to some users. Improvements in user interface could help more practitioners carry out detailed assessments. The "LCAbyg import" version offers both a relatively simple interface and the possibility for in-depth analyses, but can only be used if an LCA was previously carried out with the LCAbyg tool. This is useful for a Danish audience, but of limited relevance for international practitioners. Furthermore, this version of the tool will need regular maintenance and updates to adapt to any future change in the format of LCAbyg export files, as any change in the order of rows or columns will break the tool.

4.3. Back-end considerations: Methodological improvements and future prospects

While the tool constitutes a useful first step to integrate considerations of off-site biodiversity impacts in development projects, improvements in methodology and background environmental data are necessary to improve the tool's relevance and accuracy. As noted above, the reliance on generic environmental data from ecoinvent is problematic, since the lack of product-specific information obscures important differences between products. The most accurate product-specific data available is found in Environmental Product Declarations (EPDs), but these do not usually report spatially explicit information, and only cover a limited number of relevant indicators for biodiversity. In particular, land use, one of the most important drivers of biodiversity loss, is only covered by the Soil Quality Indicator (SQI). While it provides relevant information, the SQI is not easily convertible to an impact on biodiversity (there is no corresponding characterisation factor between SQI and damage on ecosystems in life cycle impact assessment methods). The lack of product-specific information on biodiversity impacts is therefore a major challenge to this kind of assessment.

The rationale for using the ReCiPe 2016 life cycle impact assessment method in the tool was that ReCiPe has a relatively broad coverage of relevant pressures, ecosystems and taxonomic groups [13], while being directly accessible through the ecoinvent database. This limited the complexity of importing environmental data for the user, and the related risks of user errors (the tool cannot be provided with environmental data for reasons pertaining to the ecoinvent license, so users must import the background data from ecoinvent themselves when they first download the tool). However, the fact that land occupation and land transformation, two of the most important drivers of biodiversity loss, are not spatialized in ReCiPe, severely limits the method's relevance for biodiversity assessments [14]. In the short term, implementing another impact assessment method could improve the tool's relevance. In particular, the two impact assessment methods Impact World+ [15] and LC-Impact [16] offer spatially differentiated characterization factors for land use, specific for various countries or ecoregions. While this does not address issues with the lack of product-specific spatially differentiated life cycle inventories, enabling differentiation in the background characterization factors is a crucial step forward. Both methods could be implemented in the tool with only a moderate increase in manual input from the user. This would involve importing elementary flows from the ecoinvent database, and mapping each flow with appropriate characterization factors. This involves manipulating a significant amount of data, but since the characterization factors for Impact World+ and LC-Impact are freely available online, this mapping could be automated to reduce user input. Additionally, transparency could be increased by disaggregating the biodiversity impact results into contributions from various midpoint impacts (biodiversity impacts caused by acidification, eutrophication, land use change, etc.)

However, no available life cycle impact assessment method manages to cover the full range of drivers of biodiversity loss or all fundamental aspects of biodiversity (i.e. intra- and inter-species diversity, species population and traits, ecosystem health and services) [13]. For instance, considering only species richness through an indicator of local loss of species does not address the overall health of the ecosystem, the risk posed by invasive species, etc. Furthermore, pressures such as noise- and light pollution are not covered in common life cycle impact assessment methods due to a lack of inventory data and characterization factors [11]. Such complex dynamics are difficult to capture in a single indicator, and require a set of highly location-specific metrics. This is the kind of approach used in site-specific assessments for company-level reporting frameworks such as SBTN or the EU CSRD. The CSRD does not enforce a particular set of indicators, but requires reporting on impacts close to protected area, land- and freshwater use, etc. SBTN uses indicators of species endemism, richness and extinction risk, ecosystem integrity, connectivity, ecosystem services, etc. However, since carrying out such detailed assessments over the entire supply chain would be too complex, SBTN still relies on generic environmental databases for the rest of the life cycle, beside known impact sites. SBTN requires companies to model sourcing location at least at the country level if possible, and ideally specifying more precise locations, since this influences the assessment of pressures and biodiversity metrics.

The generic data used in the Biotool (and in common LCA databases) is useful to screen and prioritise hotspots, and to fill data gaps, but it is insufficient for thorough, location-specific biodiversity impact assessments. There is therefore a crucial need to develop product-specific, spatially-differentiated life cycle inventories for construction products that constitute important biodiversity hotspots. In the long term, linking together information from CSRD reports and EPDs offers an important opportunity to harmonise approaches for biodiversity impact assessments, not least because CSRD reporting is currently the most important driver leading companies to track their biodiversity impact in the EU.

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Supplementary information: The Doughnut Biotool can be freely downloaded at https://github.com/NFrancart/doughnut-biotool

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